Pavillion Gas Well Integrity Evaluation

U.S. Environmental Protection Agency Region 8

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CONTENTS

INTRODUCTION AND PURPOSE OF EPA'S EVALUATION

The Environmental Protection Agency (EPA) Region 8 has evaluated available information on the construction of gas wells in the Pavillion, Wyoming gas field in relation to the hydrogeology of the field. The EPA is providing this evaluation as technical input to stakeholders participating in the wellbore integrity work group and for consideration in the development of the wellbore integrity study. Consistent with the joint involvement by the EPA, State and Tribal governments regarding Pavillion groundwater issues, EPA will continue to consult and coordinate with the Northern Arapaho and Eastern Shoshone Tribes of the Wind River Indian Reservation regarding this document, to further the protection of the environment and human health. EPA's transmittal of this document is intended to convey our technical considerations only and should not be construed as setting forth any position regarding the exterior boundaries of the Reservation or the exercise of State authorities in this area. The objectives of this evaluation were to:

- Summarize key industry recommended best practices for isolating Underground Sources of Drinking Water (USDWs) from oil and gas production activities;
- Categorize the construction condition of gas wells in the field based on information available in online well files and summary information provided to the wellbore integrity work group by the Wyoming Oil & Gas Conservation (WOGCC);
- Describe potential for fluid migration associated with each category of well construction condition; and
- Offer suggestions regarding test methods and evaluation procedures appropriate for each construction condition that would identify wells in that category that may need remedial cementing in order to ensure isolation of the USDW.

Concerns about wellbore integrity have been raised and discussed among Pavillion stakeholders. The concerns in general have related to the placement and condition of casing and cement in the Pavillion gas wells, whether the construction conditions pose risk that fluids have or could migrate up gas wellbores, and how that risk could be evaluated and, where appropriate, remediated. These are complex technical issues. The EPA's purpose in this evaluation was to summarize the information available regarding well construction in the Pavillion field, and offer our recommendations for appropriate annulus testing methods and approaches to determine the extent of those risks.

GAS WELL CONSTRUCTION AND ISOLATION OF GROUNDWATER RESOURCES

The following section categorizes well construction based on the relationship of open annular zones and USDWs, and attempts to explain the importance of well construction with respect to risk for fluid movement as a result of overpressurization of open annuli. Refer to the figure in Attachment 1 for an illustration of well construction terms used in this document.

In the literature, there are recommendations concerning gas well integrity and more specifically the relationship of well construction to USDWs. We offer the following observations from industry organizations regarding the design and construction of wells to protect groundwater resources. The EPA recognizes these observations and recommendations are general in nature, and that other considerations are necessary in well design such as field-specific requirements and the need for blow out prevention to be installed prior to drilling deeper zones that may exhibit gas pressures that cannot be safely penetrated without installation of blowout preventors (BOP). However, it is clear in these observations that protection of USDWs from unintended migration of gas and liquids is a priority for the industry, and that industry best practices, if followed, can prevent or minimize groundwater contamination.

It is not EPA's intention to evaluate whether well construction practices for wells in the Pavillion field are consistent with current or past regulatory requirements. Such an evaluation is separate from the question of whether well construction conditions in the field are effective in preventing fluids from migrating within or between zones and potentially impacting aquifers. It is on this latter question, and the related issue of appropriate methods for evaluation of this question, that EPA seeks to provide meaningful input. This review benefits from the identification of methods for achieving effective isolation of groundwater by oil and gas industry groups as described below.

Well Integrity Observations and Recommendations from Oil & Gas Organizations

Industry guidance and recommended practices point out that well integrity established through sound well design and installation practices are paramount considerations for protecting groundwater resources.

<u>American Petroleum Institute</u>

"All oil and natural gas exploration, development, and production operations are conducted to ensure that the environment, in particular underground sources of drinking water (USDWs, or groundwater), is protected." (API HF-1 2009)

"The primary method used for protecting groundwater during drilling operations consists of drilling the wellbore through the groundwater aquifers, immediately installing a steel pipe (called casing), and cementing this steel pipe into place. All state drilling regulations specifically address groundwater protection, including requirements for the surface casing to be set below the lowest groundwater aquifer, or USDW (DOE [2], 2009 and IWOGCC [1], 2007)." (API HF-1 2009)

"It is important to evaluate which zone(s) have potential for flow in order to plan the cement job to achieve suitable zonal isolation. Such zones should be covered with cement slurries designed to prevent flow after cementing, and the cement placement mechanics should be designed to maximize drilling fluid removal. Zones left uncemented may not flow in the short term if pore pressure is balanced by drilling fluid hydrostatic pressure. However, phenomena such as barite sag and drilling fluid dehydration may lead to [sustained casing pressure]." (API 65-2)

"Cement top selection is influenced by the location of the potential flow zones, regulatory requirements and pore pressure/fracture gradient consideration." (API 65-2)

"Accurate knowledge of pore pressure and fracture gradient profiles is necessary for successful primary cementing and helps design jobs that prevent lost circulation and annular flows. Pore pressure is a crucial piece of information needed to assess flow potential. The pore pressure and fracture gradient profiles are two of many input values used in computer simulation programs used to evaluate static and dynamic well security." (API 65-2)

Society of Petroleum Engineers

"Low cement top or exposed casing was found to be the most important indicator for surface-casing-vent flow (SCVF) and gas migration (GM). The effect of low or poor cement was evaluated on the basis of the location of the SCVF/GM compared to the cement top... the vast majority of SCVF and GM originates from formations not isolated by cement." (SPE 2009)

In addition to un-cemented well casing, "geographical location, wellbore deviation, well type (drilled and abandoned vs drilled cased and abandoned), abandonment method, oil price, regulatory changes and SCVF/GM testing" are also factors determined to be important (PPE 2009)

Oil Field Review

"... many of today's wells are at risk. Failure to isolate sources of hydrocarbon either early in the well-construction process or long after production begins has resulted in abnormally pressured casing strings and leaks of gas into zones that would otherwise not be gas-bearing."

"Abnormal pressure at the surface may often be easy to detect, although the source or root cause may be difficult to determine. Tubing and casing leaks, poor drilling and displacement practices, improper cement selection and design, and production cycling may all be factors in the development of gas leaks." Brufatto (Oil Field Review Autumn 2003)

Frac Focus

"Casing strings are an important element of well completion with respect to the protection of groundwater resources because they provide for the isolation of fresh water zones and groundwater from the inside of the well. Casing is also used to transmit flowback fluids from well treatment. In this regard, surface casing is the first line of defense and production casing provides a second layer of protection for groundwater." (Frac Focus Website)

Frac Focus also indicates that 93% of oil and gas producing states require surface casing to be set below "deepest groundwater."(Frac Focus Website)

ZONAL ISOLATION AND GAS WELL INTEGRITY

The Society of Petroleum Engineers identifies 3 requirements for a leak in the subsurface (SPE 2009):

- A leak source;
- A driving force such as annular gas pressure or a hydrostatic head differential for liquids (overpressured annulus); and
- A leakage pathway.

Gas migration into shallow aquifers requires a pathway (poorly cemented or un-cemented annulus), gas under pressure in contact with the un-cemented annulus, and pressure build up in a zone below the surface casing shoe where an open annulus is present (Groundwater 2013).

Over-pressured Annulus

An over-pressured annulus can occur as a result of two different circumstances:

- Annulus is over-pressured by production zone gas and liquid
  - Through tubing, casing and packer leaks (Figure 1)
  - Through channeling in cement placed above the production zone (Figure 2)
- Annulus is over-pressured by entry of shallow non-production zone gas and liquid (Figures 4 and 5)

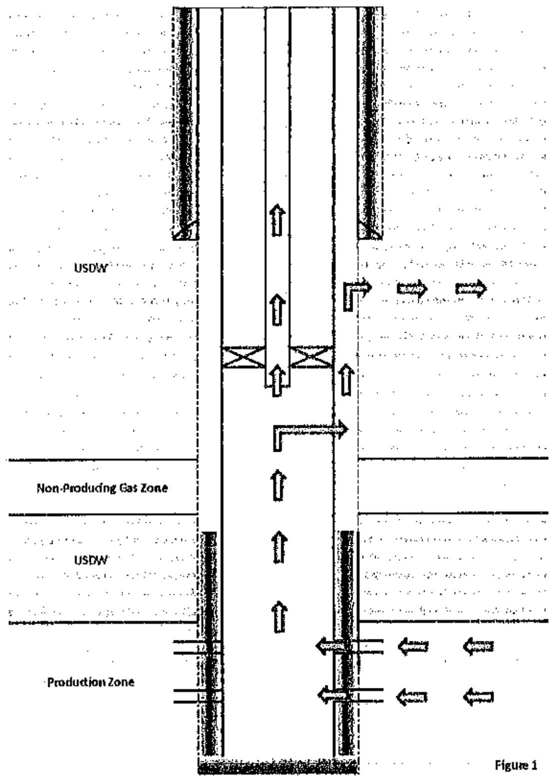
Isolation of Production Zone Gas and Liquids

The casing, packer and tubing integrity, along with an adequate cement seal above the production zone are necessary to prevent production fluids from migrating up the outside of the production casing and into aquifers above the production zones. This cement seal prevents two unacceptable results: 1) loss of mineral resource and 2) impacts to water quality in aquifers above the production zone.

<u>Casing, Tubing or Packer Failure</u>

The casing, tubing, and tubing packer provide a barrier(s) between the fluids in the production casing and tubing and the geologic formation in contact with the wellbore. The effectiveness of this barrier, or well integrity condition, can be tested and evaluated through a mechanical integrity test (MIT). The MIT is used to demonstrate that fluids inside the production casing and tubing strings are not potentially escaping through casing breaches or holes into the annulus space outside of the production casing and migrating into geologic formations (as shown in Figure 1), which could result in loss of the fluid mineral resource and degradation of groundwater. All shut-in wells in the Pavillion field have recently had or are undergoing an MIT as necessary to evaluate this condition. The EPA agrees with the validity and comprehensive nature of an MIT to evaluate conditions that would allow production fluids to escape and impact groundwater. MITs are used in the Safe Drinking Water Act Underground Injection Control (UIC) program as an approved testing method to determine casing, tubing and packer integrity. In some cases additional information may be necessary to further confirm well integrity and can be provided through radioactive tracer, temperature or noise logs.

Illustration of Production Fluid Migration through Production Casing Breach (Figure 1)

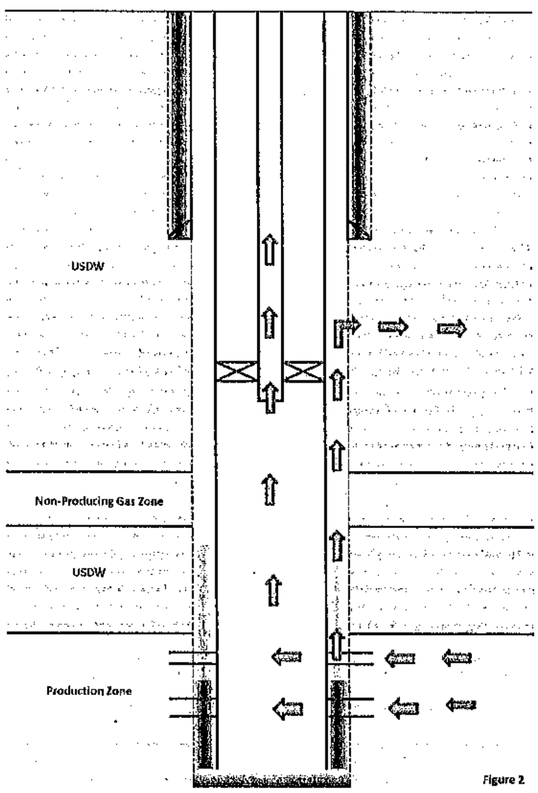


Cement Failure

Evaluation of this condition is similar to the general zonal isolation with the exception that liquid and gas are found in the bradenhead annulus originating from the production zone (Figure 2). Many authors of papers on well construction have pointed out that gas channeling as well as other poor bonding conditions can occur at the time of well construction or later in the life of the well (Oil Field Review 2003). In order to determine whether an over-pressured annulus is resulting from channels in cement above the production zone, gas and liquid analyses in addition to bradenhead pressure information are necessary to evaluate whether the gas is from the production interval or from shallow non-producing zones. This comparison can help with evaluating the origin of liquids or gas within the bradenhead. If production gas and/or liquids are chemically and isotopically similar to bradenhead fluids then the origin is likely the production zone and the cement seal above the production zone is likely inadequate. When gas and liquids are dissimilar in chemistry or isotopic signature from production fluids, then the origin is likely from zone(s) other than the production zone (i.e. shallow gas) and the cement seal isolating the production zone is likely adequate.

Additionally, the production zone cement seal can be evaluated during hydraulic fracturing by monitoring the bradenhead annulus pressure. This pressure monitoring of the bradenhead and other annuli help to ensure that hydraulic fracturing liquids are not escaping into areas other than the targeted zone. Increasing pressures in the bradenhead during hydraulic fracturing might indicate poor cement bond or lack of isolation of the production zone, and can be mitigated with additional good quality cement above the production zone. Prior to hydraulic fracturing it would be prudent to utilize Cement Bond Logs (CBLs), temperature logs, radioactive tracer surveys and noise logs to ensure good cement bond is present to prevent migration of pressurized hydraulic fracturing fluids into the open annulus above the top of cement.

Illustration of Production Fluid Migration through Cement above Production Formation (Figure 2)



Zonal Isolation of Shallow Non-production Zone Fluids

Zonal isolation of shallow non-producing zones refers to the ability of a well to prevent fluid movement between geologic formations that are in contact with the wellbore. Properly cementing the wellbore annulus and appropriate surface casing depths are the primary recommended method to ensure intra-well zonal isolation and protection of USDWs. (API HF-1)(Figure 3a)

Generalized Construction Conditions for Vertical Gas Wells

Before it can be determined what information and test method are required, vertical well construction conditions relative to USDWs or water bearing zones within a USDW need to be evaluated. The following four construction condition examples provide a generalized characterization of vertical well construction for wells with two casing strings (surface and production casing) and the possible relationship to USDWs.

- Construction Condition 1-- Surface casing fully penetrates all USDWs, the surface casing is set and cemented into a laterally extensive confining zone below the lowermost USDW, and production casing is fully cemented at a minimum above the surface casing shoe. This will be referred to as a fully cemented well in which USDWs were protected during drilling and have been subsequently isolated with cement and casing. (Figure 3a)

- Construction Condition 2-- Surface casing fully penetrates all USDWs, the surface casing is set and cemented into a laterally extensive confining zone below the lowermost USDW, but there is open annulus along the production casing above the production zone and below the surface casing shoe. This well is partially cemented. However, USDWs have been isolated during drilling and are currently isolated with surface casing and cement. (Figure 3b)

- Construction Condition 3-- Surface casing does not fully penetrate all USDWs or surface casing is not tied into a confining unit below the lowermost USDW, and the production casing has a length of open annulus below the surface casing shoe. This is a partially cemented well; however, unlike construction condition 2 (CC2) the USDW(s) is not isolated with cement. Under this condition, USDWs were not protected during drilling of production casing and are not currently protected with casing and cement. (Figure 3c)

  Note: Some well Applications for Permit to Drill (APDs) stipulate that the bottom of the surface casing be located a certain number of feet below the deepest water well within a specified lateral distance of the production well location, or that the surface casing depth is 10 or 15 percent of the total depth of the well. It should be noted that these requirements do not reflect the incorporation of site-specific hydrogeological conditions to ensure that surface casing is set into a confining unit, and that USDWs may be open to an un-cemented casing annulus below the surface casing. In hydrogeologic or pressure settings where surface casing cannot feasibly be set deep enough to protect USDWs, zonal isolation should be achieved by using additional casing and cementing, including a combination of surface, intermediate and production casing and cement placement as appropriate (API HF-1)

- Construction Condition 4-- Surface casing does not fully penetrate all USDWs nor is tied into a confining unit. However, production casing is fully cemented from total depth to a depth above the surface casing shoe. This CC does provide zonal isolation of USDWs but only after the production casing annulus has been cemented and additional information has determined that the cement is of good quality. This well will also be referred to as a "fully cemented" well in which USDWs have been isolated with cement and casing. (Figure 3d) However, it should be understood that CC4 wells may allow introduction of foreign fluids into USDW zones that were not sealed off by surface casing during the construction phase of the well prior to cementing the production casing annulus. This will be referred to as a fully cemented well in which USDWs were not protected during drilling but have been subsequently isolated with cement and casing.

Construction Condition Illustration (Figure 3)

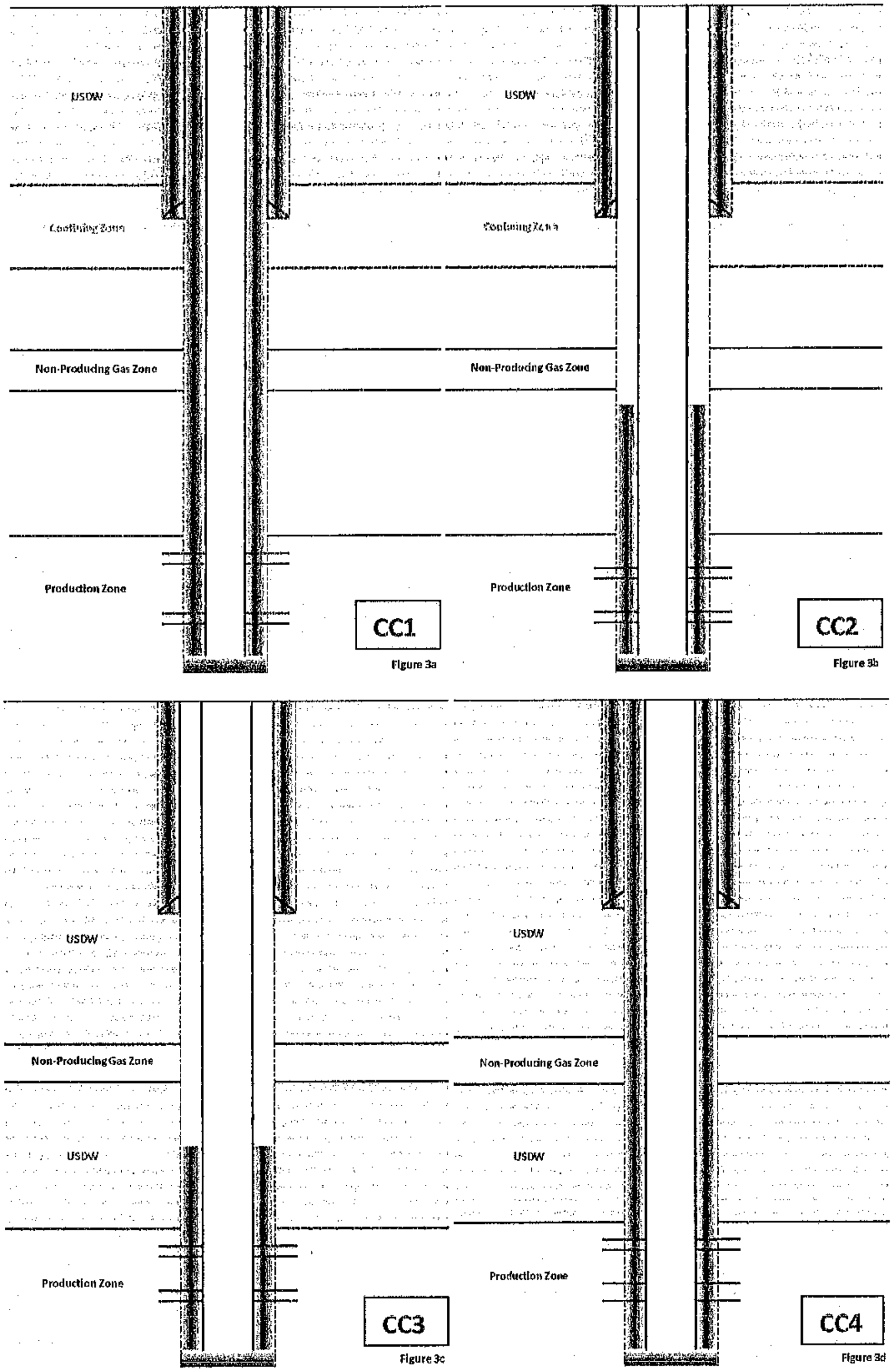


Figure 3a Figure 3b Figure 3c Figure 3d

Testing and Evaluation Methods Appropriate for Different Construction Conditions

Testing and Evaluating Well Construction Condition 1 and Construction Condition 4

Since both construction conditions for CC1 and CC4 result in a fully cemented well, methods for testing and evaluating these wells are similar and primarily include a well design and records evaluation. Typically, sundry notices and as built well schematics are evaluated for casing depths; adequate cement volumes and CBLs are used to evaluate cement condition and the location of the top of cement (TOC). Post hydraulic fracturing reports are also useful in evaluating bradenhead annulus cement conditions during high pressure events. However, even with cement to surface in all annular spaces, fluid migration through micro-channels in a cemented annulus may not be prevented and are very difficult to detect and mitigate. (Oil Field Review April 1991)

A fully cemented production annulus with appropriate CBLs supporting cement location and quality in critical zones is an indicator of the potential for good zonal isolation. Periodically conducted temperature and radioactive tracer logs are also useful for assessing continued zonal isolation throughout the operating life of the well.

For CC4 it would also be important to identify any significant fluid loss zones during the drilling of the production casing borehole and any pressure "kicks" which may identify zones that have pressures that could move fluids into open hole USDW zones below the bottom of the surface casing during drilling. In addition, records indicating overpressured drilling through USDWs could also be problematic if there are fluid losses noted within those zones.

Evaluation of CC1 could also include a formation integrity test or leak-off test after the surface casing has been set and prior to beginning to drill the production hole (API 65-2). Results from these tests would indicate the ability of the surface casing cement and confining formation to prevent flow through the confining unit upward into the USDWs above the confining unit at the time the well was constructed.

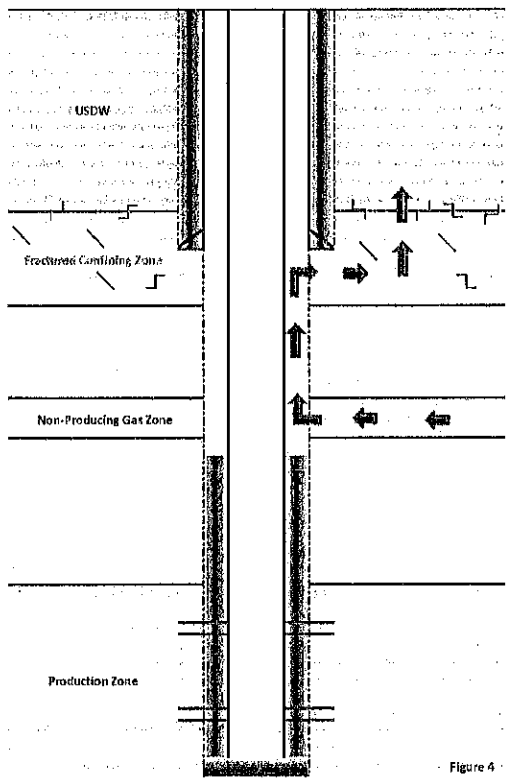
Wells constructed according to CC1 and CC4 and with good annular cement seals should not exhibit surface casing gas pressure or liquid flow at the surface.

Testing and Evaluating Well Construction Condition 2

Testing and evaluating CC2 is usually performed through an industry standard procedure where pressure in the bradenhead annulus is measured at the surface and compared to a critical pressure that is calculated based on the fracture pressure adjusted to the depth of the bottom of surface casing (Encana Bradenhead Proposal, June 2011). This adjusted pressure value is calculated using a typical or field-specific fracture gradient. If this critical pressure is exceeded, that may indicate that the integrity of the confining formation has been compromised and that, as a result, the confining zone may not be effectively isolating USDWs (as shown in Figure 4). In this instance mitigation, usually by perforating the production casing and squeezing cement into critical zones, can provide zonal isolation to protect USDWs.

This test and evaluation method is for surface casing that is designed and constructed to extend to the bottom of the lowermost USDW and is tied into a competent laterally extensive confining unit; the surface casing is cemented to surface and the cement is of good quality. Under CC2 bradenhead pressures should not be a problem unless the pressures (gas gage pressure and hydrostatic head) in the bradenhead exceeds the calculated fracture pressure at the surface casing shoe which is seated in the confining unit. This well integrity test and evaluation determine if there is a potential to fracture the confining zone that the surface casing is tied into, and allow fluid migration into the USDWs located above the confining unit (Figure 4). This test provides a margin of safety in protecting the surface casing shoe/confining zone integrity by using ½ of the actual fracture pressure and assuming that the annulus is full of 9 pounds per gallon (ppg) drilling mud. If the pressures in the bradenhead exceed the fracture pressure of the confining unit, the pressure in the bradenhead annulus could promote fractures within the confining unit allowing fluid migration into USDW zones above the confining unit.

Illustration of Fracturing of Confining Zone (Figure 4)



Information relevant to this construction condition could include a formation integrity test or leak-off test after the surface casing had been set and prior to beginning to drill the production hole (API 65-2). These test results should be in the well file and would indicate the ability of the surface casing cement and confining formation to prevent flow upward into the USDWs above the confining unit at the time the well was constructed. API recommends that after setting surface casing cement, a formation integrity test be performed and remedial measures be taken if appropriate (API 2009). Attachment 2 includes a brief summary of Encana's method using fracture pressure gradient to determine a critical pressure within the bradenhead annulus.

API HF-1 recommends that "surface casing be set at least 100 feet below the deepest USDW encountered while drilling a well." Wells under CC2 would also meet API's recommendation.

Testing and Evaluating Well Construction Condition 3

Since under CC3 the surface casing is not designed or constructed to be tied into a confining unit below the USDW, there is no confining unit fracture pressure to evaluate. When there is open annulus in contact with the USDW, as is the case under CC3, zonal isolation of the USDW does not exist.

Gas or liquid migration into the open annulus can occur when the pressure in the annulus is below the pressure in a formation. This could occur into a cemented annulus with a poor cement seal or into an open annulus. Gas can then migrate from the overpressured annulus into another formation with a lower pressure zone, or to the surface if the annulus is vented (Oil Field Review 1996). As a result testing must focus on evaluating whether fluid (gas or liquid) can flow from one zone within the open annulus to another zone within the open annulus (see Figure 5). Under CC3, differences between annulus pressure and pore pressure in formations adjacent to the open annulus need to be evaluated, rather than the exceedance of fracture pressure.

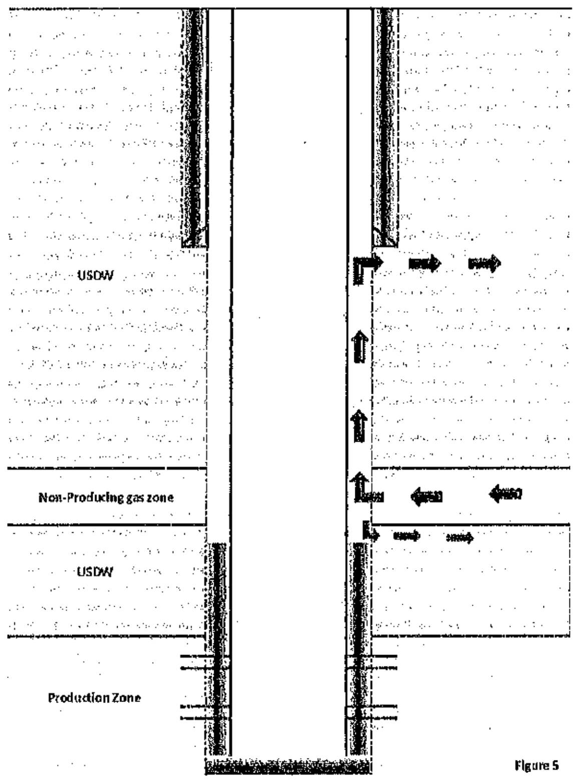
In order to assess whether annulus overpressure conditions exist that could promote gas or liquid migration from deeper into shallower zones, the following needs to be determined:

- Gas pressure in the bradenhead annulus
- Hydrostatic head for water or drilling mud (whichever is appropriate) in the bradenhead annulus
- Pore pressure gradient (which for aquifers is usually near the hydrostatic gradient for freshwater)

"If the flow of gas from the annulus is restricted and the pressure within the annulus exeeds the normal pressure in any strata open to the annulus, the annulus is considered to be overpressured" (Harrison 1983). The term overpressured refers to the ability of pressure within the bradenhead annulus (gas pressure and/or hydrostatic head) to move fluid from a higher pressure zone to a lower pressure zone (Figure 5). Under CC3 an open annulus is exposed to the USDW, and the concern is if the bradenhead annulus is overpressured, then fluids will migrate from higher pressure to lower pressure zones and potentially into USDWs in contact with the open annulus.

Wells with liquids in the bradenhead that are flowing at the surface demonstrate that the bradenhead annuli are overpressured, and there is a high potential for fluid migration or migration is actively occurring. Liquid can flow at the surface from the bradenhead even if the fracture pressure is not exceeded. It is intuitive that this is a high risk condition and mitigation should be undertaken. In the overpressure evaluation in Attachment 2, it is explained why this condition can cause fluid flow even though pressure is not above a critical pressure calculated using a fracture gradient.

Illustration of Non-Production Fluid Migration Between Zones (Figure 5)



In order to assess whether the annulus is overpressured or there is potential fluid flow or migration between zones adjacent to the open annulus, the hydrostatic head of liquids in addition to gas casing pressure within the bradenhead space need to be measured. If the combination of these two measurements exceeds formation pore pressure at the bottom of the surface casing, then liquids can move from the higher pressure zones to lower pressure zones in contact with the annulus(Harrison 1983)(Figure 6). Attachment 2 reviews the method of evaluating wells with annulus spaces open to USDWs and compares the results with using the fracture gradient method currently being used by Encana.

In circumstances where surface casing cannot feasibly be set deep enough to protect USDWs due to unusual geologic settings or pressure regimes, zonal isolation should be achieved by using additional casing and cement, including a combination of surface, intermediate and production casing and cement placement as appropriate (API HF-1).

<u>Testing and Evaluating Construction Condition 4</u>

See Section on Testing and Evaluating CC1.

Evaluating Inter-wellbore Communication During Transient Overpressured Conditions

Stimulation pressure conditions in a well's production zone can produce transient overpressured annulus conditions in nearby offset wells with open annuli within the stimulated zone. The open annulus can exist in a producing well, a shut-in well or a plugged and abandoned well. These overpressured annulus conditions, even if transient in nature, present a high risk of fluid migration when in proximity to wells with open annuli; this risk cannot be evaluated or managed without considering construction of wells in proximity to wells undergoing stimulation. (Nova Scotia 2012) (CWOGCC 2012). Nearby offset well bradenhead monitoring is necessary to detect potential pressure changes in an offset well with an open annulus that may cause gas and liquid migration into shallower zones or USDWs. Safe margins of distance for offset wells have been calculated in some fields with dense well spacing. (Groundwater 2013)

HYDRO-GEOLOGIC SETTING OF THE PAVILLION GAS FIELD

Identification of Confining Zones in the Wind River Formation

The Wind River and Fort Union formations were deposited under fluvial deposition conditions and therefore continuous three-dimensionally competent confining zones are uncommon throughout the Pavillion gas field, and would be difficult to identify. Below the Wind River formation and above the Fort Union formation some reports identify a confining unit referred to as the Indian Meadows Unit. "This unit ranges from 0 to 750 feet in thickness and no data is available on the chemical or physical characteristics of the stratigraphic unit or its areal extent" (WSGS 2011). It is unclear whether this confining unit exists within the Pavillion gas field.

USDWs of the Pavillion Gas Field

The terms groundwater, aquifer and USDW are used throughout this document. It is important to note the commonly accepted definition of these terms and the relationship between them. Groundwater is subsurface water that occurs within saturated zones in geologic deposits and formations. An aquifer is a geologic formation, a part of a geologic formation, or a group of geologic formations that will yield usable quantities of water to a well or spring. Aquifers have clear boundaries that are delineated based on geologic and hydrologic properties. USDW is a legal term derived from the Safe Drinking Water Act, which is meant to provide a focus on groundwater that is or could be used to provide drinking water. Like the term "useable groundwater,", USDW is a water management term.

Under the federal Safe Drinking Water Act, USDWs are defined broadly to include all fresh water aquifers unless they have been specifically exempted from protection. A USDW may be in current use as a source of drinking water, but also includes those fresh water aquifers with potential for future use. A USDW is defined in Title 40, Code of Federal Regulations (40 CFR) Section 144.3 as "an aquifer or portion of an aquifer which: supplies any public water system, or which contains a sufficient quantity of ground water to supply a public water system and currently supplies drinking water for human consumption or contains fewer than 10,000 milligrams/liter of Total Dissolved Solids (TDS); and is not an exempted aquifer."

An "exempted aquifer" is all or part of an aquifer which meets the definition of a USDW but which has been exempted according to the criteria found in 40 CFR Section 146.4, which specifies that the aquifer does not currently serve as a source of drinking water, and the aquifer cannot now and will not in the future serve as a source of drinking water.

Wind River Formation

The "Wind River-Bighorn Basin Plan" which was developed by the Wyoming Water Development Commission (May 2010) states, "The two aquifers primarily developed for high capacity municipal supply are the Wind River and Madison Aquifers." For this analysis the Wind River formation is considered both an aquifer and a USDW. The Wind River formation serves as an aquifer for drinking water in the Pavillion gas field area. More broadly in Fremont County and on the Wind River Reservation, the Wind River formation as well as unconsolidated alluvial and colluvial deposits provide water to individual domestic and stock wells, as well as municipal water supply wells (USGS 1995).

In the Pavillion gas field, the Wind River formation is approximately 3,300 feet thick (Encana 2011). The Wind River formation meets EPA's definition of a USDW. The community of Pavillion, Wyoming, has 5 public water supply wells completed in the Wind River formation approximately 2.5 miles west of the Pavillion gas field. In addition Riverton, Wyoming, also has several municipal water supply wells completed in the Wind River formation approximately 20 miles southeast of the Pavillion gas field.

The lenticular sandstone beds within the fluvial Wind River Formation may have sufficient hydraulic connection to consider the sequence a single aquifer at a regional scale. Higher yield water wells completed in the middle coarse-grained deposits of this formation produce several hundred gallons per minute. The Wind River formation may be fracture enhanced as a result of the deformation history creating the anticlines in the Wind River Basin (WSGS 2011). The secondary fracture systems could locally enhance hydraulic conductivity. No documents mention a confining unit within the Wind River formation other than the Indian Meadows unit located at the base of Wind River overlying the Fort Union formation.

The upper Wind River Formation currently serves as the principal source of domestic, municipal, and stock water in the Pavillion area, Fremont County and the Wind River Reservation. Forty eight percent of wells surveyed in the 1995 U.S. Geological Survey Water-Resources Investigations Report 95-4095 on Fremont County are completed in the Wind River formation. Water for agricultural irrigation is supplied primarily through the Midvale Irrigation District. Domestic wells (including stock wells) are screened as deep as 800 ft below ground surface in the area of investigation. Domestic wells within the township and range encompassing the area of investigation extend to 1055 ft bgs.

Fort Union formation

The Fort Union formation would also meet the definition of an aquifer and USDW as it contains fewer than 10,000 milliggrams per liter(mg/l) of Total Dissolved Solids (TDS) and can provide sufficient quantity of groundwater to supply a public water system. USGS reports water wells are completed in this formation (USGS 1995).

Encana's produced water disposal well (EPA permit # WY20831-04394), approximately 3.5 miles north of the Pavillion gas field, is partially screened within the Fort Union formation. An aquifer exemption was required for a specified depth and area around the injection in order to allow Encana to inject produced water into the Fort Union formation because the Fort Union formation meets the definition of a USDW.

Unconsolidated deposits (Colluvium and Alluvium)

Unconsolidated deposits occurring above the Wind River formation provide water to a number of domestic and stock water wells (USGS 1995). These deposits also meet the definition of a USDW. Some of the shallower wells at 50 feet depth may be screened in these unconsolidated deposits as well as in the upper weathered portion of the Wind River formation (WBRB 2011).

SUMMARY EVALUATION OF PAVILLION GAS WELLS

Summary of Surface Casing Depths Relative to USDWs within the Pavillion Gas Field

- Surface casing does not extend below the lowermost USDW (Fort Union formation)
- Surface casing does not extend below the Wind River formation (currently used for drinking water within the Pavillion gas field)
- Average surface casing depth is 588 feet bgs
- Surface casing in some cases is shallower than the deeper water wells in the Pavillion gas field
- Deepest water wells are 800 feet bgs
- Because gas production is occurring within the Wind River formation (starting at approximately 1100 feet bgs) the bottom of surface casing for production wells has been set above this depth.

Summary of Production Casing Cement within the Pavillion Gas Field

- Many wells are known not to be cemented to the surface or above the surface casing shoe
- Many wells do not have CBLs indicating the top of cement (TOC)
- Many wells do not have CBLs evaluating cement quality in critical zones

Pavillion Wells Categorized According to Construction Condition (Based on WOGCC 2012)

- Pavillion gas wells under CC1 – No wells within the Pavillion gas field were determined to meet this condition due to surface casing being set within the USDW and not into a confining unit below the USDW.
- Pavillion gas wells under CC2 – No wells within the Pavillion gas field were determined to meet this condition due to surface casing being set within the USDW and not into a confining unit below the USDW.

- Pavillion gas wells under CC3 – 55 wells were determined to fall within this construction condition.
- Pavillion gas wells under CC4 – 65 wells were determined to fall within this construction condition.
- Pavillion gas wells with unknown CC – 25 wells did not have enough information to determine the construction condition.

Summary of Testing Performed to Date

- MITs are being performed on shut-in wells.
- It is not clear that bradenhead annulus gas pressure monitoring had been completed for all wells in the field as of July 2012. However, EPA understands that additional testing has taken place since that time. Summary information developed later than July 2012 was not available for EPA's consideration in this evaluation.
- Hydrostatic head (fluid level in bradenhead annulus) has only been observed at four wells determined to have fluid flowing at the surface during bradenhead pressure monitoring.

Important Summary Information Needed for Determining Next Steps

- MIT
    - Wells that passed MIT
    - Wells that failed MIT
- Bradenhead gas pressure testing
    - Wells that met criteria described in Encana bradenhead procedure
    - Wells that failed to meet criteria described in Encana bradenhead procedure
- Bradenhead hydrostatic pressure
    - Has not been monitored

Summary of Mitigation Proposed by Encana

A sundry notice was filed with WOGCC in April of 2013 for production casing cement mitigation for well 12-11W which had fluid flowing at the surface in the bradenhead annulus. Other sundry notices for mitigation may have been submitted and filed. That information was not available for EPA's consideration in this evaluation.

Summary of Mitigation Performed by Encana

As of June 2012 no sundry notices were available on WOGCC's website documenting the completion or results of mitigation activity. Sundry notices reporting the completion and results of mitigation may have been submitted and filed. That information was not available for EPA's consideration in this evaluation.

REFERENCES

API Guidance Document HF1, First Edition, October 2009

API Standard 65-Part 2, Second Edition, December 2010, Isolating Potential Flow Zones During Well Construction

Colorado Oil and Gas Conservation Commission, May 29,2012, "COGCC Policy for Bradenhead Monitoring During Hydraulic Fracturing Treatments in the Greater Wattenberg Area"

Encana Pavillion Bradenhead Testing Procedure, June 2011, Encana

FracFocus, online website (http://fracfocus.org/)

Groundwater November-December 1983, Samuel S. Harrison, "Evaluating System for Ground-Water Contamination Hazards Due to Gas-Well Drilling on the Glaciated Appalation Plateau"

Groundwater May-June 1985, Samuel S. Harrison, "Contamination of Aquifers by Overpressuring the Annulus of Oil and Gas Wells"

Groundwater, July – August 2013, Jackson, Gorody, Mayer, Roy, Ryan, Stempvoort, "Groundwater Protection and Unconventional Gas Extraction: The Critical Need for Field-Based Hydrogeological Research"

Nova Scotia Hydraulic Fracturing Review Committee, March 27, 2012, Paul Precht and Don Dempster, "Report for Nova Scotia Hydraulic Fracturing Review Committee"

Oil Field Review, April 1991, Bol, Grant, Keller, Marcassa and Rozieres "Putting a Stop to Gas Channeling"

Oil Field Review, Spring 1996, Bonett and Pafitis, "Getting to the Root of Gas Migration"

Oil Field Review, Autumn 2003, Brufatto, "From Mud to Cement-Building Gas Wells"

Society of Petroleum Engineers, March 2009, Watson and Bachu, "Evaluation of the Potential for Gas and CO2 Leakage Along Wellbores"

Schlumberger, Oil Field Online Glossary

USGS 1995, Plafcan, Eddy-Miller, Ritz, and Holland II, Water Resources of Fremont County, Wyoming, U.S. Geological Survey Water Resources Investigations Report 95-4095

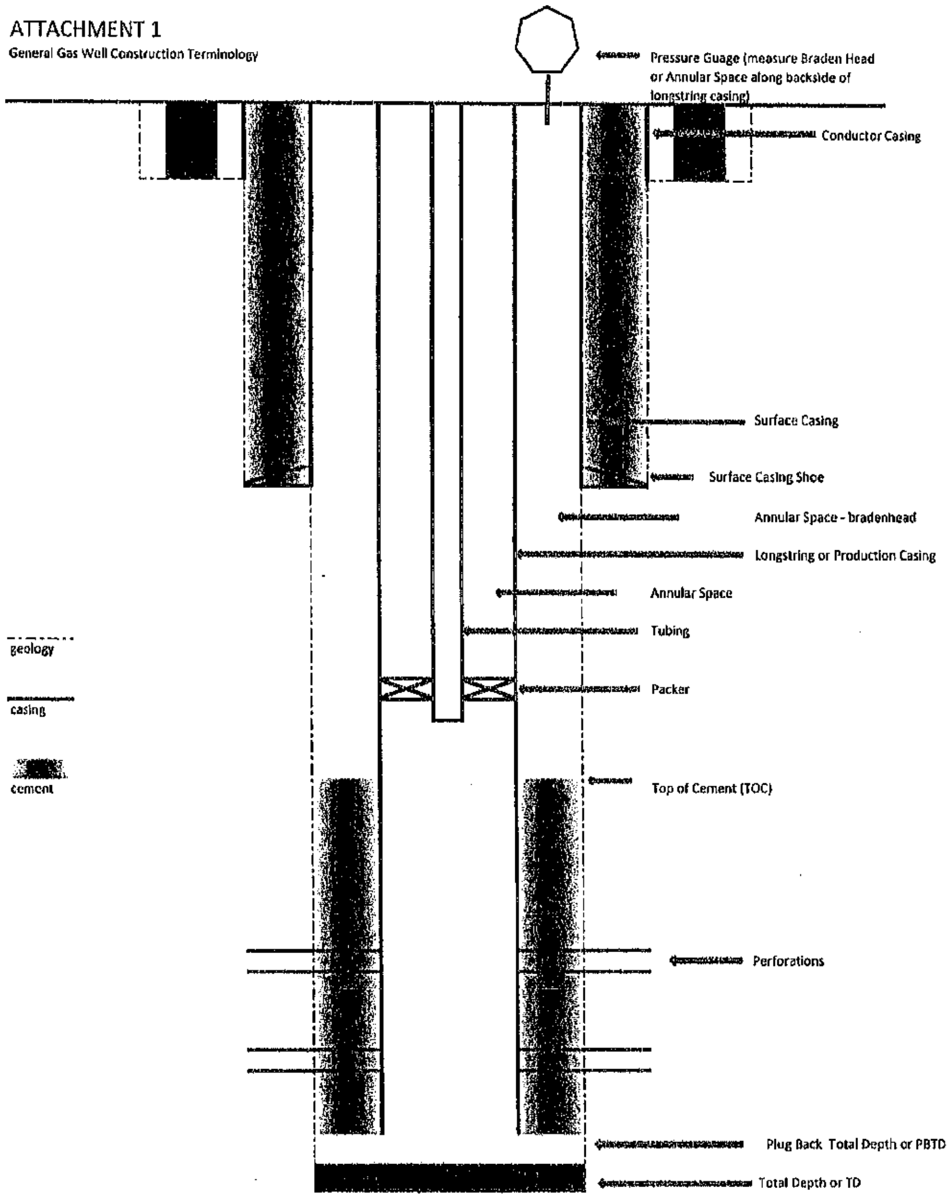
Wyoming Oil and Gas Conservation Commission, July 2012, Pavillion BH Results as of 07-17-2012.xls

Wyoming Oil and Gas Conservation Commission, Online well file website

Wyoming State Geological Survey, 2012, Taucher, Bartos, Carey, Quillinan, Hallberg, Clark, Thompson, Gribb, Worman and Gracias, Wind/Bighorn River Basin Water Plan Update, Groundwater Study Level 1 (2008-2011)

ATTACHMENT 1

General Gas Well Construction Terminology



ATTACHMENT 2

Comparison of Critical Pressure based on a fracture gradient and (CPf) and critical pressure based on overpressured annulus (CPop)

Summary of Encana bradenhead pressure evaluation method – June 2, 2011

Encana reports that for the Wind River formation the fracture pressure gradient decreases with depth from 0.85psi/ft at 3000ft and increases to 1.1 psi/ft at 1300ft. A frac gradient of 0.65 psi/ft –which is ½ the maximum frac gradient for the shallower portion of Wind River formation Pavillion gas field is used by Encana to calculate frac pressures at the surface casing shoe. It is assumed that using ½ the maximum frac gradient is done to incorporate a safety factor into the calculations.

Encana also reports a reservoir pore pressure gradient of 0.435psi/ft to 0.44 psi/ft which is normally pressured and close to the pressure due to hydrostatic head of water.

The formula used to calculate the critical pressure which is the point that represents the maximum allowable surface pressure looks like this:

(SC x 0.65psi/ft)-(SC x 0.47psi/ft)=CPf Eq 1

Or

SC(0.65psi/ft-0.47psi/ft) = CPf = Eq 2

Where:

SC is the surface casing depth in feet

0.65psi/ft is the frac gradient for Wind River formation (with safety factor imbedded)

0.47psi/ft is the assumed hydrostatic head gradient

CPf is the critical pressure in psi

The Encana proposal list the critical pressures for 3 surface casing depths

Depth	Crit Pres
500 ft	90 psi
600 ft	108 psi
700 ft	126 psi

Summary of recommended bradenhead pressure evaluation method for wells with surface casing that does not penetrate to the bottom of the USDW and is not keyed into a hydrologically significant confining unit.

The following analysis demonstrates that determining the critical pressure based on exceeding the frac pressure for the confining zone at the surface casing shoe does not evaluate whether there a potential for flow from higher pressure zones to lower pressure zones. Critical pressure based on a fracture gradient only determines if the potential exist to fracture the confining formation or zone.

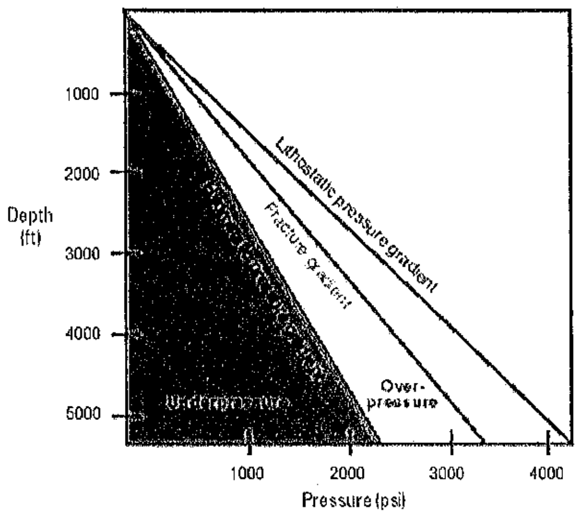


Figure 1

Overpressure -Subsurface pressure that is abnormally high, exceeding hydrostatic pressure at a given depth. The term geopressure is commonly, and incorrectly, used synonymously. Abnormally high pore pressure can occur in areas where burial of fluid-filled sediments is so rapid that pore fluids cannot escape, so the pressure of the pore fluids increases as overburden increases. Drilling into overpressured strata can be hazardous because overpressured fluids escape rapidly, so careful preparation is made in areas of known overpressure.

Abnormal pressure - Formation pressure tends to increase with depth according to the hydrostatic pressure gradient, in this case 0.433 psi/ft. Deviations from the normal pressure gradient and its associated pressure at a given depth are considered abnormal pressure.

Fracture pressure - Pressure above which injection of fluids will cause the rock formation to fracture hydraulically.

Figure 1 and definitions (from Schlumberger)

The difference between the line defining the fracture gradient and the line defining the hydrostatic pressure gradient is a zone referred to as overpressure. This is the area in yellow and demonstrates that if you have overpressure zones and zones at or below the hydrostatic pressure zone in red that open to the same well bore annulus, migration of fluids can occur. This is true during drilling and after the well casing strings have been cemented. If all of the zones open to the well bore annulus lie on the hydrostatic pressure gradient then theoretically no fluid flow would occur. However, zones with pressures that fall within the yellow would pose a potential flow if there are also zones that follow the hydrostatic gradient or are in the red underpressured zone that are open to the un-cemented annulus

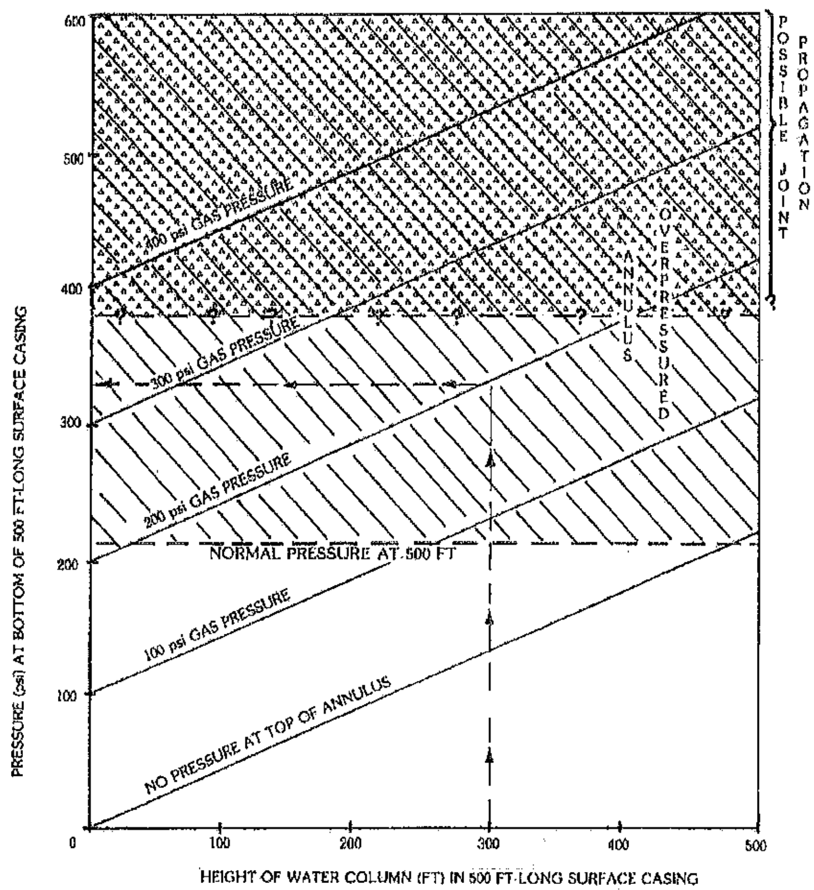


Fig. 6. Total pore pressure at the bottom of a 500-ft-long surface casing with varying gas pressure and varying amounts of water in the annulus above the bottom of the surface casing. The "normal" pore pressure in strata exposed to the annulus at the 500-ft depth was estimated by using a theoretical pressure gradient of 0.43 psi/ft. The example (arrows) shows that 300 ft of water in the surface casing with a 200-psi gas pressure above it results in a pressure of 329 psi at the bottom of the 500-ft-long surface casing.

Figure 2 (from Harrison 1985)

Figure 2 represents an example for a 500 foot depth surface casing demonstrating that overpressure in the annulus causing gas or liquid migration occurs at pressure less than a calculated fracture pressure for this hydro-geologic setting and is dependent on gas pressure and the hydrostatic pressure or height of the water column in the bradenhead annulus. In Figure 2 if it was determined that the liquid was drilling mud and not water, the calculation could use 0.47 psi/ft for 9ppg mud could be used instead of 0.433 psi/ft for water.

The formula for determining if the annulus is in an overpressure condition is:

(SC x 0.435psi/ft)-(h x 0.433psi/ft)=CPop

CPop is the critical pressure based on overpressured annulus calculated using hydrostatic head and surface pressure measurements.

SC is the surface casing depth in feet

h is the height of liquid above the surface casing shoe

0.435psi/ft is the pore pressure gradient from Encana

0.433psi/ft is the hydrostatic gradient for water (0.47psi/ft which correlates to a 9ppg mud weight could also be used if the fluid in the annulus was determined to be mud)

For a well with a 500 ft surface casing and a well annulus with no liquid above the depth of the surface casing shoe the critical pressure based on pore pressure of the formation is:

SC = 500ft

h = 0ft

(500ft x 0.435psi/ft)-(0.0ft x 0.435psi/ft) = 217psi

Notice that CPop is higher than the calculated CPf for the same depth surface casing. However, the CPop value in this example is assuming that there is no liquid above the surface casing shoe. If you add in a hydrostatic head value above the surface casing shoe or the depth of the formation of concern, you will reduce the CPop. For example:

SC = 500ft

h = 300ft

(500ft x 0.435psi/ft)-(300ft x 0.435psi/ft) = 88psi

With these values notice that CPf and CPop are almost identical and if h is increased to 400ft then:

(500ft x 0.435psi/ft)-(400ft x 0.435psi/ft) = 45.5psi

This equation does not have a built-in safety factor as does CPf. In addition, this method also assumes that the hydrostatic head in the annulus is a measured value. The height of liquid in the bradenhead annulus could be measured using an echo meter and should be measured at the same time that the bradenhead gas pressure is measured.

Below is a comparison of critical pressure values for the CPf and CPop method.

Surface Casing Shoe Depth (ft)	Surface Casing Shoe Depth (ft)					
	0	100	200	300	400	500
300	130	87	43	0	0	0
400	173	130	87	43	0	0
500	217	173	130	87	43	0
600	260	217	173	130	87	43
700	303	260	217	173	130	87
800	346	303	260	217	173	130

Table 1

Values in green are Critical Pressure (CPop) based on hydrostatic head in the bradenhead annulus and the pore pressure at the base of the surface casing shoe.

Surface Casing Shoe Depth (ft)	Calculated Critical Pressure based on frac gradient CPf
300	54
400	72
500	90
600	108
700	126
800	144

Table 2

Values in beige are Critical Pressure based on a fracture gradient and mud weight of 9.0ppg (CPf)

Notice that for a 500 foot SC shoe the CPf is 90psi and for CPop it can be a range of values from 217psi to 0psi depending on the fluid level in the bradenhead annulus above the surface casing shoe. Using Cpop the critical pressure is not below 90psi unless the water level above the is above SC shoe is more than 300 feet (less if it is mud). Therefore in some cases using the CPf method mitigation would be done when it may not be needed.

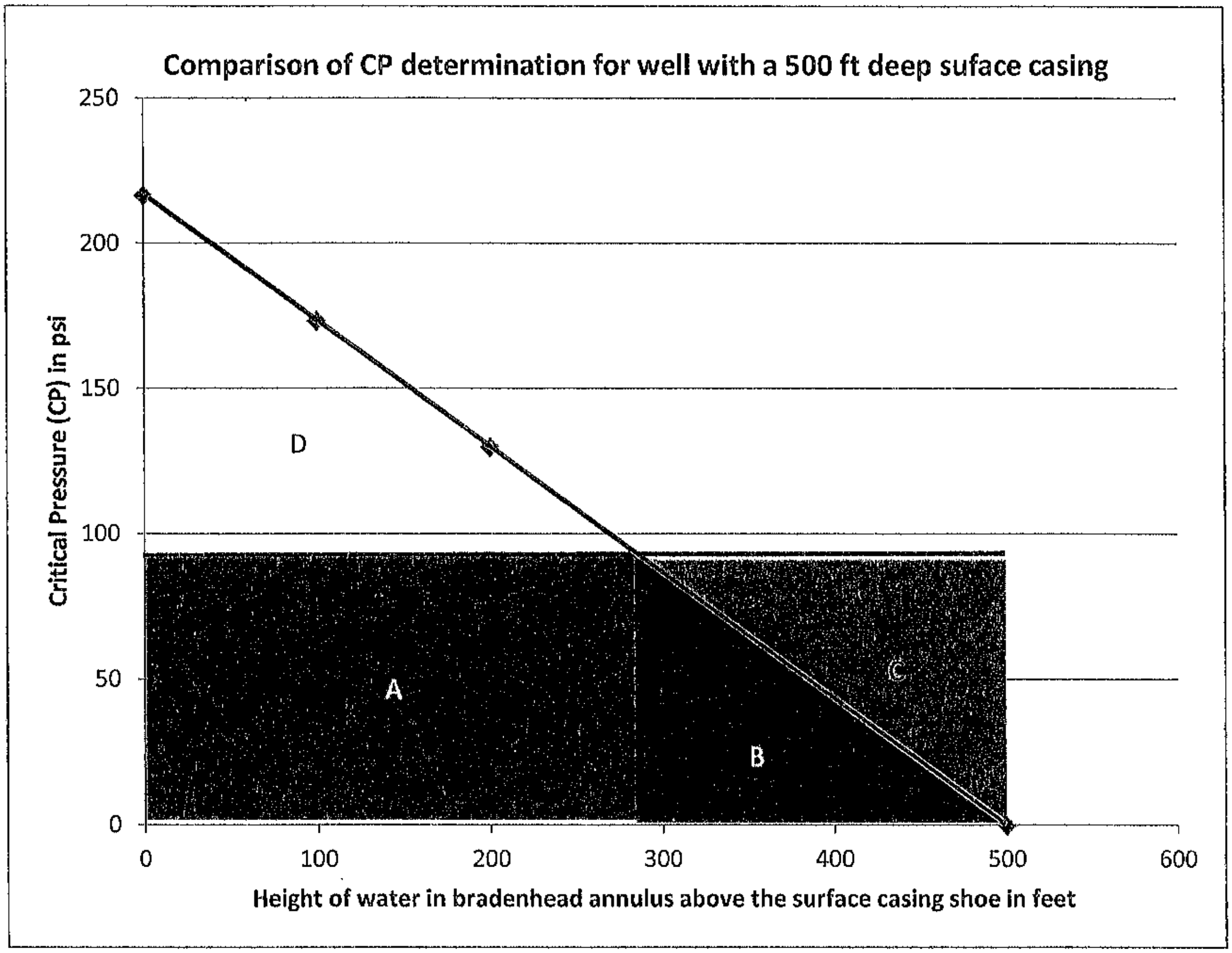


Figure 3

Area A represents acceptable pressure values using fracture gradient CPf (90 psi). Area B represents acceptable pressure values using hydrostatic head above the suface casing shoe CPop

Red line represents a CPf of 90psi calculated using the Encan proposal. The black line represents critical pressure based pore pressure of formation at 500 ft and the head of liquid above the surface casing shoe. As the head of fluid in the bradenhead annulus increases the allowable critical pressure value (CPop) in the bradenhead annulus decreases. Where the two lines intersect the critical pressure would decrease from 90psi along the gradient represented by the black line.

Area C depicts pressures less than the calculated critical pressure based on fracture pressure gradient but the pressure would be greater than the critical pressure based pore pressure of formation at 500 ft and the head of fluid above the surface casing shoe

Area D could represent the possibility that pressure values within this area (above the calculated frac gradient critical pressure) may be too conservative and mitigation may not be necessary.

One proposal could be to use a combination of the methods where pressures within areas A and B would be less than the critical pressures determined by both methods.

Measurement of annulus pressure and hydrostatic head

Gauge measurements of pressures in all annuli after a producing well has reached steady state flowing conditions should be 0 psi once the casing has been opened and bled off through the needle valve. Sustained casing pressure is determined to exist if continual bleeding down pressure is necessary. (Groundwater 2013)

Measurements of fluid levels in the bradenhead annulus can be obtained by using an echo meter. These instruments locate the approximate depth to water by reporting the number of casing collars before the water level is reached. A conservative approximation to determining the water level using an echo meter would be to use the depth to the deepest casing collar detected.