# Report on Feasibility Study of Regional Arbuckle Properties in South-Central Kansas: Now and Planning for the Future

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**Summary**

The Arbuckle Group (Arbuckle) is a resource heavily relied upon by a range of industries and municipalities in Kansas for fluid-waste disposal, oil production, storage, and freshwater. Conservation and capacity of the Arbuckle is critical for the energy industry and industrial/ municipal facilities in Kansas that extract freshwater from or dispose of wastewater into the Arbuckle Group. The capacity of the Arbuckle to accept fluid could be exceeded in the next few decades in certain areas in Kansas at current local disposal rates. Changes in Arbuckle fluid levels measured in low-volume Class I wells in Reno, Butler, Sedgwick, and McPherson counties suggest the Arbuckle potentiometric surface could already have reached the depths of shallower freshwater aquifers or will in the not-too-distant future. Routine monitoring of dynamic characteristics, establishing temporal lines of influence between current use and potential resource, and the building of a temporal database that allows predictions of fluid properties as a function of current and proposed localized use is critical to the long-term potential of the Arbuckle as a resource for industrial uses.

A feasibility study was proposed to evaluate methodologies and develop a testing protocol for accurately and functionally acquiring Arbuckle fluid data on a routine basis across a spatially optimized network of Arbuckle monitoring wells. Arbuckle SWD wells suitable for the monitoring network must penetrate at least 200 ft of the Arbuckle, have confirmed fluid connection to the formation, and have a minimum tubing/well bore ID of 1.75". To that end, static fluid level (SFL), fluid density, and bottomhole pressure using all reasonable measurements methods were to be collected in three to four "average" Class II SWD wells suitable for an annual measurement program. Barriers ranging from physical limitations within a normal functioning produced water disposal well to perceived risk and liability to the owners have, thus far, impeded completing the feasibility study as originally proposed.

As part of ongoing Kansas Geological Survey (KGS) investigations of the Arbuckle, the KGS commissioned supplemental testing in a Class I well in October 2020, directly preceding planned annual compliance testing. The objectives of this internally funded KGS study were designed to complement the objectives of the planned feasibility study funded by the Kansas Water Office (KWO). The KGS study was extensive enough to provide insights into the optimal design of data acquisition procedures necessary to produce data sets relatable to existing Class I databases. The KGS study did not evaluate proposed methodologies as was the intent of the KWO feasibility study.

Recommendations in this report for future Arbuckle monitoring are based principally on the independent KGS study. Products of the KGS study include specific types of data needed to reasonably appraise both current fluid levels and responses to introducing fluids in the Arbuckle Group, constraints on how those data were acquired, and to ensure accuracy and compatibility with the existing historic Arbuckle database. Recommended approaches involve minimally

invasive and inexpensive methods that overcome challenges associated with stratified borehole fluids of variable density, sensitivity of well construction, and threats below the cased portion of the well. It is recommended that:

- wells be pumped prior to measurement to extract borehole fluid static in the column and allow Arbuckle formation fluid to fill and stabilize within the well, thus eliminating or minimizing density variability in the fluid column;
- depth to water be measured with a wireline logging tool; and
- a fluid sample and pressure readings be collected ~100 ft below SFL.

A shallow pressure gradient survey could supplement these measurements for quality assurance.

These measurements, when taken in the prescribed fashion, can be used to accurately extrapolate bottomhole pressure and would supplement the existing, extensive database of measurements from Class I wells necessary to reasonably characterize Arbuckle fluid levels.

**Background and Introduction**

The Arbuckle Group (Arbuckle) is a resource heavily relied upon by a range of industries and municipalities in Kansas. The Arbuckle has been the source for ~30% of all the oil produced in Kansas starting in the 19th century in eastern Kansas. The earliest large oil discoveries were the Augusta (1914, Butler County), El Dorado (1915, Butler County), and Fairport (1925, Russell County) fields. Most Arbuckle production is currently on the Central Kansas Uplift. Natural gas storage for retail markets has found utility in Arbuckle structural traps. Additional storage capacity for natural gas is possible considering potential future infrastructure and associated needs. Communities in southeastern Kansas along the Missouri state line (Cherokee, Bourbon, and Crawford counties) utilize deep wells into the Arbuckle for freshwater. Since 2000, the Arbuckle has been studied as a possible zone for $CO_2$ sequestration. Early studies were concentrated at sites in south-central Kansas (Sumner County), where subsequent well measurements have indicated that reservoir capacity may be limited under gravity emplacement processes. Current sequestration studies focus on southwestern Kansas, where the Arbuckle has significant reservoir capacity to assimilate supercritical $CO_2$.

Technologies for large-scale upgrading of oilfield brines, industrial effluent, and in-situ saline formation water to useable water show limited progression in moving out of the laboratory to even pilot-project status in the next decade. Perhaps future technologies could overcome the formidable barriers to economically upgrading the many types of wastewater now entering the Arbuckle. Well into the future it might even be possible to harvest and treat/process waste fluid currently stored in the Arbuckle for limited use or mining opportunities. Continued disposal into the Arbuckle will be necessary at least for the near future. As technology advances deeper into the 21st century, abandoned or underutilized disposal and production wells may have the potential to be modified in some areas for a wide range of applications (e.g., geothermal). The Arbuckle is a unique and vast resource with untold potential waiting for technology to emerge to maximize that potential. Looking at the Arbuckle as a resource for centuries to come, someday it might be practical to produce low-temperature geothermal power or harvest formation fluids from which mineral resources can be extracted.

Historical disposal of fluids in the Arbuckle in both Class I and Class II wells has been at sustainable to moderate rates. However, yearly tests of Class I disposal wells indicate that pressure and static fluid levels are rising in the Arbuckle, particularly in south-central Kansas (Figure 1). These changes are collectively correlated to large changes in disposal volumes, which more than doubled from 2010 to 2015. Much of this disposal is from wells along the

Kansas-Oklahoma state line. Disposal volume has declined since 2015, but it has yet to return to pre-2010 levels. Some disposal wells are recording decreasing fluid levels, but the majority of these wells are still recording fluid rise.

In south-central Kansas, if fluid levels measured in low-volume Class I wells in Reno, Butler, Sedgwick, and McPherson counties continue to rise, Arbuckle fluids could eventually reach shallower aquifers — or possibly already have. After interpolating between Class I wells, it appears the possibility exists that the potentiometric surface of Arbuckle fluids could be within the Equus Beds interval at some locations within Harvey County. This observation highlights the need for accurate and precise measurements of Arbuckle fluids in spatially undersampled and economically strategic areas.

Future resource conservation and capacity of the Arbuckle is critical for the energy industry and industrial/municipal facilities in Kansas that dispose of wastewater into the Arbuckle Group. The capacity of the Arbuckle to take fluid could be exceeded in the next few decades even at current reduced disposal rates. Suggestions of regional changes in static fluid levels are based on data from a sparse few Class I disposal wells that spatially undersample the aquifer. This degree of extrapolation highlights the need for more spatially dispersed sample points for confident determinations of fluid-level changes. An in-depth study of fluid characteristics in a large number of wells with significant penetration in the Arbuckle across an eight-county area in south-central Kansas will provide a much higher-resolution database for studying static and dynamic trends. The information obtained from such a study will be crucial for management and sustainable use of the Arbuckle while protecting this important Kansas resource into the future.

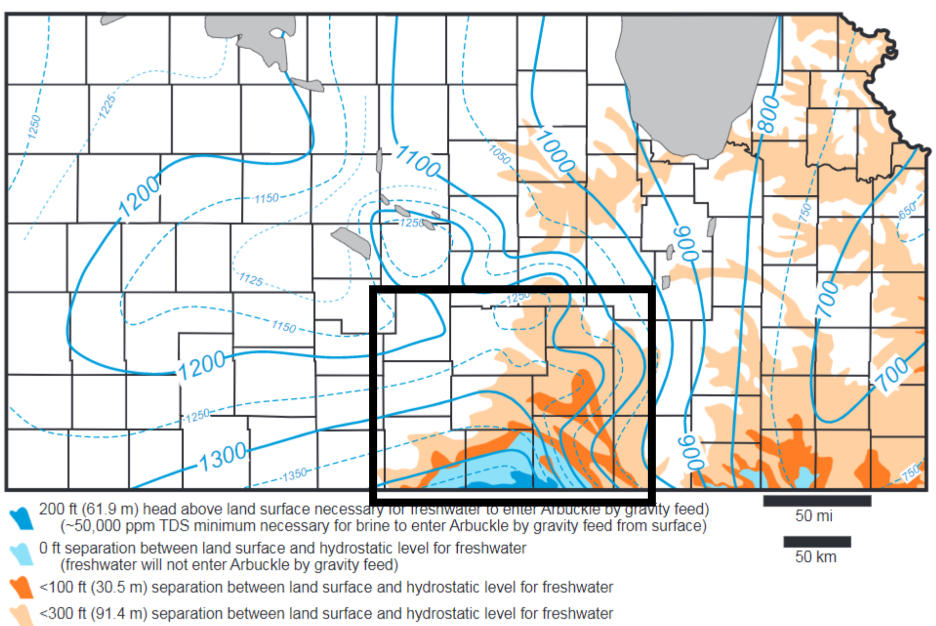


**Figure 1.** Elevation of the Arbuckle potentiometric surface (freshwater equivalent). The blue-toned regions where the elevation of the freshwater-equivalent hydrostatic level exceeds the elevation of the land surface show where freshwater cannot enter the Arbuckle by gravity alone. The black box represents the proposed south-central Kansas study that encompasses areas where the Arbuckle capacity may be limited, or the potentiometric surface is approaching the land surface or the base of shallow aquifers.

**Feasibility Study: Objectives and Barriers**

In advance of a full study to investigate critical Arbuckle fluid data across an eight-county area, a preproposal/feasibility study was designed to assess measurement methodologies and establish the protocols and procedures to be used in the full study. Data required to characterize and assess Arbuckle fluid changes are formation pressure at the bottom of the borehole (bottomhole pressure, BHP), static fluid level (SFL), and fluid density (ρ) profile. Together, these measurements describe the three variables in the hydrostatic equation:

$$P = \rho g h \ , \qquad (1)$$

where $P$ is the pressure due to the overlying fluid column, $g$ is the acceleration due to gravity, $\rho$ is density, and $h$ is the height of the fluid column (equal to the depth $d$ where BHP is measured minus SFL). Thus, equation 1 can be rewritten:

$$\mathrm{BHP} - \mathrm{P_{atm}} = \rho g(d - \mathrm{SFL}) \ , \qquad (2)$$

where $P_{atm}$ is the atmospheric pressure.

There are a variety of methods for measuring or calculating the variables in this equation. At Class I facilities, formation pressure is typically determined from Horner analysis of pressure transients recorded near the bottom of the borehole during a pressure falloff (PFO) test. This is an active test where fluid is injected until radial flow is achieved, the well is then shut in, and pressures are recorded over time (as a time series). Horner analysis uses mathematical modeling and data fitting to estimate relevant reservoir properties, including the extrapolated pressure (P*), which is equivalent to formation pressure. Pressure gradients are calculated from pressure recorded at various depths throughout the borehole during a pressure gradient survey. Pressure is linearly extrapolated using the pressure gradients of the borehole fluid and open atmosphere to determine the depth at which they intersect—the SFL. Using P* and SFL, the apparent density of the fluid column can be calculated with equation 2.

PFO tests are sophisticated approaches used by engineers to more fully characterize the reservoir and evaluate well performance. As such, these tests are more involved, are more expensive, require specialized analysis, and may be influenced by other factors (restricted flow, etc.). Therefore, PFO tests are not recommended for routine monitoring in a network of Arbuckle wells, but results from routine monitoring of Class II wells for this study must be compatible with the existing database predominantly obtained from PFO testing in Class I wells. The objective of the feasibility study is to evaluate other more practical methods for accurately determining BHP, SFL, and density and to assess the influence of diurnal (tidal) effects on the resulting measurements.

A large number of Class II oilfield brine disposal ("saltwater disposal," SWD) wells terminate in the Arbuckle in south-central Kansas, including three wells offered by Berexco to use for testing different measurement methods (Figure 2). The diameter of the pressure tool used by the wireline service company is 1.6 in. The narrowest inner diameter of two of the Berexco wells is 1.75 in, which is insufficient clearance for the pressure tool. The KGS identified additional wells that meet the minimum criteria for the study with inner diameter > 1.75 in and termination (BH) depth > 200 ft beneath the top of Arbuckle to allow representative sampling of the formation. Many of these targeted wells were located across Barber, Harper, and Sumner counties and belonged to SandRidge Energy, Inc. (SandRidge). The Kansas Corporation

Commission (KCC) provided contact information for the SandRidge employee who manages these wells. Field staff for SandRidge were very supportive of and interested in participating in the testing. Ultimately, SandRidge declined to participate due to legal issues surrounding risk and liability, this despite insurance carried by the contractor to cover potential damages.

The KGS contacted five additional operators; the KCC provided a direct contact for one of the five. Three did not respond; two indicated that they were potentially interested and that they would speak with their superiors, but ultimately did not respond despite the KGS's multiple attempts to reengage with them. Conversations between KGS and KCC staff revealed that an additional concern of operators was potential damage to the anticorrosive lining inside the tubing; however, pulling the tubing is invasive and expensive and well beyond the scope of this study. This lining, when scratched by logging tools can expose highly corrosive fluids to bare metal tubing and greatly reduce the tubing life which serves as a barrier protecting the casing and ultimately the environment outside the injection zone. Barriers related to physical limitations of wells, risk, and liability could not be overcome to perform the planned feasibility study. The KGS also pursued abandoned wells owned by the KCC, temporarily abandoned wells still owned by permit holders, and newly drilled wells but could not identify any that fit the criteria for and within the timeframe of the feasibility study.

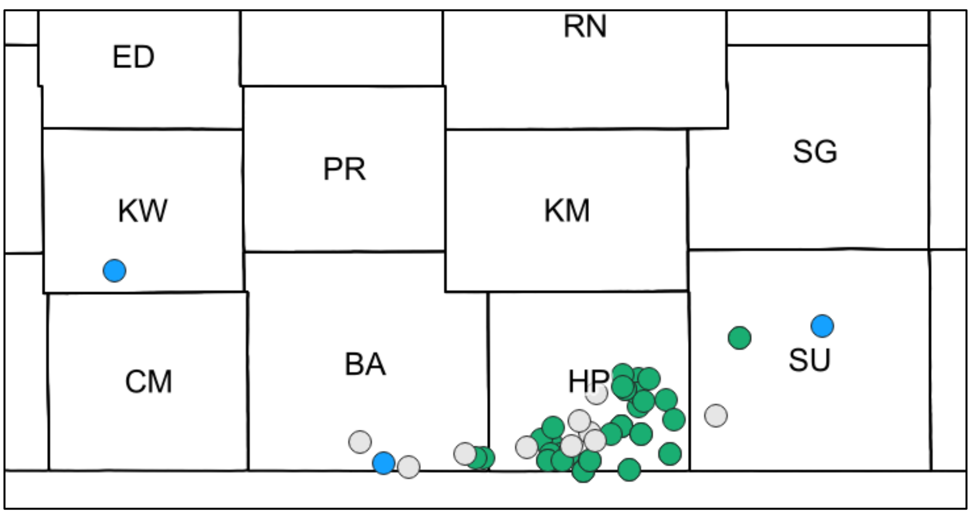


**Figure 2.** Wells in south-central Kansas proposed for the feasibility study. Blue indicates wells offered by Berexco, green indicates SandRidge wells, and gray indicates other operators.

### KGS Testing at KS-01-155-008

The KGS commissioned the testing at a Class I facility in Hutchinson in October 2020. The objective of this internal KGS study was to directly compare a few methodologies for determining BHP, SFL, and ρ to results from compliance testing in a Class I well using PFO tests. The methodologies used were similar to those proposed for the feasibility study, and wastewater disposal well KS-01-155-008 is an excellent proxy because it has significant penetration into the Arbuckle. Furthermore, the well had been inactive with no injection for a year at the time of the test, allowing for assessment of the injectate (effluent brine) and Arbuckle formation fluid mixing and potential stratification within the fluid column. In the absence of test data from Class II wells, findings from this internal KGS study can serve as a guide for identifying suitable methodologies and developing protocols to use in the future to acquire data from a designed network of Arbuckle wells compatible with the existing Class I well database.

The KGS contracted Strata, the consultant managing the KS-01-155-008 PFO test to ensure the same pressure transducer was used for both tests and therefore obtain directly relatable pressure measurements with minimal error. Prior to the PFO test, an acoustic sounder was used to estimate SFL. A bailer was lowered to 4460 ft (about the center of the open-hole portion of the well) to collect a fluid sample for density analysis. The pressure tool was secured at 4170 ft beneath the bottom of the tubing in the open-hole portion of the well, and pressure was recorded with a 10 s sample rate for 24 hrs. The pressure tool was then lowered to 4735 ft and secured. The gauge depth for the PFO test was 4735 ft and therefore the formation pressure at this depth is considered BHP. Static BHP was recorded, and the PFO test was performed. After the PFO test, pressure was measured at 500 ft intervals as the pressure tool was raised through the well (pressure gradient survey).

## Findings from KGS Testing

When two of the three variables in the hydrostatic equation are known, the third variable can be calculated using equation 2. In this internal KGS study, a variety of methods were used to directly measure or calculate all three variables (Table 1) for redundancy and quality assurance and to identify any potential sources of error or uncertainty. In this section, diurnal changes recorded during 24 hr monitoring, the hydrostatic variables measured/calculated with a variety of methods, and the impact of errors on downstream calculations are assessed.

**Table 1.** Methods used to measure or calculate ρ, SFL, and BHP.

| ρ | **SFL** | **BHP (at 4735 ft)** |
|---|---|---|
| water sample | gradient survey | PFO - P* |
| gradient survey | acoustic sounder | static BHP |
| calculated from P @ 1000 ft, SFL | calculated from P @ 1000 ft, ρ | projected from 4710 ft |
| calculated from BHP, SFL | | projected from 1000 ft |

### *Diurnal Changes*

The objective of monitoring KS-01-155-008 was to assess any non-static variability. Because this well was inactive prior to testing, the only expected changes are diurnal changes associated with Earth tides. Tides induce poroelastic changes that result in diurnal pore pressure variation with a 24 hr cycle. Continuous 24 hr monitoring revealed the expected diurnal changes on the order of 0.13 psi, which is similar to the inherent uncertainty in the pressure measurement (Figure 3). Therefore, it may not be necessary to correct for tidal effects to compare pressure measurements taken at different times.

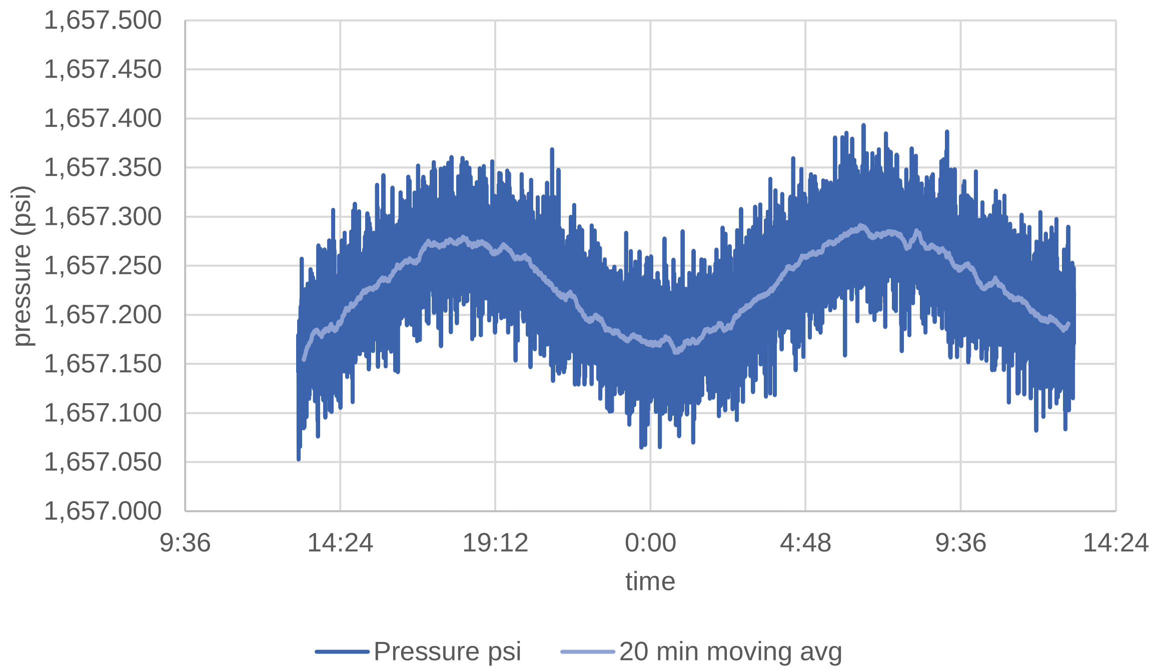


**Figure 3.** Pressure recorded at KS-01-155-008 during the 24 hr monitoring period.

*Fluid Density*

Density was directly measured from a fluid sample, and the average density was calculated for 500 ft intervals, a shallow interval, and over the entire fluid column (Table 2). Using a fluid sample collected in the middle of the open-hole portion of the well prior to any other downhole measurements, the density was 1.194 g/cc, which is unexpectedly high for Arbuckle formation fluids (closer to freshwater density). This density can be compared to the density profile calculated for the open-hole portion of the well using measurements from the pressure gradient survey.

Taking the derivative of both sides of equation 1 with respect to depth *h* and rearranging, density becomes:

$$\rho = g \, dP/dh \, . \tag{3}$$

Therefore, the average density between two points in the well is directly proportional to the pressure gradient (the change in pressure divided by the change in depth). Results from the gradient survey reveal a density inversion at depth (Figure 4). The fluid density above 4000 ft in the cased portion of the borehole is nearly constant and averages 1.194 g/cc. The average density from 4000 to 4500 ft, which is primarily open-hole, drops to 1.055 g/cc. These findings suggest that the fluid in the cased portion of the borehole is primarily the injected fluid (a brine) and the density inversion indicates less-dense Arbuckle formation fluid (and/or a mixing with injected fluid) in the open-hole portion of the well. Although the fluid sample was collected in the middle of the open-hole portion of the well, its density was equal to the average density of the fluid in the cased portion of the borehole. Therefore, the sample most likely does not provide an accurate representation of the density at the collection depth and was probably contaminated with the injected fluid from the cased portion of the borehole.

Average density was calculated at two locations in the well from a single pressure reading and SFL using equation 2. SFL from the gradient survey (discussed in the following subsection) was 981 ft. Using BHP, the average density of the fluid column between SFL and 4735 ft is 1.166 g/cc. Using the pressure at 1000 ft, the average density of the upper portion of the fluid column is 1.199 g/cc. This is consistent with a sample of fluid injected during the PFO test collected as a part of the annual compliance testing. The lower average density over the entire fluid column is consistent with the inversion observed in the density profile obtained from the gradient survey.

These results indicate that fluid density within the borehole is not constant. The most important implication is that the shallow fluid density cannot be extrapolated to the bottomhole depth. Furthermore, a fluid sample collected at depth does not provide an accurate representation due to contamination with fluid from shallower depths. The overall density of the in situ fluid column is best characterized using at least one measurement at depth to obtain the average density of the entire column (minimum requirement) or a gradient survey to calculate the density profile.

**Table 2.** Fluid density $\rho$ measured or calculated in KS-01-155-008.

| **Method** | **$\rho$ (g/cc)** |
|---|---|
| water sample @ 4460 ft | 1.194 |
| gradient survey @ 4000-4500 ft | 1.055 |
| calculated from BHP, SFL | 1.166 |
| calculated from P @ 1000 ft, SFL | 1.199 |

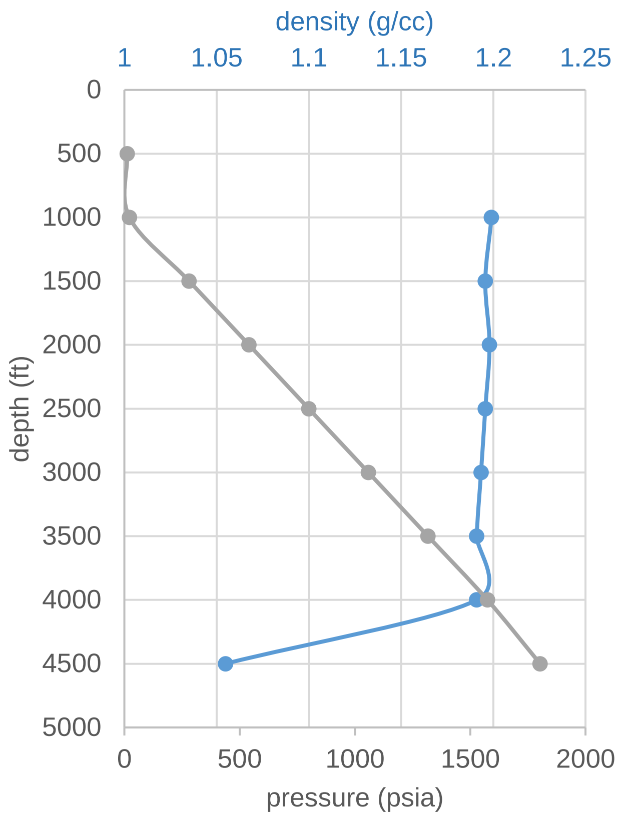


**Figure 4.** Pressure (gray) measured at 500 ft intervals, and average interval density (blue) calculated from the pressure gradient.

*Static Fluid Level*

SFL was directly calculated from the pressure gradient survey, measured using an acoustic sounder, and calculated from pressure measured at a shallow point in the fluid column (Table 3). The pressure gradient survey is used to calculate SFL for compliance testing, which was determined to be 981 ft. For the purposes of the current study, this will be considered the benchmark. The acoustic sounder was used to record 28 readings that ranged from 843 to 1118 ft. The average SFL was 970 ft with a standard deviation of 70 ft. Although the average SFL is only 11 ft greater than the actual SFL, the uncertainty is unacceptably large. Using equation 2, the density of the shallow borehole fluid (density of the injected fluid captured during compliance testing = 1.199 g/cc), and pressure recorded at 1000 ft, the resulting SFL is 981 ft and is consistent with the SFL obtained from the gradient survey.

**Table 3.** SFL measured or calculated in KS-01-155-008.

| **Method** | **SFL (ft)** | **Error (g/cc, %)** |
|---|---|---|
| gradient survey | 981 | n/a |
| acoustic sounder | 970 | 1 % |
| calculated from P @ 1000 ft, ρ | 981 | 0 % |

*Bottomhole Pressure*

BHP was calculated from the PFO test, directly measured at the BHP depth, and projected from pressures measured at shallower depths (Table 4). Formation pressure determined using pressure transient analysis (P*) from data collected during the PFO test was 1909.3 psia, which serves as the benchmark value for BHP. Immediately prior to the injection portion of the PFO test, a static pressure was measured at the same depth. Static BHP was 1909.0 psia. BHP was then calculated using pressures measured at 4170 ft (just beneath the bottom of the casing) and 1000 ft (the shallowest pressure measurement recorded in the fluid column). Pressure was projected from these depths to 4735 ft using equation 2, the atmospheric pressure and SFL determined from the gradient survey (12.3 psia and 981 ft, respectively), and the average fluid density between SFL and the measurement depth. The resulting BHP projected from 4170 ft and 1000 ft were 1948.7 psi and 1962.3 psi, respectively. Because pressure from 4170 ft to the bottomhole depth spans the open-hole interval, average fluid density for this interval should provide a more accurate extrapolation. Projecting pressure from 4170 ft using the 1.055 g/cc density from the gradient survey at 4000-4500 ft results in 1915.1 psi.

The static BHP was nearly identical to P*. This suggests that a full PFO test and pressure transient analysis are unnecessary for determining formation pressure only, and that static BHP measurements are accurate and compatible with P* calculated in wells with good connectivity with the formation under static conditions. Based on temporal pressure variations when the tool was static at bottomhole depth, a full 24 hours shut-in will not be necessary. Projecting pressure from a shallow measurement is sometimes used as an easy, cost-effective method to estimate BHP. In this case, BHP projected from 1000 ft was 53 psi greater than the actual BHP. The error in projected BHP is due to the variable fluid density profile in this well and the use of the shallow fluid density for the extrapolation to depth. Although the error is only 3% relative to true BHP, it should be noted that even small errors could lead to considerable differences in downstream calculations, as discussed in the following section. If pressure is projected from 4170 ft using the interval density, projected BHP is much more accurate. However, this requires additional information or assumptions about density at or below the depth of the pressure measurement.

**Table 4.** BHP measured or calculated in KS-01-155-008.

| Method | BHP (psia) | Error | Freshwater SFL |
|---|---|---|---|
| PFO - P* at 4735 ft | 1909.3 | n/a | 359.2 ft |
| static BHP at 4735 ft | 1909.0 | 0.3 psi (0.02%) | 359.8 ft (0.2% error) |
| projected from 4710 ft | 1948.7 | 39.4 psi (2%) | 268.3 ft (25% error) |
| projected from 4710 ft with interval $\rho$ | 1915.4 | 6.2 psi (0.3%) | 344.9 ft (4% error) |
| projected from 1000 ft | 1962.3 | 53.1 psi (3 %) | 236.7 ft (34% error) |

*Freshwater SFL Correction*

One of the primary objectives of the Arbuckle monitoring project is to calculate the freshwater-equivalent hydrostatic elevation—the elevation to which freshwater would rise in an Arbuckle well—in additional wells to refine the potentiometric surface map (Figure 1). The key measurement required to accurately calculate the freshwater-equivalent SFL is BHP. Using equation 2 and $\rho = 1$ g/cc, and P*, the freshwater SFL is 359.2 ft. Freshwater SFL calculated with the static BHP is 359.8 ft, less than 0.2% error. Freshwater SFL calculated with BHP projected from 4710 ft and 1000 ft using the average density of the overlying fluid column is 268.3 ft and 236.7 ft, respectively. Although the error in projected BHP is 3% or less, the error in resulting freshwater SFL exceeds 25%, which is well outside the acceptable range. Freshwater SFL calculated with BHP projected from 4710 ft and 1000 ft using the average density of the open-hole interval is 344.9 ft, representing a 4% error. This is much closer to the benchmark freshwater SFL but requires additional information or assumptions about density below the measurement depth.

**Conclusions: Implications for Future Arbuckle Monitoring**

Based on the results of testing in KS-01-155-008, correcting pressure measurements for tidal effects is likely unnecessary since the diurnal changes are on the order of the measurement uncertainty. The most accurate methods for determining BHP are either a static measurement or pressure transient analysis from a PFO test.

Projections from shallower depths, even within the open-hole portion of the well, would result in unacceptably large errors due to a variable density profile in brine disposal wells. One of many possible solutions to the segregation of fluids in the casing that are not representative of the formation fluid is to remove the injected fluid within the cased portion of the borehole and allow replacement with Arbuckle formation fluid. This would provide a much more consistent or constant density profile. With a constant density profile, BHP could be accurately projected from shallow measurements. With analysis of additional future data acquired to test the planned methodologies, other options for either estimating or replacing the static fluid column will likely become apparent.

SFL can be accurately estimated with a variety of methods. SFL calculated using a shallow pressure and density measurement provided results consistent with the benchmark gradient survey. This is expected as shallow pressure recording is the method most frequently used for long-term water-level monitoring. Another option would be to directly measure depth to water with an electrical wireline logging tool. The benefits of using this method would be to eliminate uncertainty associated with density, obtain knowledge of SFL in advance for appropriate emplacing of a shallow pressure tool, and provide a redundant measure of SFL for quality assurance. This logging tool measurement could be scheduled as part of any workover or SWD shut-in.

The density profile in a brine disposal well (produced water injectate) will be variable, and reduced density is possible within the perforated or open-hole portion of the well. This has significant implications for projecting pressure from shallower measurements to the bottomhole depth. Due to the density inversion, the average density of the fluid column is insufficient for pressure extrapolation and requires assumptions about density in the open-hole interval. It may be possible to use an estimate of density within this interval using assumptions derived from other measurements or sources (e.g., Arbuckle density estimated from published values of salinity). However, the uncertainty would be unknown without a direct measurement and has the potential to produce large errors for calculating the freshwater equivalent SFL.

Although not observed in the test well for this study, lower density fluid within the casing relative to the Arbuckle Formation fluids is also a possibility. The density of the injectate depends on the formation from which the produced water was pumped. This uncertainty almost guarantees that a linear extrapolation of density throughout the well column when calculating BHP will produce inaccurate results.

In light of these findings and concerns regarding risk to logging equipment in the open-hole interval, replacing the static injected fluid in the borehole with Arbuckle formation fluid will allow a reasonably accurate projection of BHP from shallow measurements while reducing risk to logging equipment and well integrity. Once the stability of formation fluids left idle for a year plus in SWD can be established and a reasonable method can be defined to load the borehole with formation fluid, long-term use of inactive SWD would provide the most cost effective (~$1,000/well if the formation fluid remains in the borehole indefinitely) and precise method for monitoring BHP and SFL in the study area.

**Building an Arbuckle Fluid Database**

Studies have clearly demonstrated the Arbuckle Group is a highly variable interval and the geologic provinces have been described as cups in an "egg carton" with respect to restrictions to and preferential pathways for fluid movement in the Arbuckle. With Class I data alone, spatial sampling will not permit meaningful regional or subregional interpretations of Arbuckle hydrology. Extrapolating between measurement points more than a few 10s to 20s of miles apart will not result in accurate representations of SFL, BHP, or water chemistry in the Arbuckle Group. Acquiring meaningful Arbuckle fluid data requires collaboration and cooperation with owners and operators of Class II SWD wells. It is not possible under any state funding scenario to collect the data necessary to characterize the current state of Arbuckle formation fluids and provide a science-based model of key fluid properties at the scale and resolution necessary for meaningful regulatory oversight without partnering with the Class II SWD community. Arbuckle formation fluids have the potential to impact seismicity, encroach on freshwater aquifers, and influence disposal efficiency. Data from routine sampling of optimally distributed Class II Arbuckle SWD wells that can be directly correlated to Class I Arbuckle disposal well databases will provide the necessary insights for adapting earthquake monitoring approaches and predictive modeling used to guide seismicity mitigation strategies.

Class II operators could provide valuable data in the study and understanding of the current state of Arbuckle fluids, any meaningful trends in the reservoir's fluid properties, and the still untapped resource potential of the interval. For active SWD wells, during mechanical integrity testing or any servicing where the well head is removed, a sample of the injectate could be obtained and an electronic sounder could be lowered into the open well (after a short shut-in period) where the SFL could be measured. Additionally, for very little additional expense, a pressure measurement about 100 ft below the top of the water column could be taken. For an inactive SWD well, pumping approximately 10 well volumes in advance of taking a fluid sample and lowering a sounder and taking a SFL reading after a stabilizing period would also provide extremely valuable data for better characterizing this resource. These data from wells that penetrate the top of Arbuckle at least 100 ft would provide an invaluable data set for preserving the Arbuckle for current as well as future uses. Key to any measurement in an Arbuckle disposal well is to ensure the fluid in the cased portion of the well has the same properties as the fluids in the uncased/screened Arbuckle interval.

Based on the testing done in KS-01-155-008 and from investigations related to construction and access to a reasonable set of Class II SWD wells, a bottomhole pressure measurement near the base of the open-hole portion of the borehole and a 500 ft interval gradient pressure survey through the entire water column provide the most representative and relatable SFL data set. Alternate methods of estimating relatable BHP will involve hole preparations for inactive wells and density measurements and assumptions about uniformity of the water column in and below the cased portion of the well. More testing is necessary in active and inactive SWD wells to fully develop the methodologies for shallow pressure measurements and associated extrapolation to BHP.