Review of US EPA's "Draft Investigation of Ground Water Contamination near Pavillion, Wyoming"

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Executive Summary

In response to residents' complaints of objectionable odors and tastes in well water near the town of Pavillion, Wyoming, the United States Environmental Protection Agency (US EPA) initiated a groundwater investigation in 2009. After four phases of sampling, and installing only five monitoring wells over a study area of 50 square miles, US EPA (2011) released its "Draft Investigation of Ground Water Contamination near Pavillion, Wyoming" report ("Study"). This critique of the US EPA Study, prepared on behalf of Halliburton Energy Services Inc., indicates that the Study design was flawed, the Study implementation (*i.e.*, field work and data quality evaluation) was very poor, and the analysis of the data is not based on sound science. Consequently, US EPA's methods and data do not support the conclusion reached in the report that "inorganic and organic constituents associated with hydraulic fracturing have contaminated ground water at and below the depth used for domestic water supply" (US EPA, 2011, p. 39).

Location and Geologic Setting

The Pavillion study area overlies the Wind River Formation, which is the principal source of domestic, municipal, and agricultural water in the area. The study area also overlies the Pavillion Gas Field, which contains approximately 169 natural gas wells that produce gas from the Wind River and the underlying Fort Union Formations. Natural gas production in the Pavillion Gas Field began in the 1960s. Most natural gas wells currently producing in the Pavillion area have been installed and developed using hydraulic fracturing (HF) methods to enhance natural gas production. The active production wells in the Pavillion area typically range in depth from 358 to 1,746 meters (1,264 to 5,728 feet) below ground surface (bgs) (WOGCC, 2012).[1]

As noted in the Study, the geology of the Wind River Formation is highly variable. A complex series of interbedded sandstone, siltstone, shale, claystone, conglomerate, and limestone underlies the area (URS, 2010a). The sandstones are water bearing (*i.e.*, a water supply source that is tapped by domestic wells in Pavillion) and have trapped natural gas at shallow depths in the region. For example, the Plunkett gas field, which draws gas from the Wind River Formation several miles south of the Pavillion Gas Field, has historically yielded natural gas from strata as shallow as 50 to 55 meters (165 to 182 feet) bgs (USGS, 1945).

US EPA Investigation

Beginning in March 2009 and ending in April 2011, US EPA conducted four sampling events as part of its Pavillion-area investigation (Phase I – IV):

- Phase I (March 2009) – US EPA collected ground water samples from 37 domestic and agricultural livestock wells and two municipal wells. With the exception of five domestic wells ranging from 205 to 244 meters (672 to 800 feet) bgs, the remaining 34 domestic and municipal well depths were less than 150 meters (492 feet) bgs, with the majority falling within a range of 50 to 150 meters (164 to 492 feet) bgs.[2]

[1] These represent the depths at which the gas well casings were perforated and the formations were hydraulically fractured.
[2] Some of the domestic wells are of unknown depth.

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- Phase II (January 2010) – US EPA collected additional groundwater samples from the domestic wells and three shallow monitoring wells that were installed near known locations of formerly unlined pits used previously to handle oil and gas drilling-related materials.
- Phases III (October 2010) and IV (April 2011) – US EPA installed two deep monitoring wells beginning in June 2010: MW01 screened at a depth of 233 to 239 meters (765 to 785 feet) bgs, and MW02 screened at a depth of 293 to 299 meters (960 to 980 feet) bgs. US EPA collected groundwater samples from these two deep monitoring wells in October 2010 and April 2011, along with a subset of domestic wells that had been sampled in previous phases.

EPA subsequently prepared a report summarizing the data collected and setting forth the Agency's conclusions based on its analysis of the data.

An environmental study such as this can be considered from the standpoint of three basic components: study design, study implementation, and data analysis. In all three components, the US EPA Study was deficient, as described below.

US EPA's Study Design Was Inherently Flawed

US EPA indicates that its Study was designed to "determine the presence, not extent, of ground water contamination in the formation and if possible to differentiate shallow source terms (pits, septic systems, agricultural and domestic practices) from deeper source terms (gas production wells)" (US EPA, 2011, p. xi).

Differentiating sources of contamination in a complex and heterogeneous setting encompassing 50 square miles, such as the Pavillion study area, requires a significant number of observation points (*e.g.*, sufficient monitoring well density) distributed throughout the study area and at a range of depths.[3] Aside from collecting samples from domestic water wells, the Study included the installation of only three shallow monitoring wells (adjacent to former surface pits used to handle oil and gas drilling-related materials) and two deep monitoring wells. The limited number of monitoring wells installed during the Study cover only a very small portion of the study area. A study with so few monitoring wells is inherently incapable of answering basic questions that are paramount when addressing whether HF activities (or other factors, such as natural gas presence) have any impact on deep groundwater quality and whether there is any correlation between deep and shallow groundwater quality (*e.g.*, at the domestic water wells). The following critical flaws render the Study incapable of addressing its stated objective of differentiating between potential source areas:

- Given the extremely limited number of monitoring wells installed for the Study, and the lack of any nested wells, the Study was not designed to determine local or regional hydraulic gradients (which determine the direction of groundwater flow – upward *versus* downward). Compounding this problem, US EPA failed to acknowledge or use existing information on the hydrogeological setting in its study design. Although the Study indicates that "[h]ydraulic gradients are *currently undefined* in the area of investigation" (US EPA, 2011, p. xiii, emphasis added), there is a wealth of information from the United States Geological Survey (USGS) and others that clearly indicates the hydraulic gradient in the study area is downward.[4] Despite this information, US EPA's analysis and conclusions presumptively – yet incorrectly – assume that regional groundwater flow is upward.

[3] We are setting aside other basic study design issues such as providing an unambiguous definition of what was meant by the "ground water contamination of the formation." The Study never provided a definition of the "formation."

[4] US EPA's two deep monitoring wells are nearly two miles apart and may not be hydraulically connected. However, to the extent they provide relevant information on hydraulic gradients, the water levels in these two wells indicate a downward hydraulic gradient.

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- The extremely limited number of monitoring wells, and the depths at which they were installed, also compromised US EPA's ability to determine whether "deep source terms" have impacted domestic wells in the study area. Two wells are entirely insufficient to characterize conditions in the large study area. Moreover, the vast majority of domestic wells in the study area (including all municipal wells) are 50 to 160 meters (164 to 525 feet) deep, whereas US EPA installed its two deep monitoring wells far below this zone – at depths of 233 to 299 meters (765 to 960 feet) bgs. These wells are inherently incapable of evaluating whether "deep source terms" are impacting the shallower domestic wells because the natural direction of groundwater flow is downward, *i.e.*, from the monitoring wells to greater depths in the formation. Moreover, the strata where US EPA's deep monitoring wells were screened are within or proximate to gas bearing zone(s). In addition, MW02 produced so little water that, in all likelihood, the zone in which it was installed would not even meet the definition of an Underground Source of Drinking Water (USDW). Thus, the deep monitoring wells were not installed at depths appropriate to characterize the local drinking water aquifers and data from these wells are not representative of drinking water aquifers in the Pavillion area.
- US EPA failed to characterize background concentrations of constituents in groundwater, especially with respect to organic constituents. Without such information, it is impossible to draw any meaningful conclusions about the potential sources of constituents detected in monitoring wells, especially in an area that is naturally rich in petroleum hydrocarbons.
- US EPA failed to adequately characterize the nature of HF stimulations in the study area. In particular, US EPA failed to characterize the volumes and types of HF stimulations, which are predominately low-volume treatments that utilize carbon dioxide (CO_2) foam. The failure to consider the type of HF stimulations that have occurred in the Pavillion area has led to flawed interpretations of the potential for HF fluid migration and the potential changes to groundwater geochemistry that would be associated with HF fluid migration.

US EPA (2011) appears to acknowledge the inherent limitations in its Study:

> [T]he existing data at this time do not establish a definitive link between deep and shallow contamination of the aquifer. An increased number of sampling points (monitoring wells) with vertical profiling in targeted locations are necessary to better define transport and fate characteristics of organic and inorganic contaminants in the ground water system and impact on domestic wells. (p. 27)

Yet, despite this acknowledgement, the Study presents the conclusion that HF activities have impacted groundwater at depths where domestic wells occur. This conclusion is not supportable, given the extremely sparse monitoring well network utilized by US EPA in its Study,[5] the fact that the two deep monitoring wells were installed at depths that are not representative of drinking water aquifers in the Pavillion area (the wells are screened in a gas producing zone significantly below the strata predominantly used for domestic wells and the water is saturated with methane), and the numerous other Study implementation problems that severely undermine the quality of the data.

[5] It is questionable whether the term "network" is appropriate, given that only two deep monitoring wells were installed.

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US EPA's Study Implementation Was Very Poor, Undermining the Reliability of the Monitoring Results

US EPA's implementation of the Study (*i.e.*, field work execution and data quality review) did not follow Agency guidance or the project Work Plan for groundwater sample collection (US EPA Region I, 1996, 2010; URS, 2010b). In addition to this fundamental flaw, US EPA failed to install and develop the deep monitoring wells properly, which compromised the groundwater quality data and resulted in faulty interpretations of groundwater chemistry. Furthermore, US EPA did not review the quality of the data adequately prior to using it, such that the Study conclusions are overreaching and unsupported by the data. Some of the Study's key implementation shortcomings are summarized below.

- During installation of the deep monitoring wells, US EPA did not keep records of the volume of drilling fluid (*i.e.*, water and mud) used and lost into the formation during the drilling process – a standard industry practice (*e.g.*, US EPA Region IV, 2008; US EPA, 1991; Driscoll, 1986) required by the project Work Plan (URS, 2010b). In addition, US EPA did not use a tracer (*e.g.*, fluorescent dye) in the drilling fluid – another standard industry practice for monitoring wells installed using mud rotary techniques (*e.g.*, Wandrey *et al.*, 2010). The use of drilling fluid volume records (to conduct a fluids balance), or the use of a tracer or dye in the drilling mud, would have enabled steps to be taken to ensure that any drilling fluid remaining in the vicinity of the borehole was removed (a process referred to as well "development") prior to groundwater sample collection.
- US EPA did not install a bentonite seal above the deep monitoring well screens, a requirement of the project Work Plan (URS, 2010b) and standard industry practice for groundwater monitoring wells (US EPA, 1991; Driscoll, 1986). Instead, Portland cement was pumped into the borehole directly above the well screen to create an approximately 15-foot thick cement plug. The lack of an adequate annular seal above the well screen is a major deficiency of the US EPA-installed monitoring wells that, in all likelihood, placed cement grout in direct contact with groundwater sampled from the well's screen. The cement grout is likely responsible for the elevated pH (~12) observed in the deep monitoring wells.
- US EPA did not follow standard practice or the project Work Plan (URS, 2010b) during development of the deep monitoring wells. At MW02, less than two (2) well volumes (compared to a standard of five (5) well volumes) were removed before well development was halted due to methane accumulation in the well. The slow recharge rate at this location (approximately 1 month after well development the water level in the well was still 89 meters (293 feet) below the static water level) is a potential indicator of inadequate well development and cement intrusion into the well screen.[6]
- The groundwater sampling methodology used at the deep monitoring wells was unconventional and did not follow current industry standards or the project Work Plan (URS, 2010b, US EPA Region I, 2010). The monitoring wells were purged at rates between 30 to 50 times higher than the flow rate recommended by US EPA to enable collection of representative aquifer samples (US EPA Region I, 2010).
- US EPA ignored standard sampling protocols, which require that a sample be collected only after field parameters (*e.g.* pH, specific conductivity) have stabilized. During Phase III, US EPA collected groundwater at MW02 despite a clear indication from the field monitoring data that water with dramatically different geochemistry had entered the well immediately prior to sample collection (*e.g.*, in the 6-six-minute interval before sample collection, the pH increased from 9.75

[6] The slow water level recovery could also be an indication of a low productivity water bearing formation in the vicinity of MW02, that would not be suitable for providing drinking water.

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to 12.22). These data clearly demonstrated additional well development was needed at MW02 prior to sample collection.

In addition to these fundamental flaws in the well installation and development, there were inherent data quality limitations that compromise the Study results (and conclusions):

- US EPA utilized a non-standard analytical test method to analyze glycols and 2-butoxyethanol (2-BE), without validating the method and confirming that it was capable of producing reliable results (*e.g.*, not prone to false positives). This unorthodox approach used by US EPA is reflected in the laboratory report narrative (US EPA Region III, 2011, emphasis added):

  > *Because the method was being developed as samples were being analyzed, it is not known if the QC [quality control] data for percent recoveries and RPDs [relative percent differences] are appropriate."*

  The reliability of the glycols and 2-BE monitoring results are highly questionable, given the use of a non-standard and unproven analytical test method. This is an important deficiency because the Study places significant importance on the glycols and 2-BE data as "implicating" HF activities. The data quality limitations call the validity of this interpretation into serious question.

- A wide variety of compounds (*e.g.*, hydrocarbons, methane, and glycols) were routinely detected in the field, equipment, and trip blank samples. For example, methane was detected in every blank sample (total of five) collected during Phase III and IV of the Study at concentrations ranging from 45 to 76 µg/L. No methane blanks were collected in Phases I and II. The routine and widespread detection of contaminants in the blanks is indicative of substandard field sampling practices. Finally, US EPA did not follow its own data quality assessment guidelines (*e.g.*, US EPA, 2006) and did not take appropriate actions in addressing the presence of blank contamination. If US EPA had followed its own data quality assessment guidance (considering all concentrations less than 5 to 10 times the concentration detected in the blanks as non-detect [7]), a large subset of the data for certain compounds, such as methane and hydrocarbons, would be considered non-detected.

In summary, the poor and non-standard practices used in implementing the Study and in assessing the quality of the data severely limit the reliability of the monitoring results for decision making. If a private party had used similar practices in such a study, the results would almost certainly have been rejected by the Agency.

US EPA's Findings and Conclusions Are Not Based on Sound Science

US EPA presents multiple "lines of reasoning" to argue that "inorganic and organic constituents associated with hydraulic fracturing have contaminated groundwater at and below the depth used for domestic water supply" (US EPA, 2011, p. 39). In the Study, US EPA hypothesizes that the presence of inorganic (high pH, potassium, and chloride) and organic (methane, petroleum hydrocarbons, glycols, and alcohols) constituents in the deep monitoring wells is attributable to HF fluids, which the Agency surmises have preferentially migrated along poorly cemented gas production wells. US EPA also alleges that methane detected in domestic water wells is the result of "enhanced" migration – a consequence of

[7] Minimum detection levels are calculated as 5 times the maximum blank concentration for most compounds, and 10 times for common laboratory contaminants such as toluene, methylene chloride, or bis(2-ethyl)hexylphthalate (US EPA, 1994).

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HF activities and increased natural gas development in the last two decades. As noted above, the data on which US EPA bases its conclusions are unreliable. Yet, even if those data were considered reliable, the technical analysis used to support US EPA's lines of reasoning is flawed for the following reasons:

- **Elevated pH, Potassium, and Chloride:** US EPA asserts that pH, potassium, and/or chloride are elevated at the deep monitoring wells as a result of HF activities. However, these conditions appear to be the result of cement grout intrusion into the monitoring well screens, and not due to migration of HF fluids. For example, most of the HF stimulations in Pavillion utilized a CO_2-based fluid (CO_2 foam fracturing), which would have an acidic pH (*i.e.*, < 7) and not the high (caustic) pH values observed in the deep monitoring wells. Therefore, HF fluids are not a plausible source of the high pH in the samples from the deep monitoring wells. At the same time, laboratory experiments and field case studies have demonstrated that the pH of cement and associated pore water can range from 12 to 13.8 (Leemann and Lothenbach, 2008; CEMEX, 2001). The pH in monitoring wells affected by cement grout intrusion can stay high (*e.g.*, > 11) even after multiple attempts to redevelop the well (Barcelona and Helfrich, 1986; Mercer *et al.*, 2007). Potassium is also a significant component of cement, with concentrations over 460 times the maximum concentration found in the deep monitoring wells having been measured in cement (Leemann and Lothenbach, 2008). Chloride was likewise a component of the cement used in constructing MW01 and MW02; calcium chloride was added to the cement mix. This accounts for the elevated chloride concentrations in samples from MW02, where well development was inadequate; elevated chloride concentrations were not found in samples from MW01, which was more extensively developed. In short, the absence of a bentonite seal in the deep monitoring wells installed by US EPA allowed unimpeded flow of cement grout to the well screen and cement-induced geochemical changes to the groundwater in its vicinity.
- **Petroleum Hydrocarbons:** The elevated petroleum hydrocarbon concentrations detected in the deep monitoring well (MW02) are associated with natural gas present in the formation. The chemical signature of petroleum hydrocarbons such as benzene, toluene, ethylbenzene, and xylenes (BTEX), and tri-methylbenzenes detected in MW02 matches that of a condensate sample collected by US EPA from a natural gas well in Pavillion – an indication that these petroleum hydrocarbons could have been derived from the natural source in the area. The petroleum hydrocarbon signature found in MW02 was absent in the other deep monitoring well (MW01), which is consistent with the heterogeneous and compartmentalized nature of the Wind River Formation in the study area.
- **Synthetic Organic Compounds:** As discussed above, the glycol and 2-BE data are unreliable and not usable for decision making. Other organic constituents, such as hydrocarbons, acetone, isopropanol, and tertiary butyl alcohol (TBA) are naturally produced by microorganisms as breakdown products of natural gas and are unlikely to be associated with HF activities.
- **Incorrect Inferences of Perceived Concentration Gradient of Degradation Products:** US EPA theorizes that the "enriched" concentrations of breakdown or degradation products of petroleum hydrocarbons (*e.g.*, acetate and benzoic acid) at MW01 (shallower well) relative to the same constituents in MW02 (deeper well) is an indication of upward groundwater migration along with degradation. This theory relies upon the (incorrect) presumption that the groundwater flow is <u>upward</u>. This presumption is apparently based on anecdotal information about "flowing" stock wells and is a flawed interpretation of regional groundwater flow. Regional studies indicate that the hydraulic head gradient in Pavillion is <u>downward</u> (*e.g.*, McGreevy *et al.*, 1969; Nelson *et al.*, 2009). Furthermore, if deep groundwater was a source of "contamination" to the domestic wells, concentrations of natural gas-related compounds (*e.g.*, diesel range organics, or DRO) would be expected to increase with depth in the domestic wells. However, there is no correlation between DRO and depth. Accordingly, the conclusion reached in the Study that HF activities are

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responsible for constituents in the aquifer "at and below the depth used for domestic water supply" is not supported by the scientific evidence.

- **Purported Migration Pathways:** US EPA theorizes that chemicals could migrate upward from the gas-bearing zone through the formation rock and *via* well annuli. These purported pathways for migration of HF fluid do not take into account the nature of HF stimulations or the hydrogeology of the Study area. During an HF stimulation, upward migration through the formation rock is highly unlikely, given that the anticipated direction of fracture propagation is horizontal. Migration of HF fluids to an adjacent production well is similarly unlikely, given the low volume of HF fluids used in the Pavillion area, short duration of the stimulations, and large available pore volume in the subsurface compared to the volume of HF fluids used. Subsequent to an HF stimulation, upward migration *via* any pathway (either through formation rock or *via* well annuli) is not plausible, because the direction of groundwater flow is downward in the Pavillion area. Furthermore, the preponderance of thick, low-permeability shale layers throughout the area (even if discontinuous) would severely restrict upward migration, even if hydraulic gradients were upward.
- **Methane:** The hypothesis presented in the Study that HF activities have enhanced the migration of methane has several flaws. The Wind River Basin (of which the Pavillion Gas Field is part) is a natural gas-rich region, and the presence of methane at shallow depths, before a majority of the gas wells were drilled and hydraulically fractured in the region, is well documented (WOGCC, 2012). In addition, there is no correlation between methane concentrations in domestic wells and proximity to gas production wells or depth. An examination of methane concentrations in domestic wells *versus* gas well density in proximity to drinking water wells demonstrates no pattern, with a number of domestic wells showing non-detect values or extremely low concentrations of methane despite being surrounded by large numbers of gas production wells. Similarly, methane concentration *versus* depth demonstrates no correlation, whereas concentrations would be expected to increase with depth if methane migration from an underlying gas-producing formation was being enhanced by HF activities. Finally, the domestic well methane data are unreliable because methane was detected in all field blanks (when collected) at concentrations of 45 to 76.4 µg/L. Only four (4) domestic wells had methane concentrations above the concentration in the blank samples, and only one (1) domestic well (PGDW30) had methane concentrations more than five times (5×) the maximum chemical concentration in blank samples. Consequently, almost all of the methane data for domestic wells would have been qualified as non-detects following US EPA data quality assessment guidance (US EPA, 1994).

In sum, the "lines of reasoning" used by US EPA – the basis for its conclusions – rely on poor quality and unreliable data (*e.g.*, glycol and methane measurements), do not take account of the scientific literature (*e.g.*, effect of cement intrusion on water quality), and do not adequately consider the available data (*e.g.*, incorrect conclusion regarding head gradients and the direction of groundwater flow).

Conclusions

Based on the fact that the Study design was inherently flawed, the Study was poorly implemented, and the analysis presented is not technically defensible, US EPA's conclusory finding that "inorganic and organic constituents associated with hydraulic fracturing have contaminated groundwater at and below the depth used for domestic water supply" is unsupportable as a scientific matter. Based on our scientific review, we would expect that a thorough peer review of the Study will identify its significant shortcomings, deficiencies that are so significant as to reject the premature findings presented in the Study.

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We recognize that US EPA is conducting an additional round of monitoring well sampling in Pavillion. To the extent that the sampling is confined to the existing monitoring wells, such sampling will not address the inherent limitations of US EPA's Study design nor the flaws in the construction of the deep monitoring wells that have compromised the data from those wells. If US EPA wishes to correct these deficiencies in its investigation, additional steps would need to be taken.[8]

As our analysis demonstrates, the data from the Agency's deep monitoring wells do not provide evidence that the deeper portion of the aquifer is contaminated by HF activities and provide no information relating to groundwater conditions in the portion of the aquifer predominantly used for drinking water. For reasons summarized above, and elaborated upon further in this report, the Study does not provide evidence that hydraulic fracturing has caused or contributed to contamination of the drinking water aquifer in the Pavillion area.

[8] It is questionable whether additional well development efforts will adequately eliminate the effects of cement on the monitoring well water quality because studies have shown that cement impacts can persist long after well installation and despite numerous attempts at well re-development (see Section 4.1).

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1 Introduction

The United States Environmental Protection Agency (US EPA) initiated a ground water investigation near the town of Pavillion, Wyoming in 2009. After four phases of sampling, and installing only a handful of monitoring wells, the US EPA (2011) released its "Draft Investigation of Ground Water Contamination near Pavillion, Wyoming" report ("Study"). This critical review of the US EPA Study, prepared on behalf of Halliburton Energy Services Inc., indicates that the Study design was flawed, the Study implementation (*i.e.*, field work and data quality evaluation) was very poor, and the analysis of the data is not based on sound science. Consequently, US EPA's methods and data do not support the conclusion reached in the report that "inorganic and organic constituents associated with hydraulic fracturing have contaminated groundwater at and below the depth used for domestic water supply" (US EPA, 2011, p. 39).

1.1 Location and Geologic Setting

The Pavillion study area overlies the Wind River Formation, which is the principal source of domestic, municipal, and agricultural water in the area. Groundwater quality in the study area is significantly affected by the recharge of irrigation water, which carries salts with it into the underlying aquifers and causes water quality to be poor in general (Morris *et al.*, 1959). The study area also overlies the Pavillion Gas Field, which contains approximately 169 natural gas wells that produce gas from the Wind River and the underlying Fort Union Formations. Historically, natural gas production in the Pavillion Gas Field dates to the 1960s, although a large number of gas wells were installed in the late 1990s through 2005. Natural gas wells currently producing in the Pavillion area have been installed and developed using hydraulic fracturing (HF) methods to enhance natural gas production. The active gas production wells in the Pavillion area typically range in depth from 385 to 1,746 meters (1,264 to 5,728 feet) below ground surface (bgs) (WOGCC, 2012).[9]

As noted in the Study, the geology of the Wind River Formation, is highly variable. The Wind River Formation is sedimentary in origin, derived from the erosion of the nearby mountain ranges. Consequently, a complex series of inter-bedded sandstone, siltstone, shale, claystone, conglomerate, and limestone underlies the area (URS, 2010a). The sandstones are of key interest since they are water bearing (*i.e.*, a water supply source that is tapped by domestic wells in Pavillion) and have also trapped natural gas at shallow depths in the region. For example, the Plunkett gas field, which draws gas from the Wind River Formation several miles south of the Pavillion Gas Field, has historically yielded natural gas from strata as shallow as 50 to 55 meters (165 to 182 feet) bgs (USGS, 1945). These gas wells date back to the 1920s to 1940s, prior to the advent of HF methods in the 1950s. In addition, methane was found at relatively shallow depths (157 to 326 m or 515 to 1,070 ft bgs) in a number of locations in Pavillion before HF activities began (WOGCC, 2012).

[9] These represent the depths at which the gas well casings were perforated and hydraulically fractured.

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1.2 US EPA Investigation

EPA received complaints from residents of Pavillion regarding objectionable odors and tastes in well water. In response, EPA initiated an investigation in 2008 under the authority of the Comprehensive Environmental Response, Compensation and Liability Act. Beginning in March 2009 and ending in April 2011, US EPA conducted four sampling events (Phase I – IV) in the Pavillion study area.

- Phase I (March 2009) – US EPA collected ground water samples from 37 domestic and agricultural livestock wells and two municipal wells. With the exception of five domestic wells ranging from 205 to 244 meters (672 to 800 feet) bgs, the remaining 34 domestic and municipal well depths were less than 150 meters (492 feet) bgs, with the majority falling within a range of 50 to 150 meters (164 to 492 feet) bgs.[10]
- Phase II (January 2010) – US EPA collected additional groundwater samples from the domestic wells and three shallow monitoring wells that were installed near known locations of formerly unlined pits used previously to handle oil and gas drilling-related materials. US EPA also collected gas and produced water samples from several area production wells.
- Phases III (October 2010) and IV (April 2011) – US EPA installed two deep monitoring wells beginning in June 2010: MW01 screened at a depth of 233 to 239 meters (765 to 785 feet) bgs, and MW02 screened at a depth of 293 to 299 meters (960 to 980 feet) bgs. US EPA collected groundwater samples from these two deep monitoring wells in October 2010 and again in April 2011 using an expanded analyte list. Phases III and IV also included sampling of a subset of domestic wells that had been sampled in previous phases.

EPA is currently in the process of conducting another round of sampling of the deep monitoring wells.

1.3 Report Organization

In our review of the US EPA Study, we first examine and discuss some of the critical and inherent flaws in the Study design (Section 2). The design flaws are so significant that, even if the Study had been implemented according to sound practices and good science, the information generated would have been unable to address one of its important stated objectives: determining whether "deep source terms" (*e.g.*, HF activities) are responsible for any constituents found in drinking water wells. In Section 3, we discuss the many flaws in the installation and development of two deep monitoring wells (MW01 and MW02). The Study reaches broad conclusions on the basis of data from these two wells, yet, as our review indicates, improper installation and development of the wells is the likely cause of many of the "anomalous" or elevated constituent concentrations that are incorrectly attributed to HF activities. Even if MW01 and MW02 had been installed and developed correctly, there are numerous scientific flaws in US EPA's analysis of the data collected from drinking water wells and monitoring wells, as discussed in Section 4. In addition, non-standard analytical methods and poor data quality severely limit the utility of the data and the conclusions drawn from them. We discuss these scientific flaws and data quality problems in Section 4.

As demonstrated throughout our analysis, the US EPA Study prematurely reached overbroad conclusions that are either unsupported by the data, based on flawed interpretations of the data, or based on unreliable data altogether (or a combination of the three). The analysis and conclusions presented in the Study do not provide evidence that hydraulic fracturing has caused or contributed to contamination of the drinking water aquifer in the Pavillion area.

[10] Some of the domestic wells are of unknown depth.

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2 US EPA's Study Design Was Inherently Flawed

US EPA indicates its Study was designed to "determine the presence, not extent, of ground water contamination in the formation and if possible to differentiate shallow source terms (pits, septic systems, agricultural and domestic practices) from deeper source terms (gas production wells)" (US EPA, 2011, p. xi).

In order to achieve these goals, the key components of the Study included:

- Collecting and analyzing samples from domestic water wells and several agricultural (livestock) wells in the Pavillion study area;
- Installing and sampling three (3) shallow monitoring wells adjacent to former surface pits previously used to handle oil and gas drilling-related materials;
- Installing and sampling two (2) deep monitoring wells, approximately two miles apart, at depths beneath most of the domestic water wells; and
- Sampling gas condensate from several gas production wells.

Yet US EPA's study was largely incapable of addressing the stated objectives. For example, while US EPA installed three shallow monitoring wells to assess contamination from former surface pits, there was nothing in the US EPA Study that addressed septic systems or agricultural and domestic practices as possible sources contributing to perceived water quality problems in local wells. US EPA also did not evaluate or establish background data for the organic constituents present in regional groundwater, and it considered background data for only a limited number of inorganic constituents based on data from United States Geological Survey (USGS) studies, thereby compromising its ability to determine whether many constituents detected in the deep monitoring wells were naturally occurring.

Perhaps the most inherently serious shortcoming of the US EPA study is that it simply was not designed to address the stated objective of determining whether "deeper source terms" were contributing to constituents in drinking water wells – almost all of which are shallower than the US EPA monitoring wells. As noted above, with the exception of five drinking water wells, the wells in the Pavillion study area are 200 meters (656 feet) deep or shallower, with most (including all of the municipal wells) falling in the 50 to 160 meter (164 to 525 feet) depth range. Yet, US EPA did not install a single monitoring well within this depth interval. Instead, both deep monitoring wells were installed nearly 100 to 150 meters (328 to 492 feet) below this interval.

2.1 US EPA Did Not Establish Hydraulic Connection or Groundwater Flow Direction Between Its Deep Monitoring Wells and Overlying Wells

One of US EPA's primary research questions was whether "deeper source terms" have contributed to contamination in overlying wells. As a prerequisite to evaluating deeper source terms, it is critical to define the direction of groundwater flow and whether the flow direction would allow for upward migration of constituents from depth. However, US EPA's study design included a very limited number

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of wells (two deep wells), and did not establish the vertical groundwater flow direction. Instead, US EPA relied on anecdotal information (*i.e.*, presence of a "flowing" stock well) to infer upward flow gradients. US EPA should have leveraged existing hydrogeologic data collected by USGS and others that indicate the groundwater flow direction throughout the Pavillion area is downward, not upward, as presumed in the Study. US EPA's inadequate Study design – inappropriate placement of wells and failure to leverage existing data – greatly undermined its ability to address its research questions, even if other aspects of the study had been done correctly.

2.1.1 US EPA Failed to Incorporate Existing Hydrogeologic Data and Groundwater Flow Patterns into Its Study Design

US EPA did not review nor incorporate into its study design the large body of existing information on regional groundwater flow patterns in the Pavillion area. Instead, US EPA incorrectly states that "[h]ydraulic gradients are *currently undefined* in the area of investigation" (US EPA, 2011, p. xiii, emphasis added). This is a critical flaw in the Study, because the direction of the hydraulic gradient is the driving factor that governs the direction of chemical migration. As discussed below, there is a wealth of hydrogeologic data that US EPA could have used to determine vertical groundwater flow patterns in the Pavillion area before designing its study.[11]

Several studies by USGS and others have been undertaken to evaluate the hydrogeology and hydrocarbon reservoirs in the Pavillion area, with some reports dating back to the 1950s (*e.g.*, Morris *et al.*, 1959; Daddow, 1992; Plafcan *et al.*, 1995). These historical hydrogeologic data indicate that flow within the Wind River Basin in the Pavillion area is downward. One approach for evaluating the direction of groundwater flow is to install a set of nested or clustered wells. Nested/clustered wells are a series of wells installed at a single location, with each well installed successively deeper than the previous one. In this configuration, the nested/clustered wells allow one to measure the water levels and chemical concentrations along a vertical profile in the aquifer and thereby determine the direction of vertical groundwater flow and chemical migration. Previously, USGS used nested wells to evaluate the direction of vertical groundwater flow in the Pavillion area and found that the direction of flow was consistently downward in a long-term (1.5-year) study (McGreevy *et al.*, 1969).

Another approach for determining the vertical direction of groundwater flow is to plot groundwater elevations from wells within a region against well depths. If groundwater elevations decrease with depth, this is an indication that flow is downward. We undertook such an analysis with recent groundwater data, which is shown in Figure 2.1 (data from James Gores and Associates, 2011). This plot shows that groundwater elevation decreases with depth in the Pavillion area, indicating that groundwater flow is downward. Note also that the water levels for MW01 and MW02 plotted on Figure 2.1 are also consistent with a downward regional hydraulic gradient.

A third approach for evaluating the direction of vertical groundwater flow is to examine reservoir pressure measurements (*i.e.*, fluid pore pressure) in gas production wells and compare them to hydrostatic (groundwater) pressures at the same depth as the gas wells. If the pore pressure is below hydrostatic, then the direction of groundwater flow is downward (*i.e.*, toward the stratum where the gas well is located). USGS has compiled pore pressures in gas wells for the upper Fort Union Formation and shallower formations (*e.g.*, the Wind River Formation). These data indicate that pore pressures are consistently less than hydrostatic pressures (Nelson *et al.*, 2009), providing yet another line of evidence that the direction of regional groundwater flow is downward.

[11] US EPA also did not incorporate information regarding bedrock fractures (e.g., McGreevy, 1969; USGS, 2008), or consider how characteristics of the fracture network could influence groundwater flow rates and directions in anisotropic media.

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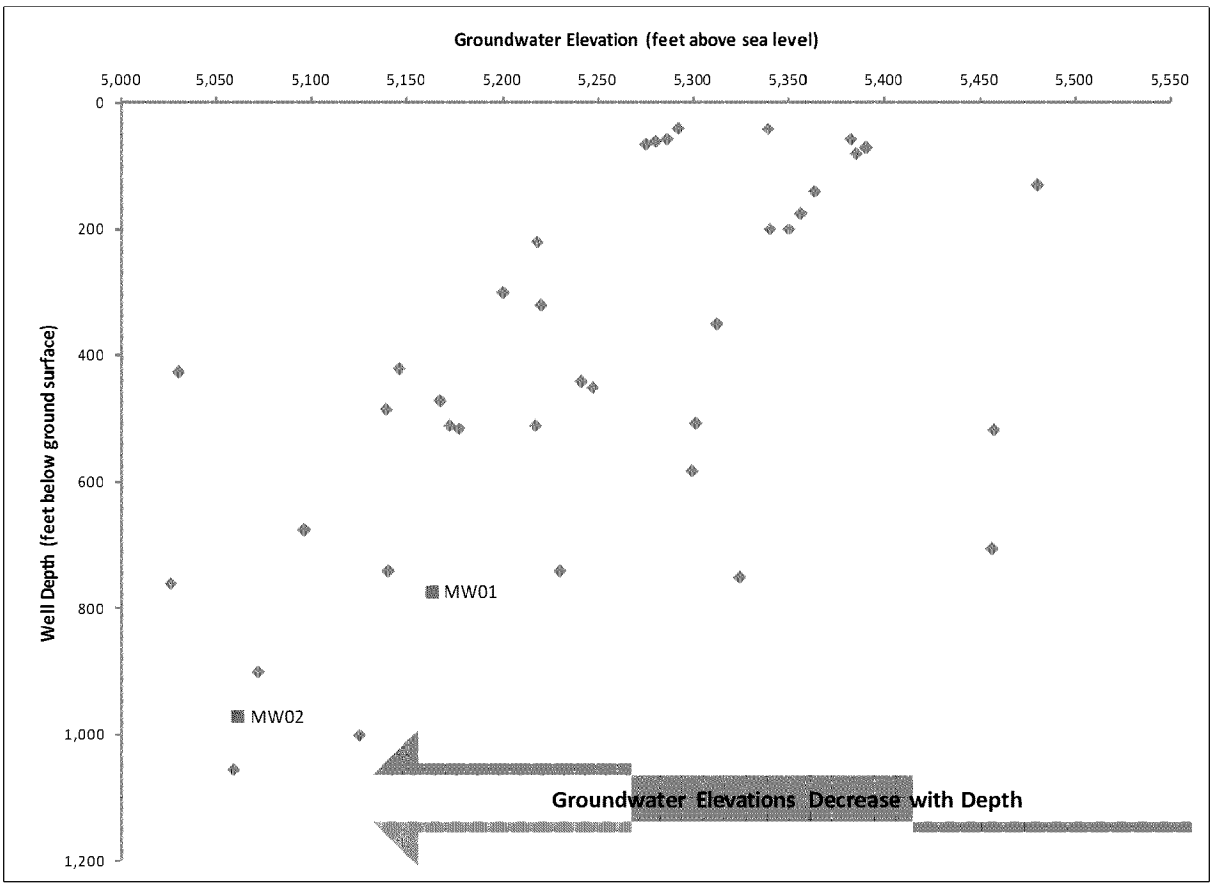

Figure 2.1 Regional Depth Trend in Groundwater Data Indicates Downward Flow

2.1.2 US EPA's Deep Monitoring Wells Are Incapable of Addressing the Study Objectives

To address the question posed by US EPA of whether "deeper source terms" contribute to contamination in overlying domestic wells, US EPA installed two (2) deep monitoring wells approximately 3,000 meters (almost two miles) apart, within a study area of approximately 130 square kilometers (50 square miles).[12] These two wells by themselves are inherently incapable of addressing whether gas production wells have contributed to the presence of any contaminants in the drinking water aquifer, particularly in the shallower portion of the aquifer where most of the domestic wells are screened. Given that there is "substantial vertical and lateral stratigraphic variation over short distances in both formations [Wind River and Fort Union]" (US EPA, 2011, p.2), the installation of only two (2) monitoring wells in a study area covering over 50 square miles clearly does not capture sufficient information to draw broad conclusions about the impact of HF activities in such a highly variable setting.

In the Study, US EPA notes that the "expense of drilling deep wells while using blowout prevention was the primary limiting factor in the limited number of wells installed" (US EPA, 2011, p. 5).[13] This is an

[12] EPA also installed three (3) shallow monitoring wells near former surface pits previously used to handle oil and gas drilling-related materials. Note that the results from the three (3) shallow monitoring wells (< 5 meters deep) do not address the question of whether HF activities have caused migration of constituents from the gas-producing zone to overlying drinking water wells.
[13] The use of blowout prevention methods is a recognition that the deep wells were penetrating into probable gas-bearing zones.

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implicit recognition that the study was "limited" not based on scientific reasons, but due to cost. Given the cost constraints and the available hydrogeologic data (discussed in Section 2.1), instead of two widely spaced wells, the Agency would have been better served installing nested wells (see Section 2.1.1) targeting shallower portions of the aquifer that are more widely used as the source of drinking water in Pavillion. This would have enabled US EPA to utilize its limited budget more effectively and led to the collection of meaningful data to better understand local groundwater flow directions and define groundwater quality – both of which are needed for assessing whether "deep sources," if any, are impacting groundwater quality at the domestic wells.

US EPA appears to acknowledge – at least implicitly – the inherent inability of its study to answer the question of whether HF activities have contributed to any contamination in drinking water wells:

> [T]he existing data at this time do not establish a definitive link between deep and shallow contamination of the aquifer. An increased number of sampling points (monitoring wells) with vertical profiling in targeted locations are necessary to better define transport and fate characteristics of organic and inorganic contaminants in the ground water system and impact on domestic wells. (p. 27)

Despite acknowledging this inherent limitation, US EPA nevertheless used anecdotal evidence of "flowing stock wells" to draw conclusions about a critical transport parameter, stating that "upward gradients exist in the area of investigation" (US EPA, 2011, p. 36). However, as discussed in Section 2.1.1, regional groundwater data collected by USGS and others indicate regional hydraulic gradients are downward. [14]

The aforementioned Study design problems have had a cascading effect and led to additional problems in US EPA's interpretation of groundwater data. Under the (incorrect) presumption that groundwater flow is upward, US EPA reasoned that the chemical concentrations measured in MW01 (the shallower well) are the result of biodegradation of chemicals during upward migration from MW02 (the deeper well). This reasoning is flawed because the Study does not establish a hydraulic connection between these two wells (they are almost two miles apart) and the regional groundwater flow direction is downward (not upward as US EPA presumes). Hence, the analysis in the US EPA Study comparing concentrations of constituents in MW01 and MW02, and inferring that the concentration gradients "support" a migration theory from the deeper strata to shallower zones is simply incorrect. In fact, the data from US EPA's deep monitoring wells are consistent with a downward hydraulic gradient. As summarized in Table 2.1, below, the static water level elevation in MW01 (1,573.6 m above sea level, ASL) was 31 meters *higher* than the water level in MW02 (1,542.6 m ASL) in April 2011. Based on this information, even if there is a hydraulic connection between MW01 and MW02 (a fact not established in the US EPA Study), the hydraulic head in MW01 is greater than that in MW02, which would cause water (and chemicals) to move *downward* in the formation.

Table 2.1 Static Water Level Measurements in MW01 and MW02 (April 2011)

Well	Elevation (m ASL)	Screened Interval Depth (m)	Static Water Depth (m)	Static Water Elevation (m ASL)
MW01	1,634.8	233 – 239	61.2	1,573.6
MW02	1,623.1	293 – 299	80.5	1,542.6
			Head Difference:	**31 m**

Note: ASL = above sea level.

[14] The occurrence of "flowing stock wells" is put into proper perspective in Section 4.4.

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Thus, the entire analysis presented in the Study that rests on comparing constituents in these two wells is scientifically unsupportable.

In summary, there is a preponderance of available information that US EPA failed to consider and include in its decision-making process during the design of the Pavillion investigation. The available regional hydrogeologic data indicate that the groundwater flow direction is downward, information the US EPA should have taken into consideration when designing installation depths for its groundwater monitoring wells. US EPA's deep monitoring wells are below the groundwater zone typically used for drinking water and only capable of evaluating downward migration of contaminants from shallower depths, not the "deep source term" that US EPA intended to evaluate.

2.2 US EPA's Study Did Not Adequately Characterize Background Groundwater Quality

A well planned field study must identify or establish background conditions so that there is a baseline against which comparisons can be made. While US EPA utilized previous USGS studies in the region to assess background concentrations for a limited number of inorganic constituents (*e.g.*, potassium and chloride), it did not characterize background concentrations for organic constituents. Yet the presence of certain organic constituents in monitoring wells and domestic wells is interpreted in the Study to implicate HF activities as the source of such constituents. Without defining background concentrations of organic constituents, the presence of organic constituents in monitoring or domestic well samples is not an indication of migration from a "deep source term." This shortcoming is significant, because it undermines US EPA's ability to differentiate the primary source of any constituent from regional background sources, which could be significant in an area that is naturally rich in petroleum hydrocarbons. For example, diesel range organic (DRO) hydrocarbons were found in a water sample obtained from a City of Pavillion public water supply well located far away (approximately 7.2 kilometers (or 4.5 miles) from where the majority of the gas production wells are present (URS, 2010a). Although these detected concentrations may be reflective of regional "background" hydrocarbon presence in the area, US EPA did not determine whether this was the case because it did not determine background concentrations for organic constituents.

2.3 US EPA's Deep Monitoring Wells Are Not Appropriate for Evaluating Groundwater Quality Within the Drinking Water Aquifer

US EPA implies that its two deep monitoring wells are installed at depths that could be used for domestic water supply.[15] Despite the existence of a few deep wells [only five (5) domestic wells sampled by US EPA were > 200 meters (656 feet) deep], domestic wells in the Pavillion area are predominantly in the range of 50 to 150 meters (164 to 492 feet) bgs. Furthermore, the City of Pavillion currently has five (5) water supply wells, which range in total depth from 151 to 158 meters (495 to 517 feet) bgs (James Gores and Associates, 2011). The monitoring well depths of 233 to 299 meters (765 to 980 feet) selected in the Study target a groundwater zone that is below the strata typically used for domestic water supply. Thus, US EPA's deep monitoring wells are not appropriately placed to characterize the dominant groundwater resource in the study area.

[15] On page 11 of the Study, US EPA indicates the rationale for the deep monitoring well depths selected: "[w]hite coarse grained sandstones in the area of investigation contain little or no shale and are targeted by local well drillers for domestic well installation."

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There are also several indications that US EPA's monitoring wells were installed in isolated strata that are characterized by poor groundwater quality (*i.e.*, that would not be used for domestic supply) and that probably do not even qualify as an Underground Source of Drinking Water (USDW). For example, the following observations were made during well installation and development:

- Methane was encountered during the installation, development, and sampling of both MW01 and MW02 (see Figures 2.2 and 2.3).[16] This finding is a clear indication that these wells were installed within or proximate to gas- bearing zone(s) and would not be utilized for domestic water supply;
- It is questionable whether the stratigraphic intervals screened by the wells, especially MW02, even meet the definition of an USDW, given the low yield of the well (*i.e.*, well went dry during development and purging). As stated in 40 CFR § 144.3(a)(2), the definition of a USDW requires that an aquifer "contains a sufficient quantity of ground water to supply a public water system." The low productivity in MW02 is an indication that the stratum may not have a sufficient quantity of groundwater to qualify as a USDW; and
- It is highly unlikely that domestic wells would target the stratigraphic horizon at MW02, given that several water-bearing sandstone units [some over 21 meters (70 feet) thick)] were encountered in the borehole at much shallower depths [183 meters (600 feet) shallower than the screened interval for MW02] without methane (*i.e.*, much more desirable from a water availability and quality standpoint; see Figure 2.3).

These observations clearly indicate that the depths at which the deep monitoring wells were installed are not representative of the dominant groundwater zone used for domestic supply in the study area. Furthermore, the wells are of low quality and low yield, arguably do not even qualify as being located within a USDW, and may be screened within or proximate to gas- bearing zone(s), all of which diminish the usefulness of the data obtained from these wells.

[16] For MW02 (Figure 2.3) no flame-ionization detector (FID) readings are reported in the boring logs, although FID measurements were taken during well development. FID readings for both MW01 and MW02 indicate the presence of methane.

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Feet (bgs)	Description	Notes
0	Silty Clay (sand content increased with depth)	
10		
35		
45	Sand - 70%; Clay 30%	
60		
70	Shale	
105		
118	Sandstone	
128	Shale	
148		
158	Sandstone	
168	Shale	
180		
186	Sandstone	
196	Shale	
204		
210	Sandstone - 90%; Shale-10%	
230		
240	Sandstone - 60%; Shale-40%	
248	Shale - 90%, Sandstone - 10%	
258	Sandstone	
278		
298		
318		
326		
336	Shale - 95%, Sandstone - 5%	
346		
358		
370	Sandstone	
380	Sandstone - 90%; Shale-10%	
390	Sandstone	
396		
400	Shale	
420		
430	Sandstone	
440		
448	Shale	
458	Sandstone	
463	Shale - 95%, Sandstone - 3%	
473	Sandstone	
486		
496	Shale - 90%, Sandstone - 10%	
506	Interbedded Sandstone (60 - 90%) and Shale (10 - 40%)	
516		
526		
535		Methane - 139 ppm. (7/24/2010)
545	Sandstone	
552		
562	Shale	
576		
596	Sandstone	
616		
636		
638		
648	Interbedded Shale (80-90%) and Sandstone (10-20%)	
660		Methane - 212 ppm. (7/26/2010)
670	Sandstone	
690		
710		Methane - 52 ppm @ 700 ft. (7/26/2010)
730		
748		
756	Shale - 80%, Sandstone - 20%	
766	WELL SCREEN AT 765-785 ft bgs	
776		
786	Sandstone	Methane - 239 ppm @ 780 ft. (7/28/2010)
796		
805		
815	Shale	
835		
855		
875		
895		
915		
935		
950		Methane - 121 ppm. (7/28/2010)
956	Sandstone	
976	Shale	
987		

Figure 2.2 EPA MW01 WELL LOG, Pavillion, WY. MW-01 was drilled between 7/17/2010 and 7/28/2010. Well development was started on 8/13/2010; Methane concentrations based on FID measurements as reported in boring logs (during well drilling); According to the daily log, methane - 56.5 ppm @ 655 ft (during well development).

Feet (bgs)	Description	Notes
0, 10, 25, 40	Silty Clay (sand content *increased* with depth)	
50, 60	Sandstone - 60%, *Clay* - 40%	
70, 80, 90, 100	Shale	
110	Limestone - 70%, Sandstone - 30%	
120, 130	Sandstone	
140	Sandstone - 50%; Shale - 50%	
150	Sandstone	
160	Sandstone - 30%; Shale - 70%	
180, 200	Shale	
210	Sandstone - 30%; Shale - 70%	
220, 230	Mostly Sandstone (80-90%); some Shale (10 - 20%)	
250, 275	Mostly Shale (60-80%); some Sandstone (20-40%)	
295, 310, 330, 340	Mostly Sandstone (70-90%); some Shale (10 - 30%)	
350, 360, 370	Mostly Sandstone (60-70%); some Shale (30 - 40%)	
380, 390, 400	Mostly Shale (70-80%); some Sandstone (20-40%)	
410	Sandstone - 60%; Shale - 40%	
420, 440	Mostly Sandstone (70-90%); some Shale (10 - 30%)	
450, 460, 480	Sandstone - 60%; Shale - 40%	
500, 520, 540, 550	Mostly Sandstone (70-90%); some Shale (10 - 30%)	
570, 590, 610, 630	Sandstone	
650, 670, 690, 710, 730, 750, 770	Shale	Water level 771.2 ft. FID reading 110 ppm. (7/20/10)
790, 810, 820, 830	Sandstone	Water level 822 ft. FID reading 90 ppm. (7/21/10)
840	Shale	
850	Sandstone	
870, 890, 910, 930	Shale	
940, 950	Mostly Shale (80%); some Sandstone (20%)	
960	Shale - 60%; Sandstone - 40%	
970, 980	Sandstone	FID reading 50 ppm @973 -984 ft, measured during drilling. (6/24/2010)
990, 997	Shale - 60%; Sandstone - 40%	

WELL SCREEN AT 960-980 ft bgs

Figure 2.3 US EPA MW02 WELL LOG, Pavillion, WY. MW-02 was drilled between 6/14/2010 and 7/1/2010. Well development was started on 7/14/2010; Only one FID/PID reading reported for this well in the boring logs (*i.e.* , during well drilling); FID readings ranged from 1,700 to 4,026 ppm in the well (Daily Log 07/27/10); FID reading ranged from 1,000 to 2,000 ppm in the well (Daily Log 07/22/2010); FID readings reported with associated water depths during well development; FID readings are an indication of methane.

2.4 US EPA Did Not Adequately Consider the Nature of the Hydraulic Fracturing Stimulations in the Study Area

The description of HF activity in the Pavillion area by US EPA is limited. US EPA appears to have reviewed information on the Wyoming Oil and Gas Conservation Commission (WOGCC) website about gas wells in the study area. However, the information presented in the Study is limited to a map of gas well locations, a distribution of gas well depths in the study area, and a listing of HF additives from Material Safety Data Sheets (MSDSs). Unfortunately, the Study does not address any other aspects of HF stimulations, including the volumes and types of HF fluids that are predominantly used in the area. This lack of information appears to have contributed to the flawed interpretations in the Study regarding the potential impacts of HF activities on Pavillion area groundwater, such as the potential effects of pH (see Section 4.1) and the potential for fluid migration (see Section 4.5).

Our review of well completion logs available on the WOGCC website has indicated that the HF stimulations in the Pavillion area are low-volume stimulations that predominantly utilize carbon dioxide (CO_2) foam as the HF fluid. HF fluid volumes, including the combined volumes of water plus CO_2, are on the order of 1,000 to 10,000 gallons per fractured well interval (WOGCC, 2012). The corresponding volumes of water are even smaller, because the majority of the foam-based fluids are CO_2 (typically 70% or more CO_2 by volume). These volumes are only a small fraction of the HF fluid volumes that are used in deep shale formations, such as the Marcellus and Barnett shales – an important distinction that is never mentioned in the US EPA report. The low-volume HF stimulations used in the Pavillion area are contrasted by the large volume of pore space available in the targeted sandstone strata – on the order of tens of millions of gallons (see Section 4.5). These sandstone strata represent large storage zones for the HF fluid, such that the most likely fate of HF fluid would be to become trapped in the same sandstone stratum where it is injected, or to be removed as flowback fluid. US EPA apparently did not consider the high likelihood for storage in its analysis.

In addition to lacking a characterization of HF fluid volumes, US EPA also did not adequately consider the dominant HF fluid used in the Pavillion area – CO_2 foam. Mixtures of CO_2 and water are acidic (*i.e.*, low pH). A prominent piece of US EPA's reasoning relies on the assumption that HF fluid is a strong base (*i.e.*, high pH). However, this assumption is incorrect (see also Section 4.1). Although some HF additives may include bases (such as potassium hydroxide), the bulk fluid itself is acidic and the large amount of CO_2 used in the HF fluid will buffer pH to low values. As an example, pure water in equilibrium with CO_2 at typical HF stimulation pressures of about 1,500 pounds per square inch would have a pH of 2.9. US EPA did not account for the presence of CO_2 on the geochemical character of the HF fluid and therefore made fundamental errors in its subsequent analysis and interpretation of the monitoring data.

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3 US EPA's Study Implementation Was Very Poor, Limiting the Reliability of the Monitoring Results

US EPA's implementation of the Study (*i.e.*, field work execution and data quality review) did not follow its own guidance or Work Plan for groundwater sample collection (US EPA, 1996; US EPA Region I, 2010; URS, 2010b). In addition, US EPA failed to install and develop the deep monitoring wells properly, thereby compromising the quality and reliability of the groundwater data, and resulting in faulty interpretations of groundwater chemistry in the Study. Furthermore, the quality of the data were not adequately reviewed (*e.g.*, QA/QC was inadequate) such that conclusions in the Study are overreaching and unsupported by the data. The following sections discuss the Study implementation shortcomings.

3.1 US EPA Did Not Follow Industry Standards and Its Own Guidance for Monitoring Well Installation

The process of installing a monitoring well, especially the deep monitoring wells installed during the Study, requires the introduction of fluids and other materials into subsurface strata during the drilling and well development process. All of these introduced materials must be completely removed from the well prior to sampling in order to produce data that are representative of natural groundwater conditions and therefore meaningful for the Study. The failure to develop the monitoring wells adequately resulted in samples that were compromised by the well drilling and development materials, rendering the data unfit for use in the Study.

US EPA failed to take a number of steps to ensure proper well installation. For example, US EPA utilized air and mud rotary drilling techniques to advance the boreholes for the installation of deep monitoring wells MW01 and MW02. When mud rotary methods are used to install a monitoring well as part of an environmental investigation, it is essential – and an industry standard practice (*e.g.*, US EPA Region IV, 2008; US EPA, 1996; Driscoll, 1986) – to maintain records of the volume of water/mud (*i.e.* drilling fluids) used, and lost into the formation, during the drilling process. These records provide the information needed to then take the appropriate steps to remove the drilling fluid lost into the formation prior to collecting groundwater samples. During the investigation, US EPA's contractors did not record fluid loss information on the boring logs or in the field notes – an omission contrary to the requirements of the Monitoring Well Installation Work Plan (URS, 2010b). This lack of record-keeping may have contributed to the Agency's failure to properly develop the deep monitoring wells. As a result of this failure, the samples may represent drilling fluid rather than groundwater from the formation, thereby compromising the validity of the data collected from the wells.

US EPA also did not use a tracer or fluorescent dye in the drilling fluid – another industry standard practice for drilling monitoring wells using a mud-based drilling fluid (*e.g.*, Wandrey *et al.*, 2010). Use of a tracer or fluorescent dye in the drilling fluid helps ensure that the monitoring wells are adequately developed before groundwater samples are collected. Once drilling has been completed and the borehole drilling fluid has been removed, well development proceeds until the concentration of the tracer or dye in recovered groundwater is below a pre-established acceptable level (*e.g.*, background). This simple technique provides definitive documentation of adequate well development, after which representative groundwater samples can be collected. US EPA did not utilize this process. As discussed in Section 3.2,

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the samples obtained from MW01 and MW02 do not appear to be representative of formation groundwater.

In addition, US EPA did not install a bentonite seal above the deep monitoring well screens, a requirement of the project Work Plan (URS, 2010b) and a standard industry practice (US EPA Region IV, 2008; Driscoll, 1986). Bentonite is a clay material that expands upon hydration, thus forming a tight seal above a monitoring well's screen and preventing formation fluids (from above the screened interval), cement grout, or surface water from migrating down the borehole annulus into the well screen region. However, US EPA did not install a bentonite seal at either of the deep monitoring wells. Instead, a "sand basket" was installed directly above the well screen, and Portland cement was pumped into the borehole to create an approximately 15-foot thick cement plug directly above the well screen and "sand basket." The lack of a bentonite seal above the well screen allowed cement grout to infiltrate into the screened interval within the deep monitoring wells, which led to the high pH, potassium, and chloride levels observed in samples from these wells (see Section 4.1).

US EPA also did not perform cased-hole logging after the installation of the deep monitoring well – a step that should have been followed to ensure that the wells were installed appropriately (Kent and Hall, 1993), given the importance of these wells and the great cost at which they were installed.[17] The particular steps that should have been performed to confirm proper installation of the well are described below.

- Run a caliper log and compare the findings to the well's construction records and the field observations to confirm the well diameter, the screen location, the total depth of the well, and the condition of the inside of the casing (holes, corrosion, *etc.*), prior to development and sample collection;
- Run a density/neutron log to verify the possible presence of gas-bearing zones and assess the locations and continuity of the screen, sand pack, seal, and the top and base of the grout; and
- Run a cement bond log to check for voids, thin areas, or decreased densities in the grout sheath around the well casing.

Overall, US EPA did not follow the project Work Plan, industry standards, or its own guidance for monitoring well installation. The atypical/non-standard practices adopted in the Study during well construction have greatly undermined the quality and reliability of data collected from these monitoring wells.

3.2 US EPA's "Development" of the Deep Monitoring Wells Did Not Comply with the Project Work Plan and Was Inadequate

As with the construction of the deep monitoring wells, US EPA did not follow standard practice or the project Work Plan during development of MW01 and MW02. To develop the monitoring wells, the US EPA Work Plan (URS, 2010b) required purging at least five (5) well volumes, achieving turbidity below

[17] US EPA has not made all of the geophysical data collected during the well installation process available to the public. As part of the deep monitoring well installation, US EPA utilized a variety of geophysical logging techniques (*i.e.*, caliper, density, resistivity, spontaneous potential, natural gamma) at the cessation of drilling, and prior to placement of well materials. US EPA utilized the resistivity information to confirm the presence of coarse-grained sandstone at the targeted depth interval, but it did not discuss or publish any of the other geophysical data. US EPA should release all of the collected geophysical data in order for reviewers to understand the findings from the geophysical techniques utilized, and their correlation with the resistivity logs, if any.

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10 nephelometric turbidity units (NTU), and stabilization of temperature, pH, and conductivity in the purge water.

At MW01, a sufficient volume of water was removed (10,960 gallons) and a turbidity reading below 10 NTU was achieved; however, temperature, pH, and conductivity were not recorded and may not have stabilized. At MW02, less than two (2) well volumes were removed before well development was halted due to methane accumulation in the well. The slow recharge rate at this location (*e.g.*, as shown in Figure 3.1, approximately one month after well development in 2010, the water level in the well was still 89 meters (293 feet) below the static water level measured in March 2011) is a potential indicator of inadequate well development (including an indication of clogged well screen), or of a zone that is incapable of delivering enough water to qualify as a USDW, or a combination of both. Moreover, the Work Plan-established turbidity target was not reached, and the other required parameters were not recorded.

An evaluation of the sampling results from MW02 also suggests that there was inadequate well development. The isotopic signature of water from MW02 in Phase III ($\delta^{18}O$ -15.55 $\delta^{2}H$ -117.41) is significantly different from that of the samples collected from this well in Phase IV ($\delta^{18}O$ -14.24 $\delta^{2}H$ -113.42). Furthermore, the isotopic signature of the Phase III sample is similar to the isotopic signature from shallower wells, suggesting that there may have been a problem with well development and possibly an effect of infiltration of irrigation water into the well.[18] The US EPA field notes reference the fact that the field in which MW02 is located was flood irrigated after the drilling of the well, but prior to the completion of the development process. During the irrigation, the water reportedly rose to a level of "at least 2 feet" around MW02 (Shaw Environmental, 2010).

At both deep monitoring wells, water jetting (injection of water into the well at the screened interval) was used to aid well development. No analytical samples of the water were collected, and thus the quality of the water added to the wells is unknown, which draws into question the reliability of sampling results from MW01 and MW02. Inadequate well development at MW02 renders the data collected from this well and the conclusions drawn from these data (*e.g.*, pH, potassium, chloride) unreliable.

[18] US EPA did not plot the results for the sample collected at MW02 during Phase III on Figure 16 of the Study and provided no explanation for omitting this data.

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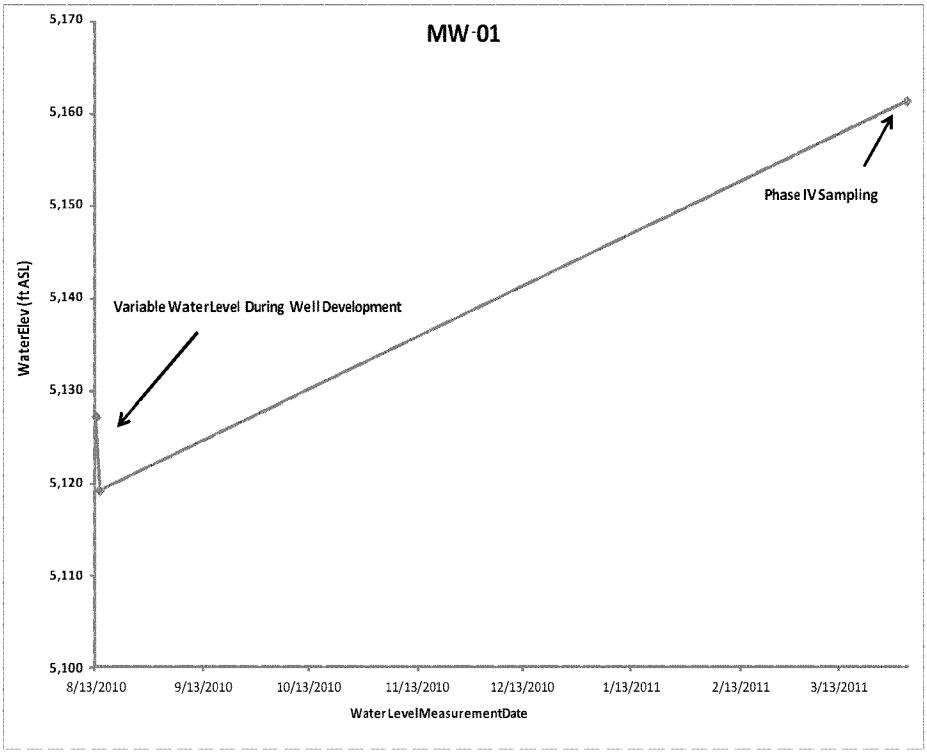

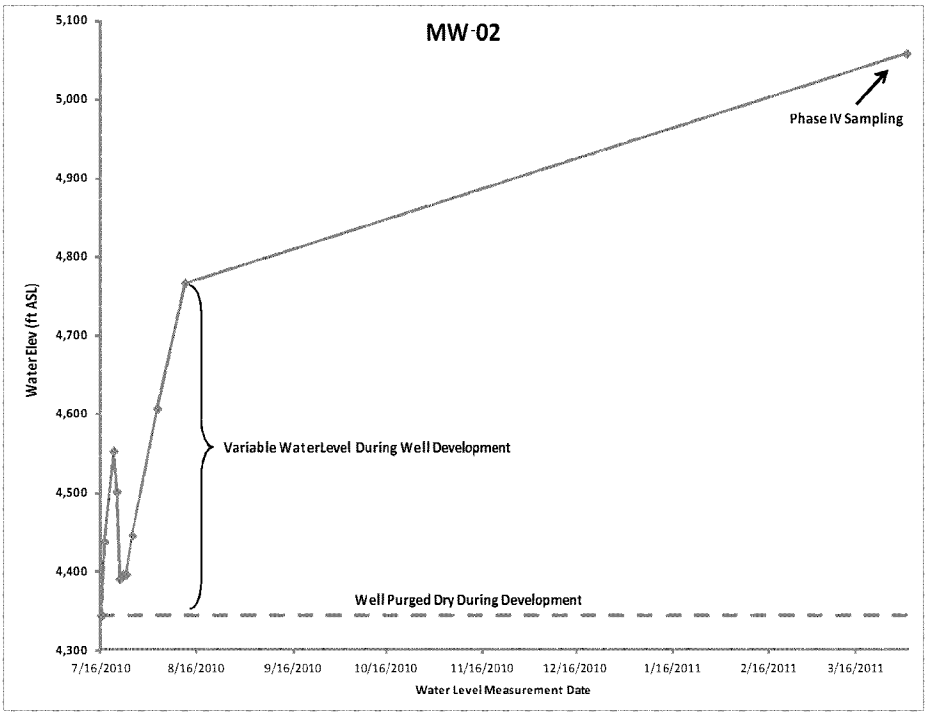

Figure 3.1 Water Level Measurements in MW01 and MW02

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3.3 US EPA Disregarded Standard Practices for Monitoring Well Sampling

In addition to the issues regarding well construction and development discussed above, the groundwater sampling methodology used at MW01 and MW02 was unconventional and did not follow current industry standards or US EPA's Work Plan (URS, 2010b; US EPA Region I, 2010). The poor practices adopted in the Study during sample collection severely affect the reliability of the groundwater quality data for the deep monitoring wells.

An extremely high purge rate was used during sample collection at the deep monitoring wells, which may have undermined the representativeness of the groundwater samples. The monitoring wells were purged at rates between 30 and 50 liters per minute (8 to 13 gallons per minute), which resulted in drawdown (water level decline within the well) far in excess of the US EPA-recommended 0.1 meters (0.3 feet) (US EPA Region I, 2010). When high flow rates are used during purging and sample collection, there is a significant potential to mobilize particles and colloids, which may bias sample results (Puls and Paul, 1995). In order to collect representative and defensible groundwater samples from wells screened in low permeability formations [inferred from slow recharge rate as shown in Figure 8 of the US EPA (2011) Study and Figure 3.1 in this report], US EPA should have followed its own guidance (US EPA Region I, 2010) on minimal drawdown sampling or utilized a passive sampling technique that does not require well purging (*e.g.*, Snap Sampler).[19]

US EPA also ignored Work Plan requirements and standard protocols for sample collection that require collection of groundwater samples after field parameters (*e.g.*, pH, temperature, specific conductivity) have stabilized. The criteria to be used for defining stabilization of field parameters were defined in the project Work Plan (US EPA Region I, 2010) and are summarized below (Table 3.1):

Table 3.1 Change in Field Parameter Measurements Prior to Sample Collection at MW02 (Phase III)

Parameter	Stabilization Criteria	Change in Field Parameter Values Prior to Sample Collection (Phase III)
Specific Conductance	±10%	+404%
Dissolved Oxygen	±10%	-100%
pH (s.u.)	± 0.1	+2.47
Oxidation/Reduction Potential (ORP) [milli volts]	± 10 milli volts	-26.5

However, US EPA collected groundwater samples at the deep monitoring wells during Phase III of the Study, when field parameters had not stabilized (Table 3.1 and Figure 3.2). In fact, the field monitoring data reported in field logs demonstrate that water with dramatically different geochemistry had entered well MW02 immediately prior to sample collection (Figure 3.2) and demonstrated significant violations of the stabilization criteria defined in the Work Plan (Table 3.1). These data clearly demonstrate that stabilization had not been achieved prior to sample collection and that additional well development was needed at MW02. US EPA not only apparently ignored these data in the field, but it failed to present or acknowledge these data in its report (US EPA, 2011).

US EPA's use of high purge rates during groundwater sampling and collection of groundwater samples when field parameters had not stabilized severely undermines the representativeness of the samples (*i.e.*, it is unclear whether the samples are representative of groundwater) and the reliability of the sampling results.

[19] During Phase IV sampling, the drawdown in MW01 was 65 feet at the time of sampling, and in MW02 the drawdown was so extensive the pump cavitated; MW02 was allowed to recover for only 10 minutes prior to collecting a sample.

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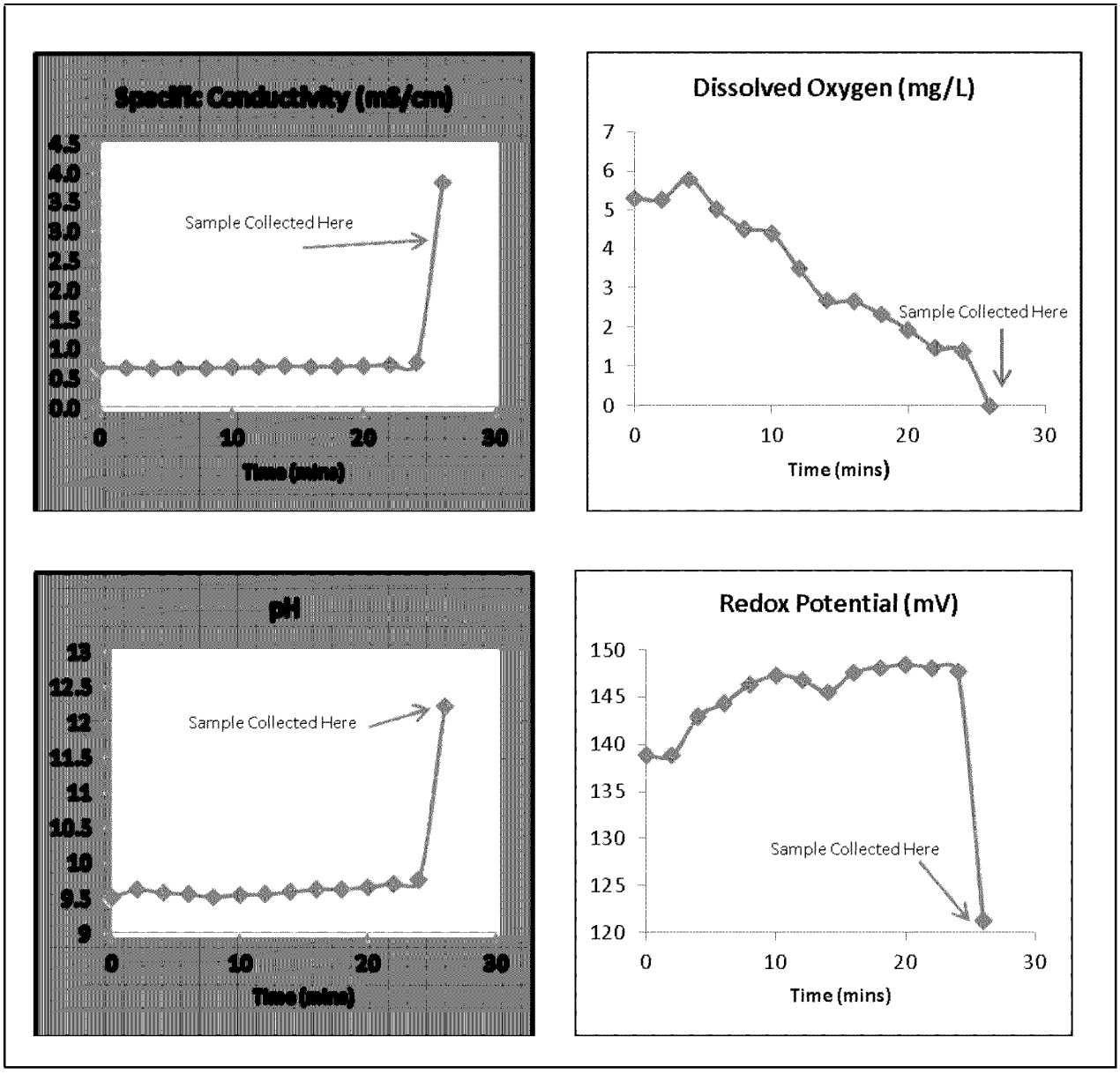

Figure 3.2 Field Parameters Measured Prior to Sample Collection at MW02 (Phase III)

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3.4 US EPA Did Not Follow Its Own Guidance for Data Quality Assessment and Utilized Unreliable Data

For decades, US EPA has recognized and espoused the need to use data of known quality for decision-making, stating "[r]eliable data must be available to answer questions concerning environmental quality and pollution abatement and control measures. This can be done only through rigorous adherence to established quality assurance techniques and practices" (Costle, 1979). Further, "these data must be scientifically valid, defensible, and of known precision and accuracy." This mandate is reflected in subsequent US EPA test method and quality assurance (QA) documents, guidance, and regulations. For example, US EPA's RCRA Test Method Manual (SW-846) states "[i]t is the goal of the U.S. Environmental Protection Agency's quality assurance (QA) program to ensure that all data be scientifically valid, defensible, and of known quality to withstand scientific and legal challenge relative to the use for which the data are obtained" (US EPA Region I, 1996).

US EPA developed a mandatory Agency-wide Quality System that applies to all US EPA organizations and non-US EPA organizations performing work on behalf of the Agency (US EPA, 2000). These quality systems provide the necessary elements to plan, implement, document, and assess the effectiveness of QA and quality control (QC) activities by US EPA and its contractors (US EPA, 2002). Investigating data quality involves both data verification and validation, followed by an iterative data quality assessment (DQA) process (US EPA, 2006). DQA is "the scientific and statistical evaluation of environmental data to determine if they meet the planning objectives of the project, and thus are of the right type, quality and quantity to support their intended use" (US EPA, 2006).

For the Pavillion project, US EPA did not follow its policy of generating data that are "scientifically valid, defensible, and of known precision and accuracy." There were a number of data quality problems during the Study that demonstrate a lack of adequate planning (*e.g.*, choice of non-standard, unvalidated analytical test methods), poor field execution (*e.g.*, routine detection of contaminants in blanks), and disregard of US EPA guidance for assessing the usability of data for decision making (*e.g.*, the Study utilizes data that should have been qualified as non-detect due to the presence of contamination in the blanks), as discussed below.

- **Use of Non-Standard Analytical Test Method:** US EPA used a non-standard, unvalidated, analytical test method for conducting the analysis for glycols and 2-butoxyethanol (2-BE). Despite experiencing issues associated with false positives with glycols during the earlier phase of the Study (US EPA, 2011, p. 27), US EPA failed to undertake a method validation to evaluate whether "instrument" related interferences could cause false positives with the method it selected in Phase IV. This demonstrates lack of planning – a critical step in the US EPA-defined DQA process. The method was still "*under development*" (US EPA, 2011; emphasis added), when samples arrived at the laboratory. Consequently, there were a number of QA/QC problems during these analyses (*e.g.*, no surrogates were used, no QC criteria were pre-defined, retention times were not properly established). Overall, given the use of a non-standard, unvalidated, analytical method used by US EPA in Phase IV for conducting the glycol and 2-BE analysis, these data are of unknown quality, have not been shown to be reproducible, and, hence, should not be used for decision-making (see Section 4.2 for additional details).
- **Field Blank Contamination:** Field blanks provide an indication of contamination introduced during sample collection and handling and, consequently, are a critical component of a DQA program. During this Study, US EPA did not collect field blank samples consistently and/or did not use a uniform approach for applying blank-related "data qualifiers" (*e.g.*, when to consider a

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value detected *versus* non-detected) as part of the DQA process. For example, no blanks were collected for methane (in water) during Phases I and II, when a majority of the domestic well water methane data were collected. When US EPA collected methane blanks in Phases III and IV, all of the blanks exhibited methane contamination (23.0 to 76.4 µg/L), yet US EPA continued to use data collected in Phases I and II. These data are highly unreliable given that a majority of the domestic well water samples found methane concentrations comparable to the blanks (see Section 4.6).

Furthermore, during the Phase IV investigation, in addition to methane, benzene, toluene ethylbenzene, and xylenes (BTEX), gasoline range organic (GRO) hydrocarbons, DRO hydrocarbons, and glycols were found in a number of trip and field blanks (Table 3.2). The widespread detection of contaminants in the field blanks indicates that the field sampling program was not "in control." In addition, during Phases III and IV, US EPA used a blank-contamination evaluation that was not consistent with the approach used in Phase II (URS, 2010b) nor consistent with US EPA guidance (*e.g.*, US EPA, 1994). If US EPA had used a consistent approach, all concentrations less than the "Blank Action Level" presented below (Table 3.2) should have been qualified as non-detect as part of the DQA process. For example, all of the DRO concentrations in domestic wells were below the Blank Action Level and should be qualified as non-detect.

Finally, US EPA sampled its deep monitoring wells on only two occasions and observed contaminated blanks in both instances. US EPA should have performed additional well development, re-sampled the wells using appropriate techniques, and developed a reliable data set prior to publishing premature conclusions in its draft Study report. Given these issues, the data generated by US EPA cannot be considered reliable; the data, and any conclusions based on them, would likely have been rejected by the Agency if such data had been submitted by a private party (*e.g.*, as part of a Superfund response action).

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Table 3.2 Summary of Blank Contamination During Phases III and IV

Compound Detected in Blank	Maximum Blank Concentration (Source) (µg/L)[a]	Blank Action Level (µg/L)[b]	Comment
Phase III			
Methane (C1)	76.4 (field blank)	382 (5x)	Results below the blank action level would be considered non-detected ("U")
Toluene	0.54 (trip blank)	5.4 (10x)	
Phase IV			
DRO	135 (field blank)	675 (5x)	
Methane (C1)	45 (field blank)	225 (5x)	
Tetraethylene Glycol	3.6 (trip blank)	18.0 (5x)	
Toluene	0.228 (trip blank)	2.8 (10x)	
m&p Xylenes	0.229 (trip blank)	1.14 (5x)	

Notes:

(a) The maximum blank concentration is the highest concentration reported across all field, trip, or equipment blanks collected and analyzed during the indicated sampling Phase.

(b) Blank action levels are calculated as 5x the maximum blank concentration for most compounds and 10x for common laboratory contaminants such as toluene, methylene chloride, or bis(2-ethyl)hexylphthalate. The 5x and 10x blank action levels are consistent with Region VIII's July 27, 2010, memorandum "Treatment of Contamination Found in Method and Field Blanks for Pavillion Groundwater Investigation Sampling" (Parker, 2010). Results less than the indicated blank action level would be considered non-detected ("U").

(c) Field or trip blank data were not located for the Phase I investigation. During Phase II, although a field blank was collected for DRO and 8270 analyses and a trip blank was collected for 8260 and GRO analyses, field or trip blank data do not appear to be reported for methane analyses in water. DRO contamination was reported in the field blank collected during the Phase II investigation; however, US EPA Region 8 reviewed the data and determined there was no impact to the DRO results reported in the associated field samples.

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4 US EPA's Findings and Conclusions Are Not Based on Sound Science

US EPA presents multiple "lines of reasoning" to argue that "inorganic and organic constituents associated with hydraulic fracturing have contaminated groundwater at and below the depth used for domestic water supply" (US EPA, 2011, p. 39). Specifically, US EPA hypothesizes that the presence of inorganic (high pH, potassium, and chloride) and organic constituents (methane, petroleum hydrocarbons, glycols, and alcohols) in the deep portion of the aquifer are attributable to HF fluids, which have preferentially migrated along poorly cemented gas production wells. US EPA also alleges that methane found in domestic water wells is the result of "enhanced" migration – a consequence of HF activities and increased natural gas development in the last two decades. As discussed in the prior sections of this report, the data collected from the deep monitoring wells are unreliable due to poor QA/QC procedures. Even if those data were valid, the following sub-sections demonstrate that the technical analysis of the data used to support US EPA's lines of reasoning is flawed and does not support the conclusions presented in the Study.

4.1 Elevated pH, Potassium, and Chloride in the Deep Monitoring Wells Are Not Associated with Hydraulic Fracturing Additives

One of US EPA's lines of reasoning is that inorganic chemistry (*i.e.*, elevated pH, potassium, and chloride concentrations) at MW01 and MW02 is indicative of HF fluid migration. This line of reasoning is flawed and ignores or discounts several obvious causes for the unusual inorganic chemistry observed in MW01 and MW02 (*e.g.*, cement and/or additives used during well drilling and development). US EPA appears to base its reasoning on a misunderstanding of the nature of the components of HF fluids, suggesting that HF fluid is a strong base [*i.e.*, analogous to potassium hydroxide (KOH)]. Although KOH may be a component of some HF fluids, as discussed below, the types of fluids predominantly used for hydraulic fracturing in the Pavillion area would more likely have been acidic. Given the obvious sources of inorganic constituents in US EPA's monitoring wells and the low pH of HF fluid (both of which US EPA either ignored or discounted), the inorganic chemistry observed in MW01 and MW02 is not associated with HF fluid migration. Rather, the inorganic chemistry is clearly associated with poor well construction and inadequate well development.[20]

4.1.1 Hydraulic Fracturing Fluids Could Not Have Caused High pH Conditions

Hydraulic fracturing in the Pavillion area predominantly used CO_2 foam-based fluids. These are low-volume stimulations, typically on the order of 3,800 to 38,000 liters (1,000 to 10,000 gallons) per fractured well interval (WOGCC, 2012). The additives used in these fluids include a variety of acids, bases, and neutral components that, together, create a buffered solution unlikely to yield the high pH found in the deep monitoring wells. Furthermore, HF fluids that utilize CO_2 (*i.e.*, foam stimulations, such

[20] Given the heterogeneity of the sedimentary deposits in the Wind River and Fort Union formations, differences in inorganic water chemistry in MW01 and MW02 arising from potential differences in the geologic origin of the respective water-bearing strata within which these wells are installed cannot be ruled out as a contributing factor for the observed differences.

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as those predominantly used in the Pavillion area) would create acidic fluids (*i.e.*, low pH) with high concentrations of carbonate/bicarbonate (the dissolution of CO_2 decreases the pH of groundwater and increases carbonate/bicarbonate concentrations; Langmuir, 1997). In contrast, the high pH water samples from the deep monitoring wells had very low concentrations of carbonate/bicarbonate. These results are clearly inconsistent with the nature of HF fluids used in the Pavillion area and, therefore, HF fluid could not have caused the high pH values (*i.e.*, values > 11) measured in the deep monitoring wells.

4.1.2 High pH, Potassium, and Chloride Concentrations Are Due to Cement

The cement used in installing the monitoring wells is a much more likely source of the pH values reported in the Study. US EPA discounts the possibility that cement was the cause of its elevated pH measurements based on the following (US EPA, 2011, p. 20):

- "Cement intrusion typically leads to pH values between 10 and 11 – below that observed in deep monitoring wells;"
- "Prolonged purging did not show decreasing pH trends;" and
- "Water chemistry results indicate that ground water from the wells was highly undersaturated with respect to cement phases (*e.g.*, portlandite)."

Each of these statements is either incorrect or based on a flawed understanding of the geochemical processes that affect groundwater pH.

4.1.2.1 Cement Is Highly Caustic and Can Result in Elevated pH in Monitoring Wells

The potential for cement grout near the well screen to contaminate groundwater is a well known problem. As discussed in Section 3 of this report, US EPA's well construction techniques were flawed and likely resulted in cement breaking through the "sand basket" above the well screen, thereby contaminating the screened interval of the well. US EPA cited the transcript of a conference discussion to support its assertion that cement contamination would only cause pH values in the range of 10-11 (*cf.*, Gibb, 1987 as cited in US EPA, 2011). This is not an authoritative source (since it is based on a conversation and not a peer-reviewed journal article or reliable data); furthermore, it does not comport with the findings of controlled field studies and laboratory experiments. Some of these findings are described below.

- Field studies have indicated that cement grout can increase groundwater pH to values greater than 11 (*e.g.*, Mercer *et al.*, 2007) and that alkalinity is dominated by the hydroxyl ion in such cases (Barcelona and Helfrich, 1986). It has also been observed that the cement contamination problem can persist for "more than 18 months after construction, despite at least 10 redevelopment attempts" (Barcelona and Helfrich, 1986). These same symptoms (*i.e.*, high pH and high hydroxyl ion alkalinity) were found in US EPA's monitoring wells.
- Controlled laboratory experiments have indicated that the pH of cement pore-water ranges from 13.2-13.8 (Leemann and Lothenbach, 2008) and cement MSDSs state that the pH range of cement is similarly in the range of 12-13 (CEMEX, 2001).

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This evidence, combined with the poor well construction that likely allowed cement to enter the well screen intervals, indicates that cement contamination is the most likely cause of the anomalous pH values in MW01 and MW02.

Cement has the potential to not only affect groundwater pH but also other inorganic chemical concentrations, including potassium. US EPA found elevated potassium concentrations in its monitoring wells (14.5 to 18.3 times higher than typical values in the Wind River Formation), but it apparently did not consider that cement could have contributed to the observed concentrations. Instead, US EPA concludes that the potassium concentrations were associated with potassium-based HF additives. This conclusion ignores the fact that cement can be a potentially significant source of potassium. For example, the concentration of potassium in the pore water of cement is extremely high, ranging from 11,800 to 25,300 mg/L (Leemann and Lothenbach, 2008). As potassium diffuses out of the cement pore spaces, it can increase potassium concentrations in the surrounding groundwater. Laboratory experiments have shown that cement-contaminated water can have a potassium concentration as high as 578 mg/L (Barcelona and Helfrich, 1986). Given the intrusion of cement into the screened intervals of MW01 and MW02, the most likely source of elevated potassium concentrations at these wells is the cement itself, not HF fluid migration.

4.1.2.2 US EPA's Geochemical Modeling Is Flawed and Does Not Support Claims About pH

US EPA's geochemical modeling analysis appears to rely on flawed data and is unreliable. The Study does not present the full list of inputs or results of the geochemical modeling; therefore, it is not possible to independently verify the appropriateness of the assumptions used in the modeling. It is clear, however, that the analytical results for inorganic chemistry from MW01 and MW02 were of poor quality and are not useable for geochemical modeling. Standard practice dictates that an inorganic chemical analysis is of sufficient quality for use in geochemical modeling if the charge balance error is less than 5% (Freeze and Cherry, 1979). Strictly speaking, all water samples are balanced with respect to charge – *i.e.*, positively charged solutes (cations) balance the negatively charged solutes (anions). In practice, a laboratory analysis may not fully characterize all solutes in a sample, which leads to a charge balance error. Although small charge balance errors are common, those that exceed 5% are an indication that the analytical results do not characterize the dissolved inorganic constituents in a sample adequately. During Phases III and IV, only one sample from the deep monitoring wells (sample from MW02 in Phase IV) had an acceptable (4.7%) charge balance error. The charge balance error for other samples ranged from 10-16%. Given the consistently high charge balance errors, the analytical results do not adequately characterize inorganic solutes at MW01 and MW02. Therefore, US EPA's geochemical modeling results are unreliable. Moreover, the fact that all of the charge balance errors are positive indicates a consistent problem with the laboratory analysis that has created biased results.

Even if one accepts the modeling results at face value, they do not support US EPA's assertion that "cement was not the cause of elevated pH" values at MW01 and MW02. US EPA's only supporting modeling result is that groundwater samples from MW01 and MW02 are under-saturated with respect to cement minerals, citing the mineral portlandite [$Ca(OH)_2$] as an example. US EPA does not put this statement into proper perspective, however. It is highly unlikely for groundwater to be saturated with respect to portlandite, given that the (undiluted) pore water in wet cement is only slightly super-saturated itself (Thomas *et al.*, 2003). These constituents will be diluted as they diffuse out of the cement into the surrounding groundwater, making it highly unlikely that one would ever find groundwater that is saturated with respect to portlandite. There are also many other geochemical reactions that affect mineral solubility, such as adsorption and ion exchange reactions that occur in the aquifer, which the geochemical modeling does not take into account. Thus, even if EPA's statements about mineral solubility were

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correct, that result alone does not exclude cement as the source of the high pH in MW01 and MW02. Furthermore, it is misleading to present the geochemical modeling results without any meaningful context, especially when there are numerous laboratory experiments and field case studies that demonstrate the significant effects cement can have on pH (*e.g.*, Barcelona and Helfrich, 1986; Thomas *et al.*, 2003; Mercer *et al.*, 2007; Leemann and Lothenbach, 2008).

In addition to the mineral solubility modeling, US EPA modeled the changes in groundwater pH that would be expected if a strong base (KOH) were dissolved into it. US EPA's basis for conducting this modeling exercise was that some HF additives may contain KOH. Although KOH may be used in some HF fluid formulations, the carrier fluid (CO_2 foam) is acidic and has an extremely high buffering capacity; therefore, HF fluids with the high pH modeled in the Study are not plausible. Thus, US EPA's modeling of KOH additions to groundwater is based on an unrealistic hypothetical scenario that is not consistent with the nature of the HF fluids used in the Pavillion area (see Section 2.5 for additional discussion of HF fluids). Therefore, the conclusion reached in the Study that the high pH in MW01 and MW02 is an indication of HF fluid migration is an incorrect interpretation of the HF fluid systems used.

4.1.2.3 Increased pH Associated with Cement Intrusion Can Persist in Monitoring Wells

The Study indicates that prolonged purging of its deep monitoring wells did not show decreasing pH trends (US EPA, 2011, p. 20), suggesting that the elevated pH could not have been associated with cement intrusion. There are two key shortcomings with this argument. First, US EPA faced significant problems in developing the deep monitoring wells; *e.g.*, only two (2) well volumes were removed from MW02 compared to an industry standard and project requirement of a minimum of five (5) well volumes (Section 3). Such inadequate well development does not constitute "prolonged purging" and does not even meet the minimum requirements for well development.[21] Second, case studies have also demonstrated that elevated pH and other cement intrusion-related water chemistry effects can persist in monitoring wells for "more than 18 months after construction, despite at least 10 redevelopment attempts" (Barcelona and Helfrich, 1986). Given that both sampling events for MW01 and MW02 occurred within 10 months of installation and well development was inadequate, continued impacts of cement intrusion on water chemistry are consistent with documented case studies from other sites.

4.1.2.4 High Chloride Is Associated with a Cement Additive Used During Installation of Monitoring Well MW02

US EPA also alleges that the presence of elevated levels of chloride in monitoring well MW02 is associated with HF additives, such as potassium chloride (US EPA, 2011, p. 34). Chloride levels are not consistent between the two wells, showing no elevation above typical concentrations in the Wind River formation in MW01 and elevated concentrations in MW02. Elevated chloride in MW02 is likely associated with the cement additive calcium chloride, which appears to have been used in MW01 and MW02 for constructing the annular seal immediately above the well screen (as indicated on field drilling logs for these wells). Calcium chloride is commonly added to cement to reduce "set" times and typically is included in the dry cement mix at a rate of 2% by volume (*i.e.*, 2 parts calcium chloride to 98 parts cement; Rapp, 1934). As discussed previously, well development at MW02 was inadequate and the low volume of water purged was not able to remove the remnant calcium chloride from the vicinity of the well screen. At MW01, larger volumes of water were removed during well development, which appears to have removed most of the calcium chloride from the screened interval of this well. Thus, the finding of

[21] This is all the more problematic because no annular bentonite seal was used to construct these monitoring wells, a practice which significantly increases the likelihood of cement intrusion into the well screen interval (see Section 3).

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high chloride concentrations in groundwater samples from MW02 is likely due to calcium chloride added to the cement to construct the well's annular seal. In all likelihood, the cement migrated into the screened interval and is the likely source of the high levels of chloride measured in MW02.

4.2 The Reliability of Synthetic Organic Compounds Data Is Questionable

US EPA alleges that the presence of "synthetic organic compounds" (glycols, alcohols, and 2-BE) in the deep monitoring wells is an indication that HF fluids have affected the groundwater quality above the natural gas producing zone. US EPA states: "A wide variety of organic chemicals was detected in the monitoring wells including: GRO, DRO, BTEX, trimethylbenzenes, phenols, naphthalenes, acetone, isopropanol, tertiary butyl alcohol (TBA), 2-BE, 2-butanone, diethylene glycol, triethylene glycol, and tetraethylene glycol" (US EPA, 2011). However, the glycol and 2-BE data were generated using a non-standard and unreliable test method and are not appropriate for use; all other constituents can be naturally occurring (see Section 4.3).

US EPA used a non-standard analytical test method to analyze groundwater samples collected from MW01 and MW02 to quantify concentrations for glycols (diethylene, triethylene, and tetraethylene) and 2-BE during Phase IV of the Study. The analyses were conducted using a LC/MS/MS method, which was not validated prior to use. It is well known that environmental measurements are not reliable unless the method used to produce the intended measurements has been adequately validated. For instance, the National Environmental Laboratory Accreditation Conference's (NELAC's) Quality System states for non-standard methods that "the method developed shall have been validated appropriately before use" (NELAC, 2002). According to the American Chemical Society, the "use of detailed testing to reveal sensitivity to interferences before adoption of a method is absolutely essential to ensure reliability" (ACS, 1980).

One of the key elements of method validation is to demonstrate that *false positives* are not being reported either due to instrument- or sample matrix-related interferences. When US EPA conducted glycol analyses at domestic wells, it could not replicate the results using two different methods and concluded that the detections were attributable to false positives due to "*interactions between the chromatographic column and organic compounds in sample water*" (US EPA, 2011, p. 27, emphasis added). Despite experiencing issues associated with false positives with glycols during the earlier phase of the Study, US EPA failed to undertake a method validation to evaluate whether instrument-related interferences could cause false positives with the method it selected in Phase IV. In addition, US EPA did not collect any field duplicates or matrix spike duplicates for glycol analyses, samples which would have helped in understanding whether the non-standard analytical method it chose in Phase IV was prone to problems (*i.e.*, interferences, false positives, or lack of precision) due to the complex sample matrix (*i.e.*, water sample saturated with methane, high pH, *etc.*).

Finally, some of the statements presented in the US EPA laboratory report narrative indicate that method development, QC, and analytical procedures were performed "on the fly" in the laboratory, which also severely affects the reliability of the glycol and 2-BE data (US EPA Region III, 2011):

> "An appropriate surrogate has not yet been identified."
>
> "Because the method was under development when samples arrived, a wide range of initial calibration standards were prepared."

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"Because several quality control criteria (matrix spike/duplicate, CCV and SCV percent recoveries) were outside QC limits, all positive results should be considered estimated and have been qualified J."

"Because the method was being developed as samples were being analyzed, it is not known if the QC data for percent recoveries and RPDs are appropriate."

"Some blanks and samples....indicated very low levels of TeG in both the main and confirmation channel, but this may be the result of background noise or a coeluting interference."

These issues undermine the reliability of the glycol and 2-BE data for several reasons. For example, without appropriate surrogates, the potential effect of matrix interferences and false positives is not well understood. Furthermore, reliable chromatographic identification of target analytes requires establishing tight retention time windows for each analyte prior to performing field sample analyses. US EPA guidance recommends that to minimize this potential for false identifications, single component standards should be used for establishing retention times, stating "[b]efore establishing retention time windows, make sure that the chromatographic system is operating reliably and that the system conditions are optimized for the target analytes and surrogates in the sample matrix to be analyzed. Make three injections of all *single component standard mixtures* and multi-component analytes (such as PCBs) over the course of a 72-hour period" (US EPA, 2003, emphasis added). Apparently US EPA only used multi-component standards to establish retention times, increasing the possibility of false positives. In addition, several QC parameters did not meet criteria, imposing uncertainty on data accuracy and precision, as well as method sensitivity.

As further evidence of the unreliability of the 2-BE data, only one of three labs that analyzed samples from MW01 and MW02 for 2-BE reported detectable results. Samples analyzed by US EPA Region III and the Kerr/Shaw laboratory (Kerr is part of the US EPA Office of Research and Development) did not report detectable 2-BE.

Overall, given the use of a non-standard, unvalidated analytical method used by US EPA in Phase IV for conducting the glycol and 2-BE analysis, these data are of unknown quality, have not been shown to be reproducible, and, hence, should not be used for decision-making.

4.3 The Detection of Petroleum Hydrocarbons and Other Organic Compounds in the Deep Monitoring Wells Is Consistent with the Presence of Natural Gas

The US EPA Study did not discuss the potential natural sources of other organic constituents (*e.g.*, GRO, DRO, BTEX, trimethylbenzenes, phenols, naphthalenes, acetone, 2-butanone, isopropanol, TBA). This omission in US EPA's Study affects at least two of the Agency's lines of reasoning. First, US EPA includes isopropanol and TBA as synthetic organic chemicals and cites their detection as evidence that HF fluids are present at MW01 and MW02. However, both of these constituents can be naturally occurring. As discussed below and in Section 4.6, US EPA installed its deep monitoring wells in strata that contain, or are proximate to, natural gas. Isopropanol and TBA are known to be microbial breakdown products of natural gas (and other types of naturally occurring organic matter) formed naturally during fermentation processes (Jones and Woods, 1986; Jones *et al.*, 2007; API, 2012). Conditions that are conducive to fermentation (*i.e.*, low oxidation-reduction potential, low dissolved oxygen concentrations, and the presence of natural organic matter, such as natural gas) are present in the

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strata where MW01 and MW02 were installed, further increasing the likelihood of a range of fermentation products being present.

One of US EPA's other lines of reasoning is that petroleum hydrocarbons (BTEX, trimethylbenzenes, naphthalene, GRO, and DRO) were detected in one or both of the deep monitoring wells (US EPA, 2011, p. 35). The detection of many constituents is questionable, however, given the contamination of field blanks (Sections 3.4 and 4.6). Thus, US EPA's data are not reliable for drawing conclusions about the presence or migration of contaminants. However, even if one assumes that the data are valid, the data would indicate that hydrocarbons found in the deep monitoring wells are consistent with those associated with natural gas, rather than providing evidence of hydraulic fracturing as suggested in the Study.

According to US EPA, MSDSs obtained from WOGCC indicate that aromatic solvents (containing BTEX) and diesel were used in hydraulic fracturing in the Pavillion area (US EPA, 2011, p. 23).[22] US EPA concludes that there is a deep source of hydrocarbons (*i.e.*, HF activity), based on the potential presence of these constituents in some HF additives and the presence of some of these constituents in US EPA's deep monitoring wells. US EPA also considered and ruled out the potential for naturally occurring hydrocarbons to be responsible for the constituent concentrations observed in the deep monitoring wells. However, US EPA did not fully evaluate the data, which clearly show that the hydrocarbons are associated with pre-existing (*i.e.*, before HF activities began) natural sources in the study area, not HF-enhanced migration. The clear association of hydrocarbons with natural sources is supported by the observations detailed below.

- The deep monitoring wells are screened in natural gas-rich horizons, as indicated by the elevated flame-ionization detector (FID) screening measurements noted during well installation, development (Figures 2.2 and 2.3), and sampling,[23] as well as the methane concentrations observed in water and gas samples obtained from these wells (US EPA, 2011).
- Natural gas-rich horizons commonly contain other petroleum hydrocarbons (*e.g.*, BTEX, trimethylbenzenes, GRO, and DRO), as demonstrated by the presence of these constituents in gas condensate. In fact, the petroleum hydrocarbons found in the deep monitoring wells were also found at high concentrations in the condensate samples collected at gas production wells in Pavillion (URS, 2010a, Table 10). There was considerable variability noted in the BTEX and aromatic hydrocarbon content in the Pavillion condensate samples, despite there being limited variability in the light hydrocarbon gas composition (*i.e.*, all Pavillion natural gas samples have methane between 90 to 95%; Table A3b, US EPA, 2011). The variability in BTEX and aromatic hydrocarbon content is a symptom of the natural heterogeneity in the region and is consistent with the variability observed at MW01 and MW02.[24] Moreover, the BTEX signature at MW02 is consistent with the signature of the condensate sample PGPP06 (Figure 4.1). This evidence further demonstrates that the BTEX and other petroleum hydrocarbons detected at this very deep monitoring well (installed in a natural gas-rich horizon) are associated with pre-existing natural gas and not HF fluids.

[22] It is not clear whether the MSDSs obtained by US EPA from the WOGCC were for HF jobs conducted in Pavillion or at other locations in the State of Wyoming.
[23] US EPA states that methane gas bubbles were observed during sample collection and these may have led to some of the fluctuation in field parameters observed during sample collection (US EPA, 2011, pp. 12-13)
[24] Low BTEX concentrations comparable to those measured in blanks were reported in MW01. These data should have been qualified as non-detects, consistent with US EPA data evaluation guidance (Parker, 2010).

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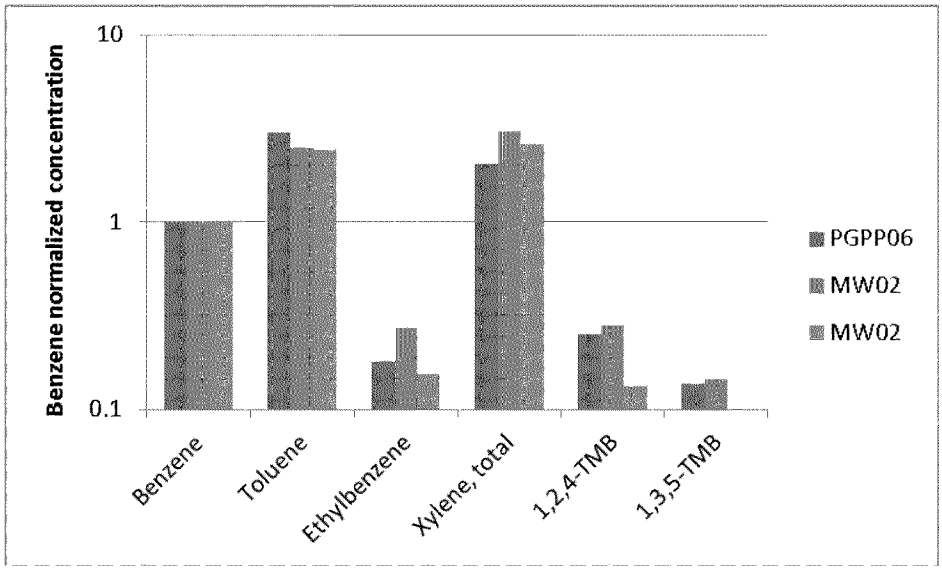

Figure 4.1 Comparison of Hydrocarbon Distributions in Gas Condensate Sample PGPP06 and Deep Monitoring Well MW02

- The distribution of DROs in domestic wells is consistent with the natural presence of hydrocarbons and heterogeneity in the study area or an artifact of the poor sampling practices utilized in the Study (see Section 3). If there were a contaminant source present at depth and contaminated groundwater was moving upward, then concentrations should exhibit an increasing trend with depth. However, the DRO concentrations do not increase with depth (Figure 4.2). It should also be emphasized that, due to DRO in QA (blank) samples, the DRO results for the drinking water samples are all below the Blank Action Level and should be considered non-detects (see Section 3.4).

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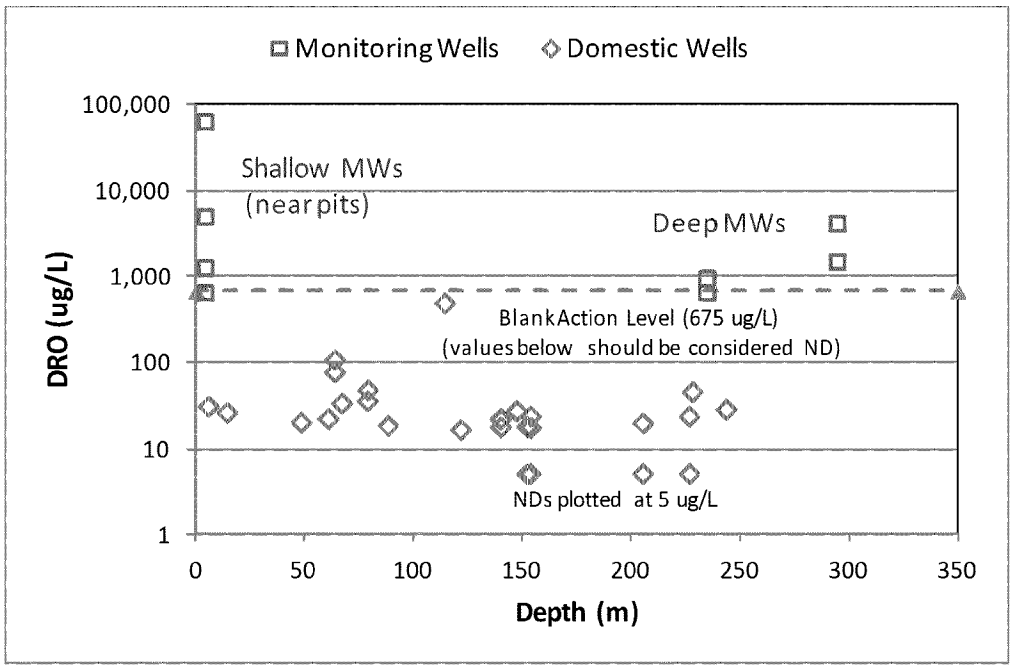

Figure 4.2 Concentrations of Diesel Range Organics (DRO) *versus* Depth

Finally, the basis for US EPA's statement that contamination is present in "domestic wells proximal to the deep monitoring wells" (US EPA, 2011, p. 27) is unclear. Water quality in the domestic wells complies with federal drinking water standards except at two wells (for nitrate, phthalate, and lead; URS, 2010a), but these constituents are not related to hydraulic fracturing. If the basis for this statement is the possible detection of low levels of hydrocarbons (*e.g.*, GRO, DRO, methane), then US EPA's reasoning is not supportable; much of this data should be flagged as non-detect due to blank contamination (see Section 3.4).

As summarized above, multiple lines of evidence point toward naturally occurring hydrocarbons as the source of hydrocarbons in the deep monitoring wells. In addition, the absence (or low detection) of petroleum hydrocarbons in the domestic wells and the lack of a depth trend (*i.e.*, absence of an increase in concentrations with depth) are clear indications that natural gas-related hydrocarbons present at depth are not affecting groundwater quality in the Pavillion area. These lines of evidence run contrary to the HF-enhanced migration theory put forth in the US EPA Study.

4.4 US EPA Incorrectly Concludes There Is "Upward Flow" Based on Chemical Concentration Gradients

The US EPA Study points to differences in chemical concentrations in MW01 *versus* MW02 as one of the "lines of evidence" to infer an "upward flow" of chemicals and groundwater in the formation. US EPA argues this has led to the presence of HF fluid constituents in the deeper portion of the aquifer:

> Detections of organic chemicals are more numerous and exhibit higher concentrations in the deeper of the two monitoring wells. This observation, along with trends in methane, potassium, chloride, and pH, suggest a deep source (> 299 m bgs) of contamination. Natural breakdown products of organic contaminants like BTEX and glycols include

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> acetate and benzoic acid are more enriched in the shallower of these two monitoring wells, suggesting upward/lateral migration with natural degradation. (p. 23)

The thrust of the argument is that "higher" concentrations of chemicals in MW02 (the deeper well) and "lower" concentrations of these constituents in MW 01 (along with potential breakdown products), are used as "evidence" of upward migration in the formation. Apparently, without any other confirming analysis, US EPA has presumptively assumed that there is an upward migration pathway connecting these two wells, which is a necessary condition for the inferences in the Study to have any validity. However, as discussed above, US EPA's inference is based on data that are unreliable. Even if the data were valid, US EPA has not presented evidence that the differences in chemical concentrations in MW01 and MW02 represent anything other than inherent variability in the chemical conditions at the two locations, which are nearly two miles apart.

The "breakdown products" mentioned in the Study, including acetate and benzoic acid, are formed naturally by microbial fermentation processes (Jones and Woods, 1986). These constituents would be expected to be present in the gas-bearing zones where MW01 and MW02 were installed as a result of biodegradation of preexisting natural gas. Furthermore, one of the drilling additives used during the deep monitoring well installation, Quick-Trol Gold, is composed of 60 to 100% polysaccharides and would be expected to biodegrade into a variety of breakdown products, including acetate and benzoic acid. Thus, the breakdown products observed in US EPA's deep monitoring wells are most likely due to fermentation of pre-existing organic compounds in groundwater and possibly drilling additives – not presumptive indicators of migration from deeper groundwater zones.

Moreover, the argument that the concentration differences are explained by "upward flow" necessarily requires an upward hydraulic gradient within the aquifer. As discussed in Section 2.1 of this report, a number of regional hydrogeologic studies have consistently demonstrated that vertical hydraulic gradients in the Pavillion area are downward. For example, downward flow gradients were noted consistently in a long-term (1.5-year) study undertaken at a monitoring well cluster in the Wind River Formation (McGreevy *et al*., 1969). Despite this and other information on the downward regional gradient (see Section 2.1), US EPA states incorrectly that there is no hydraulic gradient information for the area.[25]

In addition to the regional downward gradient, the natural gas production wells would further enhance downward flow, since each gas extraction well acts as a hydrologic "sink" (not unlike a "straw") that extracts methane and water from the formation. The extraction of fluids induces a zone of low hydraulic head in the well and surrounding fracture zone and causes water within the formation to flow toward the gas wells, rather than upward away from them.

The only argument for inferring an upward head gradient offered in the Study is the presence of a "flowing" stock well (*e.g.*, PGDW44, a 229-meter deep well). However, the presence of a flowing or artesian well indicates that there is a significant confining layer present that has hydraulically isolated the underlying strata from overlying deposits (Freeze and Cherry, 1979). The presence of such a confining layer (*e.g.*, shale) would effectively isolate deep groundwater from shallow groundwater, rather than providing a significant pathway for upward migration across a low-permeability layer (as speculated by US EPA). Thus, this US EPA "line of evidence" is in fact not supported by any evidence.

[25] The US EPA Study is silent on the static water level data in MW01 and MW02 relative to what this information suggests regarding hydraulic head gradients in the Pavillion study area.

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4.5 US EPA Did Not Consider the Nature of Hydraulic Fracturing Operations and Its Hypothesis that Hydraulic Fracturing Fluids Migrated Preferentially Along Gas Production Well Annuli Is Speculation

In one of its lines of reasoning, US EPA implies that the hydraulic fracturing of thin, discontinuous sandstone units and the lack of a laterally continuous shale unit would allow for the vertical migration of HF fluid and methane. US EPA also states that "vertical migration of fluids could also occur via nearby wellbores," citing well Pavillion Fee 34-03R as an example of a well with no cement in a portion of the well bore, which US EPA implies would serve as a preferential migration pathway. These statements are purely speculative and inconsistent with site-specific data.

Both of US EPA's migration theories – vertical migration through the formation rock and migration via well annuli – do not take into account the nature of HF stimulations or the hydrogeology of the Study area. Migration along these pathways can be considered during two periods – the HF stimulation period when pressure is being actively applied to the target zone and the post-HF period when fluids are being pumped out of the well. During both periods, the hydrogeologic conditions of the Study area would sequester HF constituents at depth and prevent upward migration to drinking water aquifers, as discussed below.

During the HF stimulation period, fractures are expected to propagate horizontally, with some limited fracture growth vertically at the depths where HF occurs in Pavillion (Fisher and Warpinski, 2011). Therefore, HF fluids would primarily migrate laterally within the sandstone unit and not upward to overlying drinking water aquifers. Purported upward migration through the formation rock for any significant distance or *via* well annuli is highly unlikely during the HF stimulation period for the following reasons:

- The volume of pore space between adjacent gas wells is on the order of millions to tens of millions of gallons for typical values of rock interval thickness (3-10 feet; WOGCC, 2012) and porosity (0.06 to 0.3; Nelson *et al*., 2009) in the Pavillion area. The significant available pore volume is expected to trap the relatively small volumes of introduced fluids (see below) without displacing formation fluids significantly.
- Sandstone intervals in the Pavillion area were treated with low-volume HF stimulations – typically on the order of 1,000 to 10,000 gallons of fluid per fractured well interval (WOGCC, 2012).[26] Given that the available pore volume is many orders of magnitude larger than the low-volume HF treatments, it is highly unlikely that the introduced HF fluid or naturally occurring methane could migrate a significant distance laterally and/or vertically through these pore spaces.
- In addition, HF duration (*i.e.*, application of high pressures to the formation) is relatively short (*i.e.*, a few hours), with all intervals at a typical well being hydraulically fractured in a total of one (1) to two (2) days. The short duration of the pressure application would not allow for migration of HF constituents across the horizontal/vertical distances speculated in the Study.

In addition to these factors, which would sequester HF fluids at depth, US EPA's theory regarding vertical migration of fluids *via* nearby wellbores ignores the distances that the fluids would have to travel during the short HF stimulation period. Gas wells in the Pavillion area are typically spaced 285 meters (936 feet) apart (*i.e.*, median spacing) and at least several hundred (and usually several thousand) feet deeper than drinking water wells (based on WOGCC, 2012). For HF fluids to preferentially migrate *via* the outer

[26] This is in contrast to the fluid volumes used in shale plays, which can involve millions of gallons of HF fluids.

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annulus of a neighboring gas production well, the HF fluids would have to travel a significant distance both laterally and vertically to reach domestic water wells. For instance, in the example pointed out by US EPA (2011, p. 30), the distance between Pavillion Fee 41-10 and Pavillion Fee 34-03R is approximately 600 meters (1,970 feet). The vertical separation between the shallowest interval hydraulically fractured at Pavillion 41-10 and monitoring well MW01 is approximately 250 meters (800 feet). Therefore, for US EPA's preferential migration hypothesis to be valid, HF fluids introduced at the shallowest interval at Pavillion 41-10 would have to migrate 600 meters (1,970 feet) laterally and then 250 meters (800 feet) vertically up the annulus of Pavillion Fee 34-03R to reach the elevation at which MW01 is screened. The fluids would then have had to migrate another 500 meters (1,640 feet) laterally to reach MW01 [*i.e.*, a total migration distance of 1,350 meters (4,400 feet)]. This is a far-fetched scenario when the nature of the HF activities undertaken in Pavillion is considered.

During the post-HF period, fluids within the production well's radius of influence will be captured by the well. Any trapped HF fluid (in pinched-off fractures or beyond the well's radius of influence) will migrate in the direction of the regional hydraulic gradient. Given that the regional hydraulic gradient is downward (as discussed in the previous section), upward migration of HF constituents along either pathway (through formation rock or *via* well annuli) is also not plausible. Moreover, even if an upward hydraulic gradient existed, the prevalence of numerous overlying shale layers – even if discontinuous – would make upward migration of HF constituents highly unlikely. As recognized in the Study, the underlying geologic strata within the study area are highly variable with sandstone lenses of limited thickness interspersed among thicker shale layers (see Figure 4.3). In order to reach the depths of MW01 and MW02, constituents of HF fluids would have to migrate upward through over 400 feet of these interspersed layers, following what US EPA acknowledges would be a "tortuous path." Given the low permeability of the intervening layers of shale, the migration of any "trapped" HF fluids (*i.e.*, those that are not recovered at the gas well) would be significantly impeded and the time taken for HF fluids to follow the "tortuous path for upward migration" would be very long (US EPA, 2011, p. 37).

Given the nature of HF stimulations utilized and hydrogeologic conditions in Pavillion, it is highly unlikely that HF fluids could have migrated – either preferentially along the annulus of neighboring gas wells or *via* fractures or pores within the bedrock – and reached the depth horizon where the US EPA deep monitoring wells are screened, even in the presence of an upward hydraulic gradient. Given the existing downward gradient, such migration is simply implausible.

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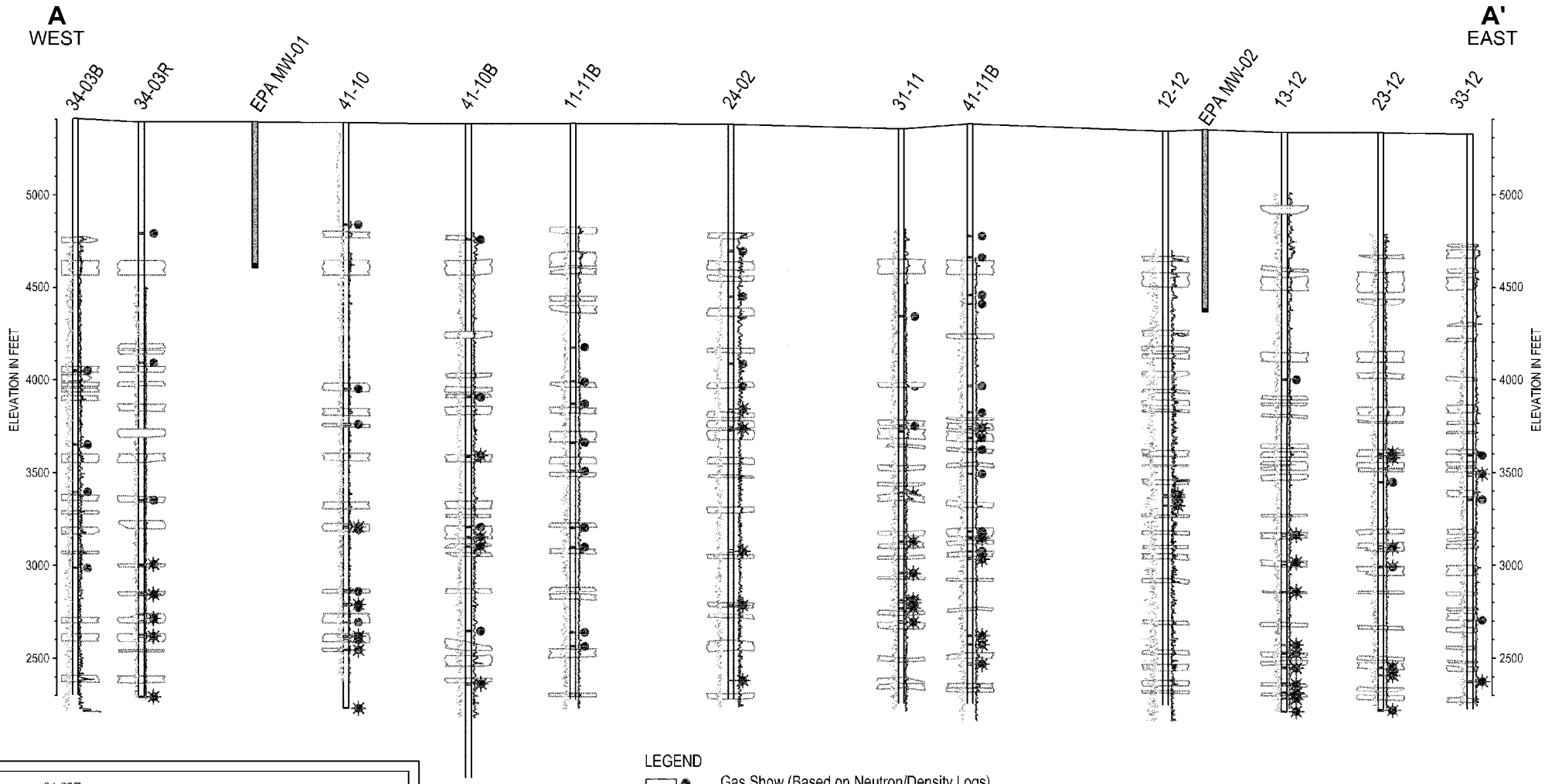

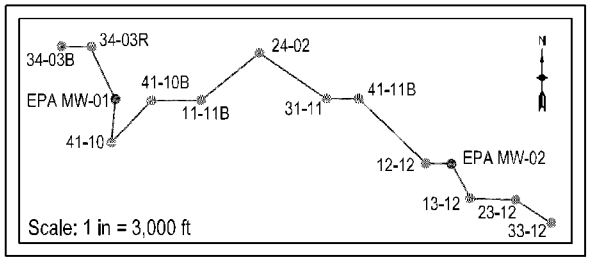

LEGEND

- Gas Show (Based on Neutron/Density Logs)
- Gas Completion Using Hydraulic Fracturing
- Gamma Ray and Resistivity Log
- Major Sand Interval, Lateral Extent Unknown (Based on Gamma Ray and Resistivity Logs)
- Shale Interval, Lateral Extent Unknown (Based on Gamma Ray and Resistivity Logs)
- No Lithology Data Available

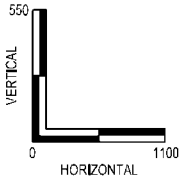

Figure 4-3 - Geologic Cross Section with Interpreted Lithology and Gas Shows
Pavillion Gas Field
Pavillion, Wyoming

4.6 US EPA's Enhanced Methane Migration Hypothesis Is Not Supported by the Data

As one of its "lines of reasoning," US EPA suggests that the pattern of methane detected in drinking water wells is the result of "enhanced" methane migration due to HF activities. However, the Agency's suggestion is flawed. First, there were significant data quality problems with the methane data, rendering them of questionable utility for reaching any meaningful conclusions. Second, given the gas-rich nature of the study area, it is not surprising that some drinking water wells contain methane and likely contained methane prior to when any fracturing activities occurred. Lastly, an examination of the distribution of methane data does not support US EPA's hypothesis, even if one takes the data at face value.

4.6.1 Methane Is Prevalent Regionally

As noted in the Study, the Pavillion Gas Field is in an area of highly variable geology. The Wind River Formation is a methane-rich deposit that has been producing natural gas for many years, pre-dating the advent of hydraulic fracturing. For example, the Plunkett Gas Field, which draws gas from the Wind River Formation several miles south of the Pavillion Gas Field, historically has yielded natural gas from strata as shallow as 55 meters (165 to 182 feet) bgs (USGS, 1945). These gas wells date back to the 1920s through 1940s, prior to the advent of HF methods in the 1950s. Thus, from a regional perspective, the presence of methane in well water is not a conclusive indicator of HF-induced contamination.

The presence of shallow methane in the Pavillion region is consistent with the region's geology and has been documented in a number of studies. For example, Johnson *et al.* (2007) indicate that thermogenic natural gas is not generated within the Wind River Formation, but rather within one or more underlying geologic units (*e.g.*, the Upper Cretaceous Meeteetse Formation and/or Paleocene Fort Union Formation), and thermogenic natural gas is "pervasive in Cretaceous and lower Tertiary strata." Following generation, natural gas "migrated vertically and laterally into the first available sandstone reservoir." However, "in faulted and fractured zones [such as those present beneath the Pavillion Gas Field], these gases migrated vertically much farther...There is good evidence that mature gases from deep sources migrated into units as young as the Eocene Wind River Formation" (Johnson *et al.*, 2007).[27] The majority of these natural gas reservoirs are found within the Wind River and Fort Union Formations at depths ranging from 400 to 1,800 meters (1,300 to 5,900 feet), but shallower deposits of natural gas have been identified during drilling operations. Independent review of mud logs available on the WOGCC website and information provided in the US EPA Study indicate at least six (6) independent observations of shallow methane in the Pavillion area at depths ranging from 159 to 326 meters (515 to 1,070 feet):

[27] The upward migration of natural gas can occur even though hydraulic gradients are downward, due to the buoyancy effect (*i.e.*, natural gas is much less dense than water and will tend to float), and because natural gas migrates by diffusion from locations of higher concentrations to regions of lower concentrations. Both of these phenomena explain why natural gas movement in the Pavillion area is upward. In contrast, water moves as a function of hydraulic gradients, and the regional hydraulic gradients are downward.

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Table 4.1 Observations of Shallow Methane Prior to Hydraulic Fracturing Activity in the Study Area

Name	Depth	Year	Source
Taylor Patented 1	157 – 181 m	1976	WOGCC mud log
Tenneco-Garrett #1	198 – 232 m	1979	WOGCC mud log
Pavillion 12-3	317 m, 326 m	1980	WOGCC mud log
Unnamed Gas Strike	198 m	1965 - 1973	US EPA (2011), p. 27
Unnamed Gas Strike	208 m	1965 - 1973	US EPA (2011), p. 27
Unnamed Gas Strike	252 m	1965 - 1973	US EPA (2011), p. 27

These observations indicate clearly that, given the highly heterogeneous nature of this formation and the age and thermal maturity of the underlying natural gas source rocks, shallow deposits of natural gas were found throughout the Wind River Formation prior to implementation of HF operations in the area in the late 1980s.[28]

The US EPA Study also indicates that a natural gas blowout occurred during drilling at 159 m-bgs while drilling adjacent to PGDW05. US EPA utilized blowout preventers during the installation of its deep monitoring wells—an implicit acknowledgement that shallow methane is present in the vicinity of these wells. In addition, the highest FID readings during installation of MW01 were recorded between 152 to 213 meters (500 to 700 feet) – a similar depth range as the blowout at PGDW05 and another indication of natural gas at these intervals. Methane was also noted in MW02 during well development/sampling, and gas samples were also collected at the well. All this information is indicative of gas-rich strata at relatively shallow depths.

4.6.2 Methane in Domestic Wells Does Not Exhibit the Pattern Suggested by US EPA

US EPA suggests that the methane concentration in domestic well samples is generally higher for those wells that are in proximity to gas production wells (US EPA, 2011, Figure 18c). That depiction of the methane data is misleading.

We have plotted the methane data for the domestic wells as a function of the number of gas production wells located within 600 meters (the same proximity used by US EPA, 2011, in Figure 18c). As seen in Figure 4.4, below, there is no discernible relationship between the methane concentrations in drinking water wells and the numbers of gas production wells within 600 meters. As the number of proximate gas wells increases, methane is just as likely to be non-detectable as it is to be detected. This result is not consistent with the hypothesis that natural gas production (or HF activities) have enhanced methane migration. If that were true, one would expect to see a clear relationship between higher methane concentrations *versus* the intensity of gas production and HF activities; there is no such relationship.

[28] The variable nature of "gas shows" within the Pavillion gas field is also shown in Figure 4.3. The gas shows on that figure are based on neutron/density logs, which like mud logs indicated in Table 3.1, are another method of assessing the likely presences of natural gas-bearing strata.

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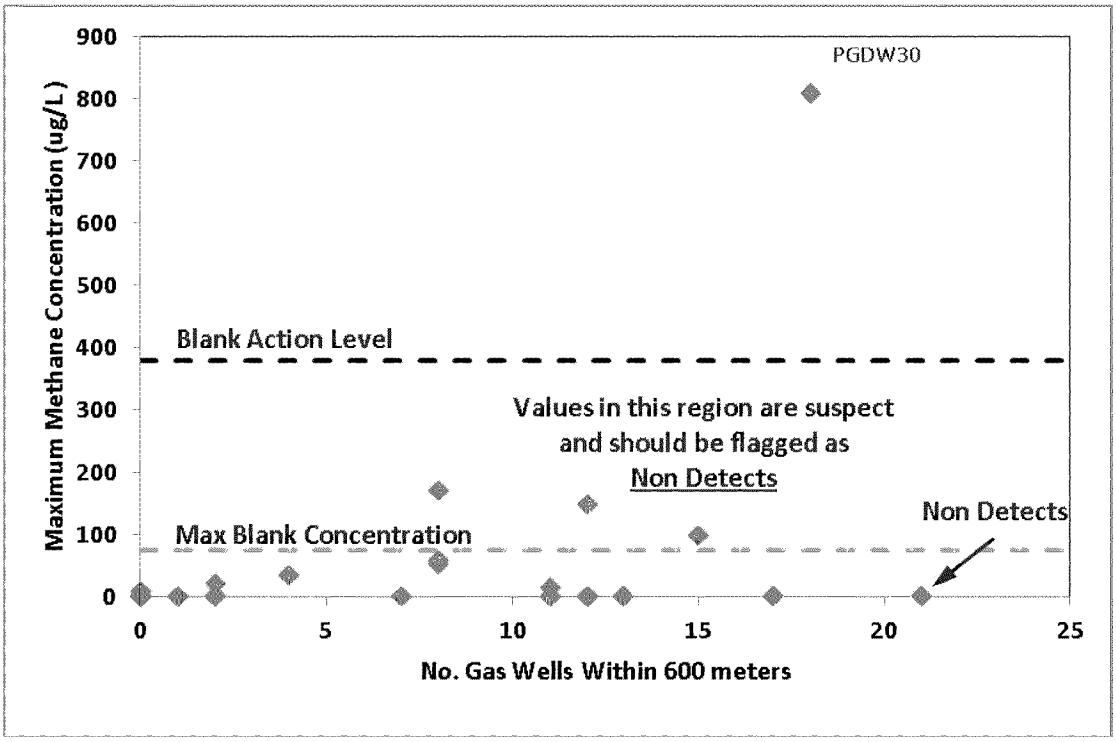

Figure 4.4 Methane in Drinking Water Wells as a Function of Proximity to Gas Wells

If HF activities associated with natural gas production were contributing to an increase in methane in drinking water wells, one would also expect to observe a spatial correlation indicative of a methane "plume" within the area where gas wells are prevalent. Figure 4.5 provides the maximum methane concentration in drinking water wells for the Pavillion study area, also depicting the locations of gas production wells. Taking the methane data at face value (*i.e.*, ignoring the blank contamination problems), there is no apparent spatial pattern in the methane data. For example, no methane is found at many domestic wells located in close proximity to gas wells (*i.e.*, no "bulls eye" around production wells). The lack of any spatial pattern within the active gas producing area runs counter to the theory that methane in drinking water wells is more prevalent where gas production (HF activities) occur.

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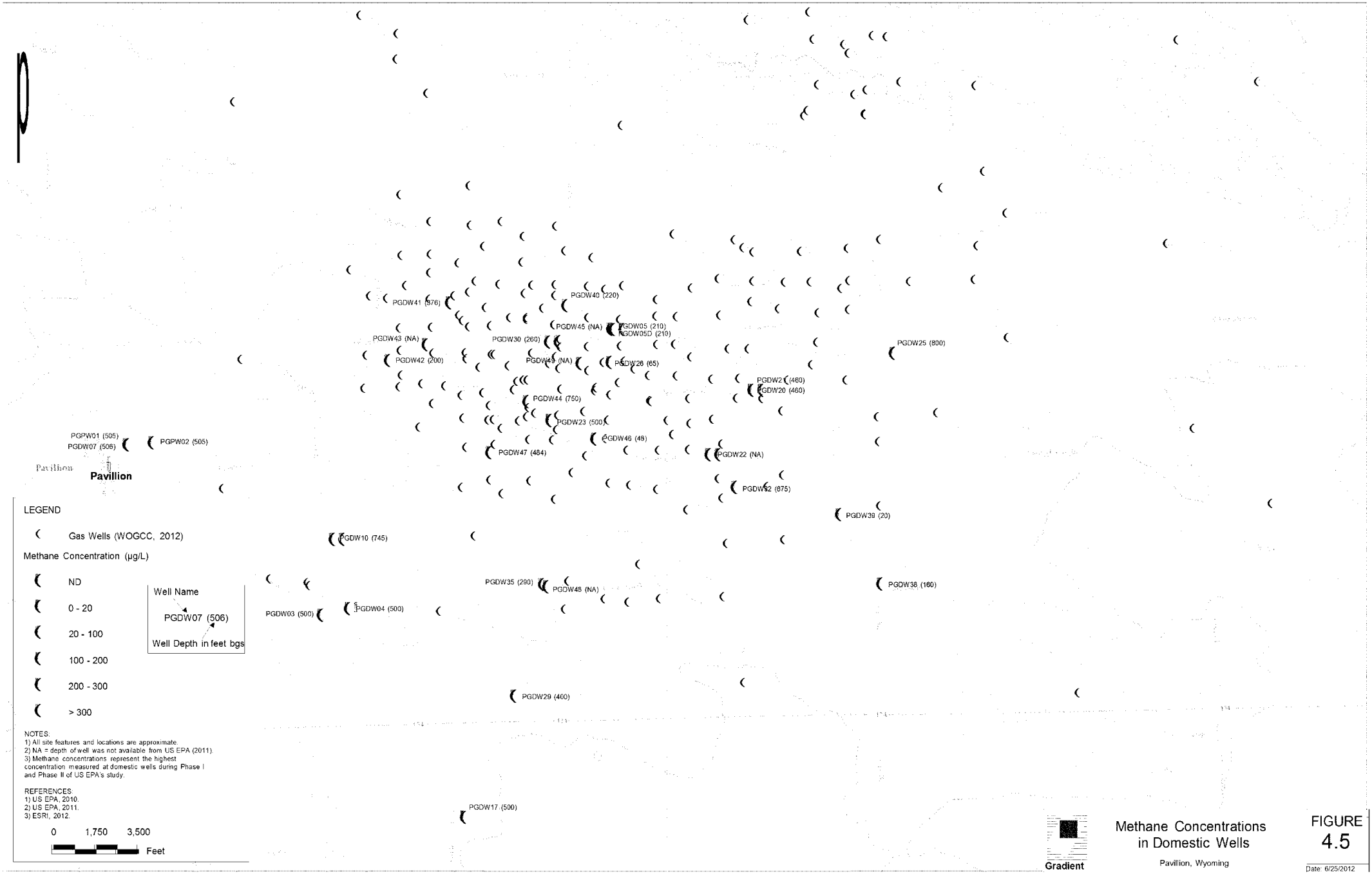

Methane Concentrations in Domestic Wells

Pavillion, Wyoming

FIGURE 4.5

Date: 6/25/2012

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In addition, if methane were being released as a result of HF activities, as asserted by US EPA, one could also expect to see increasing methane concentrations with depth, where wells are in closer proximity to the gas production zones. As shown in Figure 4.6, there is no correlation between methane concentration and depth. In fact, if there is any pattern in the methane concentrations in the domestic wells at all, there is perhaps a slight tendency for higher methane concentrations in shallower wells than deeper wells. This pattern is inconsistent with the hypothesis that HF activities (*i.e.*, "deep source terms") are contributing to the methane concentrations in domestic wells.

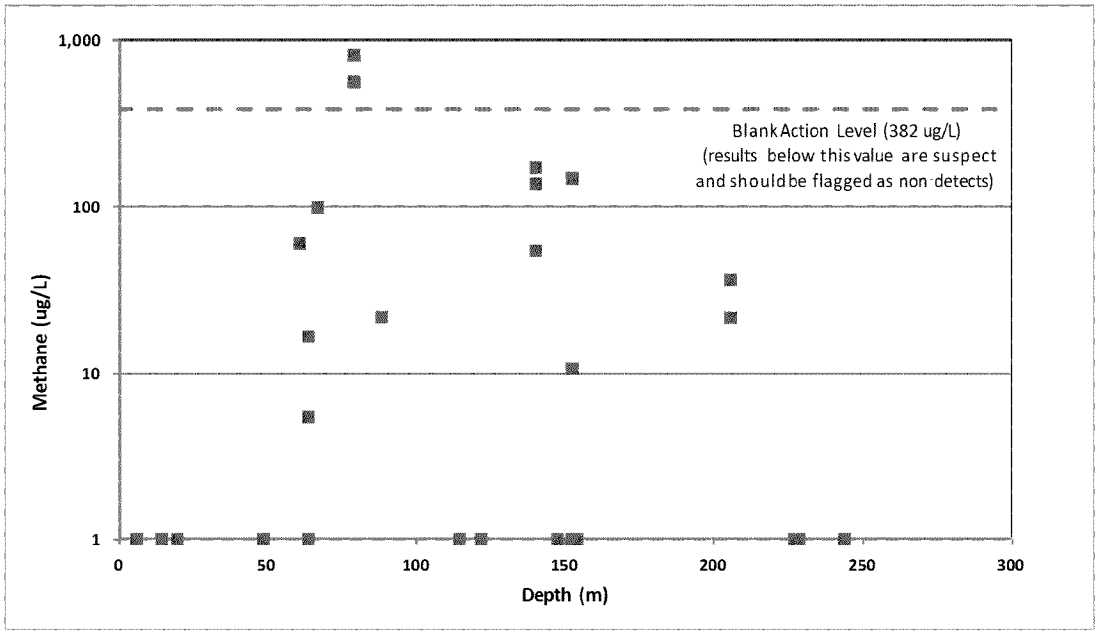

Figure 4.6 Methane Concentration in Domestic Wells *versus* Well Depth

4.6.3 US EPA's Isotopic Analysis of Methane Patterns Hinges on the Results of Only Three Wells and Is Misleading

As another line of reasoning, the US EPA Study states that the "absence of ethane and propane in three of four domestic wells having sufficient methane to allow isotopic analysis...suggests the presence of gas of thermogenic origin in domestic wells undergoing biodegradation" (US EPA, 2011, p. 29). In support of this conclusion, the Study states: "[v]alues of $\delta^{13}C$-CH_4 more positive than -64$_{0/00}$ and $C_1/(C_2+C_3)$ ratios above 1000 are often interpreted to indicate gas of mixed biogenic-thermogenic origin or gas of biogenic origin undergoing biodegradation" (US EPA, 2011, p. 29). On this basis, the US EPA hypothesizes, "[t]his observation is consistent with a pattern of dispersion and degradation with upward migration" (US EPA, 2011, p. 29). The conclusion reached is highly speculative and inconclusive for several reasons:

- Contrary to the claim in the Study, the interpretation is based on the sample results from only *three* domestic wells (PGDW20, PGDW30, and PGDW32), not four as the Study asserts; US EPA double counts two rounds of sampling from PGDW30.
- Of these wells, PGDW32 had no detectable methane in the Phase IV sampling, and only low levels in previous phases (21.4 µg/L in Phase I and 36.3 µg/L in Phase II). This draws into question whether methane is reliably present in this well, especially given the consistent detection of methane in blank samples. As discussed previously in Section 3.4 and in more detail below (in

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Section 4.6.4), the validity of the detected methane results for domestic wells is questionable given the pervasive methane contamination in field/trip blanks.

- Neither PGDW30 nor PGDW32 had detectable ethane (C_2) or propane (C_3). Therefore, the ratio of $C_1/(C_2+C_3)$ is undefined. In Figure 18a of its report, US EPA arbitrarily plots this ratio as 100,000, giving the artificial and misleading appearance that it was significantly different than the ratios plotted for the "thermogenic" region.[29] Figure 4.7 below re-plots these data using the detection limits to calculate the $C_1/(C_2+C_3)$ ratio. This shows that the methane in PGDW30 and PGDW32 is primarily thermogenic in origin with small amounts of oxidation, as would be expected for groundwater overlying a gas-bearing region. These data do not support US EPA's implication of enhanced migration due to HF activities.
- PGDW20 (140.2 m bgs), which is plotted in Figure 18a in the "thermogenic" region, is 65.5 meters (215 feet) shallower than PGDW32 (205.7 m bgs). Thus, this well does not exhibit a pattern of "dispersion and degradation with upward migration" as hypothesized.

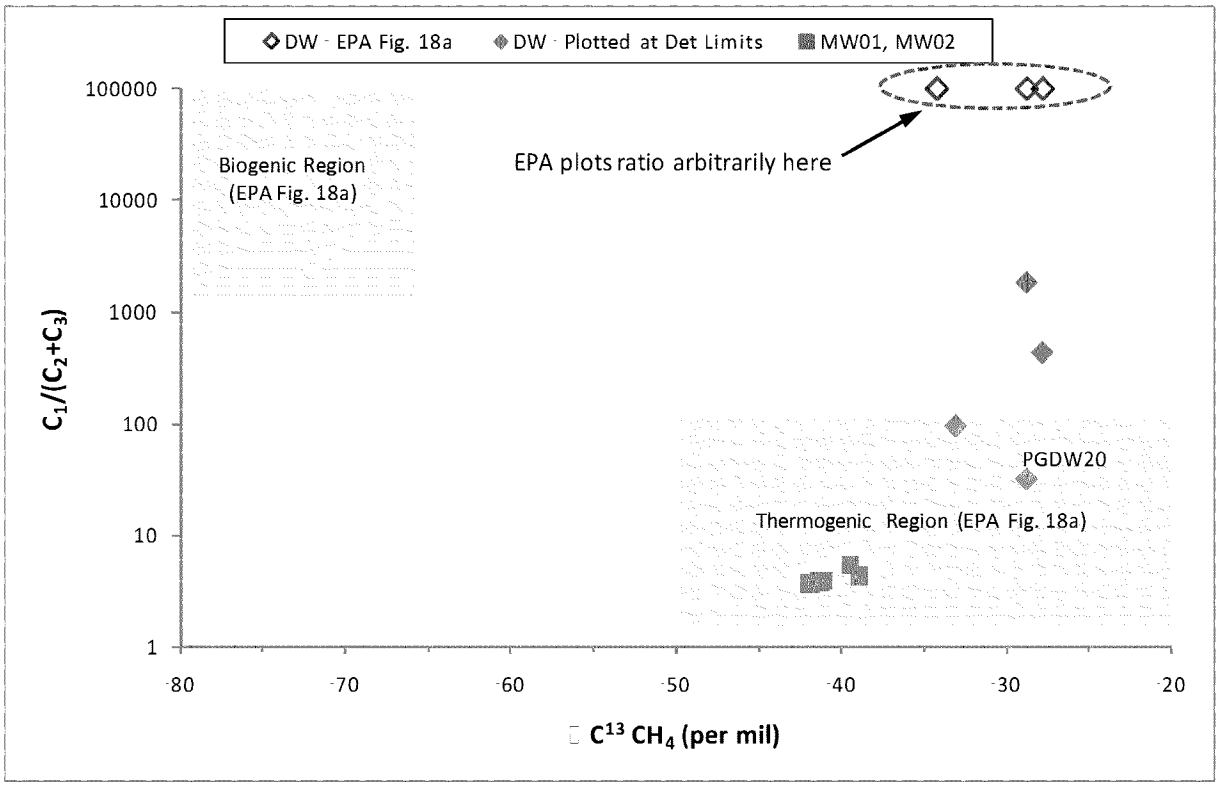

Figure 4.7 Ratio of Methane to Ethane Plus Propane [C1/(C2+C3)] *versus* C13 CH4 for Domestic Wells and Deep Monitoring Wells

[29] Also note that some of the carbon isotope data used in the US EPA report to create Figure 18a and b (US EPA, 2011) differ from the values in the Phase II study (URS, 2010b). Carbon isotope measurements were reported for condensate samples obtained from gas production wells in Pavillion and from 8 domestic wells during Phase II (URS, 2010b, Table 14). US EPA does not explain this data inconsistency. In addition, US EPA has not made the laboratory reports for the Phase II isotopic data available to the public. Therefore, there is no way for reviewers to understand the reason(s) for the inconsistent data. Finally, in its draft report (US EPA, 2011), without explanation, US EPA does not use the carbon isotopic signature data obtained from sampling the 8 domestic wells in Phase II (URS, 2010b).

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For these reasons, the isotopic analyses for three domestic wells is of little, if any, value in addressing the question of whether HF activities have had any impact on domestic well water quality.[30]

4.6.4 Methane Data Quality Problems Limit the Utility of the Data

The methane data have significant quality problems that severely affect the reliability of these measurements. In Phases III and IV of the Study, methane concentrations in field blanks were as high as 76.4 and 45 µg/L, respectively. This led US EPA to reject all Phase IV data where the sum of methane and ethane concentrations were less than 100 µg/L (US EPA, 2011, footnote on Table A3a). It is not clear why, despite the high detections in the corresponding blanks, US EPA did not reject any Phase III methane data. US EPA did not collect any methane blanks in Phases I and II, although given the consistent detections of methane in the Phase III and IV blanks, it is likely that Phase I and II data were also affected by blank contamination. Given these data quality problems, conclusions drawn from these unreliable methane data are likewise unreliable.

[30] Not only is the analysis of little value, even if there were an indication of some potential biogenic component to the methane in these few samples, that does not provide any evidence of "migration" from deeper strata as the Study implies.

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5 Conclusions

In response to residents' complaints of objectionabl e odors and tastes in well water near the town of Pavillion, Wyoming, US EPA initiated a groundwater investigation in 2009. After four phases of sampling and installing only a handful of monitoring wells, US EPA released its Study titled, "Draft Investigation of Ground Water Contamination Near Pavillion, Wyoming" report (US EPA, 2011). This critical review of the US EPA Study indicates that the Study design was flawed, the Study implementation (*i.e.*, field work and data quality evaluation) was extremely poor, and the analysis of the data is not based on sound science. Consequent ly, US EPA's methods and data do not support the conclusion reached in its Study that "inorganic and organic constituents associated with hydraulic fracturing have contaminated ground water at and below the depth used for domestic water supply" (US EPA, 2011, p. 39). The significant shortcomings of the Study are summarized below.

US EPA's Study Design Was Inherently Flawed

- In a study area covering approximately 50 square miles, US EPA installed only two (2) deep monitoring wells approximately two miles apart. The lack of a sufficient number of wells and the lack of any wells providing a "vertical profile" of hydraulic gradients and chemical constituents yielded results of limited value in addressing one of the key Study objectives: determining whether "deep source terms" (*e.g.*, from HF activities) had impacted drinking water aquifers in the Pavillion area.
- US EPA failed to consider existing information on the hydrogeological setting in its study design that indicated the vertical hydraulic gradient (*i.e.*, direction of groundwater flow) is downward in the study area. Despite this available information, US EPA's analysis and conclusions presumed incorrectly that regional groundwater flow is upward.
- US EPA failed to install its deep monitoring wells at appropriate depths. The depths of US EPA's deep monitoring wells are below the typical depths of domestic wells in the region, and they are not able to evaluate "deep source terms" because the natural direction of groundwater flow is downward (*i.e.*, from the monitoring wells to greater depths in the formation).
- US EPA failed to characterize background concentrations of constituents in groundwater, especially with respect to organic constituents. Without such information, it is impossible to draw any meaningful conclusions about the potential sources of constituents detected in monitoring wells, especially in an area that is naturally rich in petroleum hydrocarbons.
- US EPA failed to adequately consider the nature of HF stimulations in the study area. The HF treatments are predominately low-volume and utilized CO_2 foam. These characteristics limit both the potential for HF fluid migration and changes to groundwater geochemistry that would be associated with HF fluid migration.

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US EPA's Study Implementation Was Very Poor, Limiting the Reliability of the Monitoring Results

- US EPA's implementation of the Study (*i.e.*, field work execution and data quality review) did not follow its own guidance or Work Plan for groundwater sample collection in the Pavillion area (US EPA, 1996; US EPA Region I, 2010; URS, 2010b).
- US EPA failed to install, develop, and sample the deep monitoring wells properly, which has compromised the groundwater data and resulted in faulty interpretations of groundwater chemistry. The lack of bentonite seals in all likelihood allowed cement grout to impact groundwater in the vicinity of the well screens; the grout intrusion may have contributed to poor well development (which itself was substandard). Cement grout in the screened interval was likely the primary cause of elevated pH, chloride, and potassium concentrations observed in the deep monitoring wells. Moreover, US EPA's groundwater sampling techniques (*e.g.*, high purge rates) were unconventional, and the Agency collected samples despite sharp changes in field parameters (*e.g.*, pH, specific conductivity) during the purging process – an indication that samples may not be representative of local formation groundwater.
- US EPA did not review the quality of the data adequately prior to utilizing the information for drawing conclusions and has therefore made statements that are overreaching and unsupported by the data. For example, US EPA used non-standard analytical test methods to analyze glycols and 2-BE without proper method validation, causing these results to be highly questionable. Additionally, a wide variety of compounds (*e.g.*, hydrocarbons, methane, and glycols) were routinely detected in the field and trip blanks – an indication of sloppy field sampling practices. US EPA did not follow its own DQA guidance and did not take appropriate actions in addressing the presence of blank contamination. If it had, a large subset of the data for certain compounds, such as methane and hydrocarbons, would have been considered non-detects.

US EPA's Findings and Conclusions Are Not Based on Sound Science

- **Elevated pH, Potassium, and Chloride:** US EPA asserts that pH, potassium, or chloride are elevated at the deep monitoring wells as a result of HF activities. However, the evidence indicates that these conditions are in all likelihood a result of cement grout intrusion into the monitoring well screens and poor well development, and not due to migration of HF fluids.
- **Petroleum Hydrocarbons:** US EPA incorrectly assumed that petroleum hydrocarbons detected in the deep monitoring wells were from a deep source. As discussed in our report, the elevated petroleum hydrocarbon concentrations detected in the deeper of the two monitoring wells (MW02) are associated with natural gas presence in the formation. The chemical signature of petroleum hydrocarbons (BTEX, tri-methylbenzenes) detected in MW02 matches that of a condensate sample collected from a natural gas well by US EPA in Pavillion.
- **Synthetic Organic Compounds:** US EPA used non-standard and unvalidated methods to analyze glycol and 2-BE. These data are unreliable and not usable for decision-making. The other organic compounds attributed to HF activities by US EPA (*e.g.*, TBA, isopropanol) can occur naturally in petroleum hydrocarbon-rich subsurface environments.
- **Direction of Vertical Groundwater Flow:** US EPA presumed incorrectly that the direction of vertical groundwater flow was upward, even though there is a wealth of available data that indicate the hydraulic gradient (and flow) is downward. Furthermore, the theory presented in the Study that "chemical gradients" between MW02 and MW01 are an indication of upward vertical

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flow is flawed, given that these two deep monitoring wells are nearly two (2) miles apart, are set in an extremely heterogeneous formation, and are unlikely to be hydraulically connected. Indeed, if these two monitoring wells are hydraulically connected, the vertical hydraulic gradient between the two is downward.

- **Purported Migration Pathways:** US EPA theorizes that chemicals could migrate upward from the gas-bearing zone through the formation rock and *via* well annuli. These purported pathways for migration of HF fluid do not take into account the nature of HF stimulations or the hydrogeology of the Study area. During an HF stimulation, upward migration through the formation rock is highly unlikely, given that the anticipated direction of fracture propagation is horizontal. Migration of HF fluids to an adjacent production well is similarly unlikely, given the low volume of HF fluids used in the Pavillion area, short duration of the stimulations, and large available pore volume in the subsurface compared to the volume of HF fluids used. Subsequent to an HF stimulation, upward migration *via* any pathway (either through formation rock or *via* well annuli) is not plausible, because the direction of groundwater flow is downward in the Pavillion area. Furthermore, the preponderance of thick, low-permeability shale layers throughout the area (even if discontinuous) would severely restrict upward migration, even if hydraulic gradients were upward.
- **Methane:** The hypothesis presented in the Study that HF activities have enhanced the migration of methane has several significant deficiencies. The Wind River Basin (of which the Pavillion Gas Field is part) is a natural gas-rich region, and the presence of methane at shallow depths, before a majority of the gas wells were drilled and hydraulically fractured in the region, is well documented (WOGCC, 2012). The methane measurements in domestic well water do not show any trend with depth, nor do they exhibit any trends as a function of proximity to gas production wells, factors that run counter to the theory that HF activities have enhanced methane migration. Moreover, the domestic well methane data are unreliable because methane was detected in all field blanks (when collected) at concentrations of 45 to 76.4 μg/L.

In summary, the Study prematurely reached overly broad conclusions that are not supported by the available data. Based on our scientific review, we would expect that a thorough peer review of the Study will identify its significant shortcomings (such as those identified in this review) – deficiencies that are so significant as to reject the conclusory findings presented in the Study.

As our analysis demonstrates, the data from the Agency's deep monitoring wells do not provide evidence that the deeper portion of the aquifer is contaminated by HF activities and provide no information relating to groundwater conditions in the portion of the aquifer predominantly used for drinking water. For reasons summarized above, and elaborated upon in this report, the Study does not provide evidence that hydraulic fracturing has caused or contributed to contamination of the drinking water aquifer in the Pavillion area.

We recognize that US EPA is conducting an additional round of monitoring well sampling in Pavillion. To the extent that the sampling is confined to the existing monitoring wells, such sampling will not address the inherent limitations of US EPA's Study design, nor will it address the flaws in the construction of the deep monitoring wells that have compromised the data from those wells.[31] If US EPA wishes to correct these deficiencies in its investigation, additional steps would need to be taken.

[31] It is questionable whether additional well development efforts will adequately eliminate the effects of cement on the monitoring well water quality because studies have shown that cement impacts can persist long after well installation and despite numerous attempts at well re-development (see Section 4.1).

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References

American Chemical Society (ACS). 1980. "Guidelines for Data Acquisition and Data Quality Evaluation in Environmental Chemistry." *Anal. Chem.* 52(14):2242-2249.

American Petroleum Institute. 2012. "Tertiary Butyl Alcohol (TBA) Biodegradation: Some Frequently Asked Questions." Accessed on March 15, 2012 at http://api.org/~/media/Files/EHS/Clean_Water/Bulletins/26_Bull.ashx , 6p., March 5.

Barcelona, MJ; Helfrich, JA. 1986. "Well construction and purging effects on ground-water samples." *Environ. Sci. Technol.* 20(11):1179-1184.

CEMEX, Inc. 2001. "Material Safety Data Sheet (MSDS) for Portland Cement." 7p., March.

Costle, D. [US EPA]. 1979. Memorandum to US EPA Administrators and General Counsel. 7p., June 14.

Daddow, RL. 1992. "Ground-Water and Water-Quality Data through 1991 for Selected Wells on the Wind River Indian Reservation, Wyoming." USGS Open-File Report 92-455. 131p.

Driscoll, FG. 1986. *Groundwater and Wells (Second Edition)*. Johnson Division, St. Paul, MN, 1089p.

ESRI, 2012. "World Topographic Map."

Fisher, K; Warpinski, N. 2011. "Hydraulic fracture-height growth: Real data." SPE 145949. In *SPE Annual Technical Conference and Exhibition*, Denver, CO, October 30 – November 2, 18p.

Freeze, RA; Cherry, JA. 1979. *Groundwater*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 604p.

James Gores and Associates. 2011. "Pavillion Area Water Supply Level I Study (Preliminary Interim Draft)." Report to Wyoming Water Development Commission (Cheyenne, WY). 139p., August.

Johnson, C; Finn, TM; Kirschbaum, MA; Roberts, SB; Roberts, LNR; Cook, T; Taylor, DJ. 2007. "The Cretaceous-Lower Tertiary Composite Total Petroleum System, Wind River Basin, Wyoming." In: *Petroleum Systems and Geologic Assessment of Oil and Gas in the Wind River Basin Province, Wyoming*. USGS Wind River Basin Province Assessment Team, U.S. Geological Survey Digital Data Series DDS-69-J. Accessed at http://pubs.usgs.gov/dds/dds-069/dds-069-j/chapters.html.

Jones, DT; Woods, DR. 1986. "Acetone-butanol fermentation revisited." *Microbiol. Rev.* 50(4):484-524.

Jones, J; Smith, C; Hyman, M; Skinner, K. 2007. "Microbial isobutane oxidation: An unexpected source of TBA from gasoline?" In *Ninth International In Situ and On-Site Bioremediation Symposium*, Baltimore, MD, May 7-10. Accessed on March 15, 2012 at http://www.scopus.com, 1p.

EPAPAV0093696

Kent, DC; Hall, RV. 1993. "Borehole Geophysics Applied To The Evaluation Of Groundwater Monitoring Well Construction And Integrity." Publication A-126, University Center for Water Research Oklahoma State University Stillwater, Oklahoma.

Langmuir, D. 1997. *Aqueous Environmental Geochemistry*. Prentice Hall Inc., Upper Saddle River, NJ, 600p.

Leemann, A; Lothenbach, B. 2008. "The influence of potassium-sodium ratio in cement on concrete expansion due to alkali-aggregate reaction." *Cement Concrete Res.* 38(10):1162-1168.

McGreevy, LJ; Hodson, WH; Rucker, SJ IV. 1969. "Ground-Water Resources of the Wind River Indian Reservation, Wyoming." USGS Water-Supply Paper.

Mercer, JW; Erickson, J; Slenska, M. 2007. "Potential Cross Contamination Due to Drilling in Source Areas." 22p., November 6.

Morris, DA; Hackett, OM; Vanlier, KE; Moulder, EA. 1959. "Ground-Water Resources of Riverton Irrigation Project Area, Wyoming." USGS Water-Supply Paper 1375. 215p.

National Environment Laboratory Accreditation Conference (NELAC). 2002. "Quality Systems." Section 5.5.4.4. July 12.

Nelson, PH; Trainor, PK; Finn, TM. 2009. "Gas, Oil, and Water Production in the Wind River Basin, Wyoming." USGS Scientific Investigations Report 2008-5225. 41p.

Parker, R. [US EPA Region VIII]. 2010. Memorandum to C. Poulet (ATSDR) re: Treatment of contamination found in method and field blanks for Pavillion groundwater investigation sampling. 3p., July 27.

Plafcan, M; Eddy-Miller, CA; Ritz, GF; Holland, JPR II. 1995. "Water Resources of Fremont County, Wyoming." USGS Water-Resources Investigations Report 95-4095, 139p.

Puls, RW; Paul, CJ. 1995. "Low-Flow Purging and Sampling of Ground Water Monitoring Wells with Dedicated Systems." *Ground Water Monit. Rem.* 15(1):116-123.

Rapp, P. 1934. "Effect of calcium chloride on Portland cements and concretes." *Highway Research Board Proceedings* 14(Part 1):341-381.

Shaw Environmental and Infrastructure, Inc. (Shaw Environmental). 2010. "Final Monitoring Well Installation Work Plan, Pavillion, Wyoming." Report to US EPA, National Risk Management Research Laboratory (Ada, OK). Accessed on March 08, 2012 at http://www.epa.gov/region8/superfund/wy/pavillion/docs.html, 347p., May.

Thomas, JJ; Rothstein, D; Jennings, HM; Christensen, BJ. 2003. "Effect of hydration temperature on the solubility behavior of Ca-, S-, Al-, and Si-bearing solid phases in Portland cement pastes." *Cement Concrete Res.* 33(12):2037-2047.

EPAPAV0093697

URS Operating Services, Inc. (URS). 2010a. "Expanded Site Investigation - Analytical Results Report: Pavillion Area Ground Water Investigation, Pavillion, Fremont County, Wyoming (Final)." Report to US EPA Region VIII, Superfund Technical Assessment and Response Team 3 (START 3) TDD No. 0901-01. Accessed on February 23, 2012 at http://www.ep a.gov/region8/superfund/wy/pavillion/#9, August 30.

URS Operating Services, Inc. (URS). 2010b. "Expanded Site Investigation - Field Sampling Plan: Pavillion Area Groundwater Investigation, Pavillion, Fremont County, Wyoming." Report to US EPA Region VIII, Superfund Technical Assessment and Response Team 3 (START 3), TDD No. 0901-01. 52p., January 6.

US EPA Region I. 1996. "Low Stress (Low Flow) Purging and Sampling Procedure for the Collection of Ground Water Samples from Monitoring Wells (Revision 2)." SOP GW 0001 (Revision 2). 13p., July 30.

US EPA Region I. 2010. "Low Stress (Low Flow) Purging and Sampling Procedure for the Collection of Ground Water Samples from Monitoring Wells (Revision 3)." EQASOP-GW 001 (Revision 3). 30p., January 19.

US EPA Region III. 2011. "Pavillion GW Investigation: Final Analytical Report." Office of Analytical Services and Quality Assurance (Fort Meade, MD). 32p., July 18.

US EPA Region IV. 2008. "Design and Installation of Monitoring Wells." SESDGUID-101-RO. Accessed on March 05, 2012 at http://www.epa.gov/ region4/sesd/fbqstp/Design-and-Installation-of-Monitoring-Wells.pdf, 33p., February 18.

US EPA. 1991. "Handbook of Suggested Practices for the Design and Installation of Ground-Water Monitoring Wells." Office of Research and Development, EPA/600/4-89/034. 224p., March.

US EPA. 1994. "USEPA Contract Laboratory Program national functional guidelines for organic data review: Multi-media, multi-concentration (ILMO 1.0) and low concentration water (OLCO 1.0) (Draft)." Office of Solid Waste and Emergency Response. December.

US EPA. 1996. "Low-Flow (Minimal Drawdown) Ground-Water Sampling Procedures." Office of Research and Development, Office of Solid Waste and Emergency Response, EPA/540/S-95/504. 12p., April.

US EPA. 2000. "Policy and Program Requirements for the Mandatory Agency-Wide Quality System." Classification No. 5360.0 A2. 13p., May 5.

US EPA. 2002. "Guidance for Developing Quality Systems for Environmental Programs." Office of Environmental Information, EPA QA/G-1; EPA/240/R-02/008. 82p., November.

US EPA. 2003 "Method 8000C: Determinative Chromatographic Separations (Revision 3)." 66p., March.

US EPA. 2006. "Data Quality Assessment: A Reviewer's Guide." Office of Environmental Information, EPA QA/G-9R; EPA/240/B-06/002. 61p., February.

EPAPAV0093698

US EPA. 2011. "Investigation of Ground Water Contamination near Pavillion, Wyoming (Draft)." National Risk Management Research Laboratory (Ada, OK). Accessed on February 15, 2012 at http://www.epa.gov/region8/superfund/wy/pavilli on/EPA_ReportOnPavillion_Dec-8-2011.pdf, 121p., December 8.

US Geological Survey (USGS). 1945. "Wells Drilled for Oil and Gas in Wyoming." Oil and Gas Leasing Division. 286p.

Wandrey, M; Morozova, D; Zettlitzer, M; Wurdema nn, H. 2010. "Assessing drilling mud and technical fluid contamination in rock core and brine samples intended for microbiological monitoring at the CO2 storage site in Ketzin using fluorescent dye tracers." *Int. J. Greenhouse Gas Control* 4(6):972-980.

Wyoming Oil and Gas Conservation Commission (WOGCC). 2012. "Wyoming Oil and Gas Conservation Commission [Website]." Accessed on March 01, 2012 at http://wogcc.state.wy.us/.

EPAPAV0093699