Review of Powhatan Salt Company Solution Mining Well Permits for Storage of Natural Gas Liquids at the Mountaineer NGL Storage Facility near Clarington, Ohio

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About PSE Healthy Energy

Physicians, Scientists, and Engineers for Healthy Energy (PSE Healthy Energy) is a multidisciplinary, non-profit energy science and policy research institute that studies the way energy production and use impact public health and the environment.

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About the Authors

Dr. DiGiulio is a senior research scientist at Physicians, Scientists, and Engineers (PSE) for Healthy Energy and an affiliate at the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado. Dr. DiGiulio completed a B.S. in environmental engineering at Temple University, a M.S. in environmental science at Drexel University, and a Ph.D. in soil, water, and environmental science at the University of Arizona. During his 31 years with the U.S. Environmental Protection Agency (EPA), he conducted research on gas flow-based subsurface remediation (soil vacuum extraction, bioventing), groundwater sampling methodology, soil-gas sampling methodology, gas permeability testing, intrusion of subsurface vapors into indoor air (vapor intrusion), subsurface methane and carbon dioxide migration (stray gas), and solute transport of contaminants in soil and groundwater including that associated with hydraulic fracturing and pits used to dispose oil and gas waste. He assisted in development of EPA's original guidance on vapor intrusion and the EPA's Class VI Rule on geologic sequestration of carbon dioxide. While with the EPA, he routinely provided technical assistance to EPA regional offices and assisted in numerous enforcement actions. The focus of his current work is on understanding environmental impact from oil and gas development in the United States and abroad, especially in regard to surface and groundwater resources. He has served as an expert witness in litigation relevant to oil and gas development, has testified before State oil and gas commissions on proposed regulation, and has testified before Congress on the impact of oil and gas development on water resources.

Dr. Rossi completed a B.S. in Civil and Environmental Engineering from Penn State in 2009, and received his Ph.D. in Geology and Environmental Science at the University of Pittsburgh in 2016. His dissertation research focused on soil biogeochemistry and how land use and human activities affect hydrologic regimes, and by extension, major and trace metal dynamics. Following the completion of his dissertation, Dr. Rossi was a visiting scholar at the University of Pittsburgh, and devised a project to reconstruct the environmental legacy of industrial activities and coal-fired electricity generation in the Pittsburgh Metropolitan Area. Dr. Rossi held his first postdoctoral appointment in 2017 at Temple University, where he examined the impact of land use and green infrastructure on surface and groundwater hydrology within the Philadelphia Metropolitan Area. In 2017 Dr. Rossi was awarded a NatureNet Science Fellowship with the Nature Conservancy, and conducted postdoctoral research on oxygen dynamics in agricultural soils at Stanford University. Dr. Rossi's current work is on the impact of produced water from oil and gas activities on groundwater systems.

Background

The Powhatan Salt Company (PSC) submitted permit applications to the Ohio Department of Natural Resources (ODNR) for the installation of three salt solution mining wells near Clarington, Ohio along the Ohio River on March 5, 2020. The stated purpose of cavern creation is to store liquid petroleum gas (LPG) including propane (HD5 consumer grade and HD10 commercial grade) and butane/isobutene, as well as ethane and other Y-grade or blended dry natural gas liquids (NGLs) (CEC 2018). The facility will be operated by Mountaineer NGL Storage LLC and provide approximately 2 million barrels (bbls) of baseline storage capacity, with at least 25,000 bbls per day of cycling capacity (load-in and load-out) (CEC 2018). Each storage well will have the capacity to separately store a minimum of 300,000 bbls (CEC 2018).

The ODNR opened a 30-day comment period on these permits on January 7th. PSE Healthy Energy (PSE) was tasked by the Environmental Integrity Project and Earthjustice with reviewing these permit applications. PSE developed a report dated February 4, 2021 outlining technical concerns with permit applications. After obligatory consideration of public comments, including comments submitted by PSE, the ODNR then issued revised well permits on March 8, 2021 and opened another 30-day public comment period. PSE was tasked by the Environmental Integrity Project and Earthjustice with reviewing these revised permit applications.

Methods

The basis of this review is information provided in permit application packages, information generated by PSC or Mountaineer NGL directly associated with permit applications but inexplicably not included in permit application packages, regulations on solution mining in Ohio, Federal Code of Regulations, American Petroleum Institute (API) Recommended Practices (RP) on natural gas and NGL storage in salt caverns, and background information pertinent to risk associated with NGL storage in solution-mined caverns in the peer-reviewed literature. These sources of information are outlined below.

(1) Permit application packages provided to the ODNR in March 2020.

(2) Draft permits and fact sheets on permits issued by the ODNR in March 2021.

(3) Surface and Ground Waters Protection Plan, Powhatan Site, Monroe County, Ohio. Prepared for: Mountaineer NGL Storage LLC, 6295 Greenwood Plaza Blvd, Greenwood Village, CO 80111. Prepared by: Civil & Environmental Consultants, Inc., 333 Baldwin Road, Pittsburgh, PA 15205. Submitted to: Ohio Environmental Protection Agency, Division of Drinking Waters, 50 West Town Street, Suite 700, Columbus, OH 43216-1049, CEC Project 153-016.0036, Ohio EPA File DSW401 165049, May 2017, (Revised February 2018)

(4) Assessment of Salt Barrier Between Powhatan Salt Company and Westlake Caverns. Prepared for: Powhatan Salt Company, 6295 Greenwood Plaza Boulevard, Greenwood Village, CO 80111. Prepared by Thomas Eyermann, Revised September 29, 2017, Revision 1

(5) Ohio Administrative Code 1501:9 Division of Mineral Resources Management – Oil and Gas, Chapter 1501:9-7 Solution Mining Projects.

(6) Federal Register/Vol. 85, No. 29/February 12, 2020/Rules and Regulations. Department of Transportation, Pipeline and Hazardous Materials Safety Administration, 49 CFR Parts 191, 192, and 195, Pipeline Safety: Safety of Underground Natural gas Storage Facilities.

(7) Design and Operation of Solution-Mined Salt Caverns Used for Natural Gas Storage. American Petroleum Institute (API) Recommended Practice (RP) 1170. First Edition, July 2015

(8) Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs. American Petroleum Institute (API) Recommended Practices (RP) 1171. First Edition, September 2015.

(9) Recommendations in Design and Operation of Solution-Mined Salt Caverns Used for Liquid Hydrocarbon Storage, American Petroleum Institute (API) Recommended Practices (RP) 1115, Second Edition, November 2018.

(10) Geologic Assessment of the Burger Power Plant and Surrounding Vicinity for Potential Injection of Carbon Dioxide by Lawrence H. Wickstrom, Ernie R. Slucher, Mark T. Baranoski, and Douglas J. Mullett. Submitted to Ohio Department of Natural Resources, Division of Geological Survey 2045 Morse Road, Building C-1, Columbus, Ohio 43229-6693, Columbus 2008, Open-File Report 2008-1

(11) A Geologic Study to Determine the Potential to Create an Appalachian Storage Hub for Natural Gas Liquids. Final Report. July 31, 2017. Appalachian Oil & Gas Research Consortium. Editors: Kristin M. Carter and Douglas G. Patchen. Authors: Kristin M. Carter, Douglas G. Patchen, Jessica P. Moore, Mohammad Fakhari, Gary W. Daft, Jr., Michael Solis, Brian J. Dunst, Robin V. Anthony, Katherine W. Schmid, Kyle Metz, Philip Dinterman, Julie M. Bloxson, Erica N. Schubert, John Saucer. July 31, 2017

(12) Discussion on risks associated with solution mining and storage of NGLs in caverns in the peer-reviewed literature as follows.

Bérest, P. Cases, causes and classifications of craters above salt caverns. International Journal of Rock Mechanics and Mining Sciences 100 (2017) 318–329.

Bérest, P.; Brouard, B. Safety of Salt Caverns Used for Underground Storage Blow Out; Mechanical Instability; Seepage; Cavern Abandonment. Oil & Gas Science and Technology – Rev. IFP, Vol. 58 (2003), No. 3, pp. 361-384.

Bérest, P.; Réveillère, A.; Evans, D.; Stöwer, M. Review and analysis of historical leakages from storage salt caverns wells. Oil & Gas Science and Technology - Rev. IFP Energies nouvelles 74, 27 (2019)

Habibi, R. An investigation into design concepts, design methods and stability criteria of salt caverns. Oil & Gas Science and Technology - Rev. IFP Energies nouvelles 74, 14 (2019)

Liu, W.; Zhang, Z.; Fan, J.; Jiang, D.; Daemen, J.J.K. Research on the Stability and Treatments of Natural Gas Storage Caverns with Different Shapes in Bedded Salt Rocks. IEEE Access. Digital Object Identifier 10.1109/Access.2020.2967078 (2020a).

Liu, W.; Zhang, Z.; Fan, J.; Jiang, D.; Li, Z.; Chen, J. Research on gas leakage and collapse in the cavern roof of underground natural gas storage in thinly bedded salt rocks. Journal of Energy Storage, 31, (2020b) 101669.

Warren, J.K. 2013. Evaporites, A Geological Compendium, Second Edition, Springer Cham Heidelberg New York Dordrecht London, ISBN 978-3-319-13511-3, ISBN 978-3-319-13512-0 (eBook), DOI 10.1007/978-3-319-13512-0

Discussion

In its report dated February 4, 2021, PSE submitted 58 sets of comments on drilling, solution mining, and storage of NGLs of which 7 sets of comments were at least in part addressed in the submitted permits. Of the remaining 51 sets of comments, the ODNR provided a sufficient response to 3 sets of comments, insufficient response to 6 sets of comments, and no response to 42 sets of comments (**Table 1**). An insufficient response or no response to comments is concerning because submitted comments were based on the American Petroleum Institute's (API) Recommended Practices for Design and Operation of Solution-Mined Salt Caverns Used for Natural Gas Storage (RP 1170), Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs (RP 1171), and Design and Operation of Solution-Mined Salt Caverns Used for Liquid Hydrocarbon Storage (RP 1115). API's recommended practices developed in these documents are based on years of research and practical operating experience by engineers and scientists in industry and should not be ignored.

The permit application packages were constrained to drilling of wells for solution mining and limited aspects of solution mining. Virtually no information was provided on geological characterization in permit applications or in draft permits issued by the ODNR as would be expected for any drilling or subsurface mining process. For the drilling of wells, basic aspects of well design were missing in permit applications such as collapse and burst strength of casing and cement application procedures. ODNR did however require the use of centralizers in their draft permits.

There was little or no discussion on basic elements of monitoring during solution mining such as cavern roof and blanket monitoring, and basic elements of cavern design such as cavern neck specification, and pillar distance spacing. The ODNR did require cavern shape monitoring during solution mining in their draft permits. Cavern shape monitoring however does not appear to be required during NGL storage. Remaining outstanding issues still raise concerns regarding due diligence in permit applications. Issued draft permits still do not address the storage of NGLs in solution mined caverns at all. This is notable since the explicit purpose of solution mining in permit applications is to store NGLs. It is critical to integrate the storage of NGLs into the permitting process since aspects of monitoring during the solution mining process overlap with monitoring during NGL storage.

To our knowledge, there are no regulations in Ohio specifically addressing the storage of NGLs in caverns, depleted oil and gas fields, or in aquifers creating a regulatory void in this state. However, the storage of natural gas in Ohio is regulated by the Pipeline and Hazardous Materials Safety Administration (PHMSA). While there are some differences in monitoring storage of natural gas and NGLs, most recommendations in the American Petroleum Institute's (API) Recommended Practices (RP) for storage of natural gas in caverns (API RP 1170) and storage of NGLs in caverns (API RP 1115) are identical supporting the need to regulate storage of NGLs in a manner similar to natural gas in permit applications.

In February 2020, PHMSA finalized rules for underground storage of natural gas (Federal Register 2020). The installation of wells, solution mining, and storage of natural gas in caverns must now be compliant with API RP 1170 and Section 8 of API RP 1171 which fully integrate the installation of solution-mining wells, the process of solution mining, workover prior to gas storage, and gas storage itself. PHMSA mandated compliance with Section 8 of API RP 1171 because it provides more prescriptive practices than API RP 1170 for how an operator must develop, implement, and document a program to manage risks that could affect the functional integrity of storage operation (Federal Register 2020). Extending the applicability of the recommended practices in Section 8 of RP 1171 closed a potential safety gap for salt cavern storage facilities and may prevent future failures at these facilities (Federal Register 2020). PHMSA adopted the API RPs without modification where statements using the term "shall" constitute mandatory requirements and statements using the term "should" are not mandatory but should be considered.

While federal regulations do not specifically speak to storage of NGLs, one reason provided in federal rule-making for regulating storage of natural gas are releases and explosions at NGL facilities. For instance, PHMSA describes an incident on April 7, 1992 when an uncontrolled release of NGLs near a salt cavern near Brenham, Texas formed a heavier-than-air gas cloud that exploded killing three people, injuring 21 people, and caused property damage in excess of $9 million (Federal Register 2020). The ignition of the approximately 30-foot gas cloud caused ground movement measuring 3.5 to 4.0 on the Richter scale (Bérest and Brouard, 2003).

NGL storage accidents have occurred elsewhere. For instance, in February, 1973, a blowout occurred in Elk City Oklahoma where several 30-ton boulders were lifted into an upright position and siltstone blocks weighing 50-100 pounds were thrown as a far as 75 feet from a (30 ft by 50 ft) by 20-foot deep crater. The crater was 2,300 feet (0.44 miles) from the NGL wellhead. During subsurface flow, liquid propane vaporized to a gas (Bérest et al. 2019). In another incident, in September, 1980 in Mont Belvieu, Texas, gas (70% ethane, 30% propane) accumulated in the foundation of a house causing an explosion and the evacuation of additional houses (Bérest and Brouard, 2003). Bérest et al. (2019) discuss other NGL cavern storage accidents elsewhere (e.g., Conway-Yoder Field, KS; Minoela, TX; Clute, TX). Hence, despite federal regulations not specifically speaking to storage of NGLs, storage of NGLs is not safer than storage of natural gas.

In a report contracted by Mountaineer NGL Storage LLC prepared by Civil & Environmental Consultants (CEC) (revised February 2018), it is stated that, *"In addition to the DOGRM UIC regulations, the salt caverns will be developed and operated as an underground natural gas storage facility in accordance with the PHMSA Interim Final Rule (IFR), published as 81 Federal Register 91860 Docket No. PHMSA–2016–0016, and the corresponding American Petroleum Institute's Recommended Practices (RP) 1170 for Design and Operation of Solution-mined Salt Caverns used for Natural Gas Storage."* This statement or an equivalent statement should have accompanied draft permits issued by the ODNR. A statement by a contractor for Mountaineer NGL Storage LLC does not obligate the Powhattan Salt Company to abide by API's Recommended Practices for solution mining. There is no language in the actual submitted permits or in ODNR's draft permits which indicate an intent to do so.

Adherence with these API documents is of critical importance because, as stated, there are no regulations in the State of Ohio specifically addressing NGL storage in caverns. API RPs 1170, 1171, and 1115 are fully integrated recommendations and mandates for well installation, solution mining and operation of natural gas and NGL storage facilities. Full integration of activities is necessary for the safe operation of underground NGL storage. This makes it critical that NGL storage be fully considered during solution mining.

A detailed review of permit applications submitted by the PSC for solution mining and ODNR's draft permits in three caverns to store natural gas liquids is provided in **Table 1**. Comments were submitted in the context of the requirement in the Ohio Administrative Code 1501:9, Chapter 1501:9-7 or stipulated requirements ("shall" statements) in API RP 1170, 1171, and 1115. Collectively, the deficiencies presented in **Table 1**, illustrate lack of due diligence and the need to integrate NGL storage in permit applications to ensure public safety.

Conclusion

In summary, for the drilling of wells, basic aspects of well design and solution mining are missing in permit applications. These issues raise concerns regarding due diligence in these permit applications. Given safety considerations for underground storage of an explosive, flammable product, we strongly recommend that ODNR require the operator to provide evidence of compliance with mandatory portions ("shall" statements) of API RP 1170, 1171, and 1115 in permit applications. Compliance with mandatory portions of API RP 1170, 1171, and 1115 in permit applications is critical because the State of Ohio does not have regulations specifically addressing underground storage of NGLs, creating the potential for an unacceptable regulatory void if ODNR does not ensure compliance in these permit applications. API recommended practices developed in these documents are based on years of research and practical operating experience by engineers and scientists in industry. Noncompliance with mandatory provisions in these documents would pose a significant public health risk to individuals living in and near Clarington, OH.

Table 1. Summary of recommended and stipulated elements of API Recommended Practices for storage of natural gas and NGLs in solution-mined salt caverns, ODNR requirements for solution mining permit applications, and ODNR response to Earthjustice/PSE comments

	Recommended for NGL Storage in API RP 1115	**Required for NGL Storage in API RP 1115**	**Recommended for Natural Gas Storage in API 1170 and 1171**	**Required for Natural Gas Storage in API 1170 and 1171**	**ODNR Requirements for Solution Mining Permit Applications**	**Earthjustice/PSE Healthy Energy Comments**	**ODNR Response to Comments**
Geological Characterization							
General Geologic Characterization	X		X		X	As stated in API RP 1170 and 1115, data used in a geologic site characterization should incorporate subregional and regional data from all readily available sources. ODNR regulations require a discussion of local geology in permit applications. From materials provided in the permit applications, there was either no attempt to do this or information gathered was not presented. Without these materials it is difficult to assess the suitability of the intended injection area for a structurally sound solution mined cavern. Carter et al. (2017) provided a conceptualization of the Salina Group relevant to the vicinity of the Mountaineer NGL facility (Figure 1). Overlying and underlying formations are illustrated in addition to variation in lithology in the Salina Group. The Salina Group consists of interbedded dolomite, anhydrite, shale, and halite. These layers are subdivided into seven stratigraphic intervals (units A–G). Halite is found with the B, D, E and F units, while anhydrites are found within the A, C and G units (Wickstrom et al 2008). The Salina F4 Salt is currently being solution-mined along the Ohio River and is the thickest salt within the Salina Group (Carter et al. 2017). However, a thin, persistent dolomite/anhydrite zone is present below the F4 Salt, with a second, but thinner, salt layer at the base. As stated in API RP 1170 and 1115, geologic maps should be used to assess and communicate geologic uncertainty. For bedded salt deposits, as is the case here, geologic maps generally emphasize stratigraphy, bed thickness, and lithologic controls on solubility and cavern stability similar to that illustrated by Carter et al. (2017). It is assumed that solution mining will be limited to the Salina F4 Salt because of the presence of laterally extensive dolomite/anhydrite layer at the base of the Salina F4 Salt. However, this should be explicitly stated in the permit applications. If the PSC intends on penetrating this layer, it should be	No response

						also be explicitly stated. At a minimum, the ODNR should require geologic maps in permit application packages that clearly illustrate targeted units.	
Geologic Characterization of the Salt Deposit	X		X		X	As stated in API RP 1170 and 1115, structure maps for both the top and base of the salt plus a salt isopach map should be developed for hydrocarbon storage. Again, ODNR regulations require a discussion of local geology that is lacking in permit application packages. Carter et al. (2017) mapped four areas along the Ohio River where the Salina F4 Salt is sufficiently thick (>100 feet) for NGL storage. Carter et al. (2017) state that developing salt caverns for NGL storage requires the identification of salt formations that are relatively "clean" and have adequate thicknesses to support both product storage and allow for residual insoluble materials that may accumulate at the base of the caverns over time. They explain that the presence of high-quality salt is preferred to maintain cavern integrity and eliminate the likelihood of weak zones and lateral migration pathways. Therefore, understanding lateral and vertical variability within the salt interval is important. There is a need to correlate interbedded dolomite or anhydrite within the salt. In the area closest to the Mountaineer NGL storage facility, the Salina F4 Salt appears to be less than 100 feet thick (Figure 2). The Salina F4 Salt isopach maps generated by Carter et al. (2017) illustrate net salt thicknesses interpreted to be entirely comprised of salt above a persistent dolomite or anhydrite zone and does not include the thickness of that zone or any salt below the dolomite or anhydrite zone. Mountaineer NGL Storage LLC drilled a test borehole having a lease name "Core Hole 1" with API Well Number 34-111-2-4666-00-00 that was plugged on 9/6/2016. The Well Completion Record (Form 8) indicated that the top and bottom of the "Salina Salt" at the borehole were at 6596 and 6738 feet respectively (thickness of 142 feet). However, it is unclear whether this thickness is for the Salina Formation or the Salina F4 Salt. Carter et al. (2017) prepared a west-east cross section using geophysical logs in the area of the Mountaineer NGL facility illustrating considerable thinning out of the Salina F4 Salt toward the Mountaineer NGL Facility (Figures 3 and 4). The ODNR should require clear mapping of halite units within the Salina Formation where caverns are to be installed in permit applications prior to approval in order to verify these units are able to remain structurally sound during solution mining and/or storage operations	No response
Characterization of overlying formations	X		X		X	In bedded salt deposits, overlying rock deposits usually have much greater porosity and permeability than rock salt (Liu et al. 2020b). Hence for product storage in bedded salt deposits, once a portion of the cavern roof is damaged, leakage of product is inevitable (Liu et al. 2020b). As stated in APR RP 1170 and 1115, an evaluation of solution mining for storage of natural gas or NGL should include an evaluation of overlying formations. Breach of a cavern roof or well integrity issues may result in migration of NGLs. Again, ODNR regulations require a discussion of local geology in a permit application. Geophysical logs which cut across the Burger Well proposed for geological sequestration of carbon dioxide indicate that the Bass Island Dolomite lies	Insufficient Response. The ODNR states that the Powhatan Salt Company LLC shall maintain a written record of any fluids encountered in the "Big Lime" section, and provide this information on the well completion record. As the "Big Lime" appears to be a driller's name for the Bass Island Dolomite (and other units of

						directly above the Silurian Salina Group (Wickstrom et al. 2008). Within many wells of eastern Ohio, this interval appears to consist of a carbonate breccia zone. Where observed as a breccia, this zone has very high porosity and permeability. Several brine-injection wells utilize this zone in Ohio, with reported injection rates as high as 37 gallons per minute. This interval has had little detailed study in the subsurface of eastern Ohio (Wickstrom et al. 2008). ODNR should require that overlying units and their associated integrity be discussed in permit applications. At the very least, this would ensure there is no possibility of brine migration from the solution mined formations to overlying formations.	the Salina Group), it appears that the ODNR wishes to acquire more information about this unit in an area where it is relatively under-characterized. However, there is still no requirement for Powhatan Salt Company to discuss the integrity of this unit against fluid migration.
Location of Nearby Faults	X		X			In the event of leak through casing or a cavern itself, a fault could facilitate transport of NGLs away from caverns. It appears that a 3D seismic study has been conducted (Eyermann 2017) with a noted absence of faults in the immediate area of the proposed caverns.	Addressed in permit applications
Area of Review	X		X		X	In determining the Area of Review (AOR), ODNR states that the following factors shall be taken into consideration: chemistry of injected and formation fluids, hydrogeology, population, groundwater use and dependence, and historical practices in the area. ODNR regulations require that for solution mining projects consisting of more than one well, an AOR shall be the project area plus a circumscribing area the width of which is not less than ¼-mile. PSC chose an AOR of ¼ mile but provided no justification for this distance. Permit application materials illustrate the AOR of the three proposed UIC wells. The horizontal lateral of CNX Gas Co well API 34-111-2-48-5 (Figure 5) is at the boundary of the AOR. This well is producing from the Point Pleasant Formation at a depth of 10,740 feet. The lateral lines of several oil and gas wells lie directly across the Ohio River in West Virginia (Figure 6). The producing depths of these wells could not be determined from the West Virginia Resource Management Plan Viewer. The Viewer just lists depths of wells as "<3,000 feet" and "deep." The area surrounding the Mountaineer NGL storage facility is one of intense surface and subsurface activity including underground mining (Figure 7). The presence of legacy mining activities and nearby hydraulic fracturing activity likely has altered the natural hydrogeological setting and warrants an expansion of the AOR beyond 0.25 mi to adequately constrain risks to nearby populations. Depending on subsurface temperature and pressure, NGLs can transition to a gas phase as well migrate as a liquid phase. In 2013, natural gas that migrated 1.5 miles from a hydraulic fracturing well (API 34111242560000) managed by Triad Hunter caused a gas blow out at the nearby #28 Brine Well (API 4705101381) at the Natrium plant in West Virginia. However, gas can migrate distances far greater than this distance from a leak in casing or from a cavern itself. This is best exemplified by a natural gas leak in the Yaggy Gas Storage Facility in Hutchinson, Kansas. The Yaggy field of salt caverns was originally developed in the 1980s for storage of propane. In 2001, a gas explosion and fire destroyed two buildings in Hutchinson and a	No response

						mobile home park more than 7 miles from the facility (Warren 2016). After the accident, poor regulation was incriminated as a causative factor by several experts (Berest and Brouard 2003). The Kansas Department of Health and Environment subsequently modified regulations including requirements for corrosion control and mandatory double casing in wells (Warren 2016). Also, the ongoing Washington County Produced Water Investigation highlights concerns about arbitrarily delineating a ¼-mile AOR. Produced water from the Redbird #4 Injection Well traveled at least 2000 feet vertically and over 5 miles laterally in the Ohio Shale prior to extraction of brine in wells producing from the Berea Sandstone. It is difficult to understand how ODNR could have permitted an injection well in a shale formation limited to secondary permeability in natural fractures. In this scenario, lack of matrix permeability and flow in fractures would have been expected, and did, travel extensive distances. A similar situation exists for NGL storage in salt. Matrix permeability in undisturbed halite is negligible. While halite is to some degree "self-healing", if product cycling or subsidence induces fractures in halite or surrounding limestone or dolostone, product migration would be extensive. It is recommended that the AOR be extended – the degree of which would be subject to additional technical evaluation.	
Wireline Logging for Lithology	X		X		X	Based on Figure 4 of Wickstrom et al. (2008), there do not appear to be wells with geophysical logs in the vicinity of the permitted areas. ODNR regulations for solution mining require that "appropriate" logs be conducted for new solution mines by a "knowledgeable" log analyst. As stated in APR RP 1170 and 1115, geophysical logs to support solution mining should include gamma ray, litho-density, compensated neutron, compensated sonic, dipole or array sonic, and caliper logs. These logs are also useful to characterize overlying strata. Extensive open-hole logging occurred in September 2016 in Core Hole 1. However, there is no description of this logging in the permit application, or more importantly, an explanation of the significance of these findings. It is unclear why this information was collected by the operator, and presumably interpreted by a trained geophysicist, but not included in the permit applications. ODNR should require an interpretation of geophysical logs in permit application packages. The interpretation of geophysical logs should include a discussion of subunits within the Salina Formation and delineation of the F4 Salt unit.	Insufficient response. The ODNR states that the Powhatan Salt Company LLC shall run at minimum, a gamma ray, compensated density-neutron, and resistivity geophysical log. Each log shall be submitted to the Division's UIC Section within 48 hours after the geophysical logging has been accomplished. The ODNR still does not require an interpretation of geophysical logs in permit application packages. The interpretation of geophysical logs should include a discussion of subunits within the Salina Formation and delineation of the F4 Salt unit.
Identification of base of a USDW.	X		X		X	API RP 1170 and 1115 recommend setting surface casing below the depth of the deepest Underground Source of Drinking Water (USDW). ODNR regulations for solution mining mandate protection of an USDW. API RP 1170 and 1115 recommends identification of the base of an USDW using spontaneous potential (SP) or resistivity logs. Resistivity logging was conducted on Core Hole 1 in September 2016 however the permit application	No response

						provides no description of the base of USDWs. According to ODNR regulations, the operator must determine the base of the lowest USDW in the area and provide evidence of this determination to the ODNR. This basic regulatory requirement was not addressed in permit applications.	
Wireline logging for Mineralogy	X		X			As discussed in API RP 1170 and 1115, wireline logging could provide insight on salt purity, non-salt stringers or interbeds, and the presence of potassium – magnesium (K-Mg) salts that are highly soluble and creep prone. As previously discussed, there is no interpretation of geophysical logs in permit applications. Bedded salt is more likely to enclose layered intrasalt beds with varying levers of solubility and fracture intensity (Warren 2016) that affect cavern shape during solution mining and potential loss of fluids in caverns during storage, thus posing a risk to cavern stability and impermeability.	No response
Population relying on USDW for drinking water source					X	ODNR regulations require a description of the population relying on USDWs for a drinking water source and the proximity of injection points to withdrawal of drinking water in the project area. This information appears to be required irrespective of whether drinking water wells are within combined AORs and is lacking in permit applications. There are three water supply wells serving the City of Clarington southwest of the Mountaineer NGL Storage outside the AOR (Figure 8). Well No 367285 is 76 feet deep and screened in limestone. Well No. 416051 is 70 feet deep and screened in sand and gravel. Well No. 361434 is 70 feet deep and screened in sand and gravel.	No response
Core Data to Support Geological and Mineralogical Characterization	X		X			Halite (NaCl) masses typically contain thinner intercalated layers, composed either of less soluble salts such as anhydrite ($CaSO_4$) or dolomite ($CaMg(CO_3)_2$), or more soluble salts, such as carnallite ($KClMgCl_2 \cdot 6(H_2O)$) or bischofite ($MgCl_2 \cdot 6(H_2O)$) (Warren 2016). With less soluble salt layers intersecting a cavern edge there is a tendency to form unsupported ledges and bevels which eventually collapse to the floor of the expanding cavity. This can damage the roof in the vicinity of the feeder pipe or break the drill string. In the case of more soluble beds, their rapid solution can leave behind blocks of unstable halite, which have a propensity for collapse, or can lead to cavity shapes that become enlarged in one direction and encroach on the structural integrity of the well design, especially when there are adjacent solution cavities (Warren 2016) as is the case here. API RP 1170 and 1115 recommend that estimates of the insoluble percentage in the salt mass be determined from core samples and open-hole logs during the drilling phase. Two pairs of samples were cut from cores collected from Core Hole 1. One sample was retrieved from the "middle of the upper salt zone (6,598 feet to 6,688 feet)" (90-foot salt section) and another sample from the middle of the "lower salt zone (6,708 feet to 6,738 feet)" (30-foot salt section). Is the upper "salt zone" the Salina F4 Salt? If so, PSC should explicitly state so. These cores do not address the mineralogy of the 20-foot depth interval between 6,688 feet to 6,708 feet. It is possible that this 20-foot depth interval represents a non-salt dolomite/anhydrite layer. What is the "lower salt zone"	No response

						below this layer? It is unclear from the permit materials how the operator will address a non-salt layer in the cavern design. This ambiguity directly results from the lack of geologic documents, and absence of any discussion of cavern design/geometry in the permit materials. Insoluble residue tests were conducted. The first core contained 2.48% insoluble residue consisting of anhydrite (78%), dolomite (20%), and quartz (2%). The second core contained 0.74% insoluble residue consisting of anhydrite (77.6%), dolomite (17.4%), and quartz (5.0%).	
Geomechanical Testing							
Core Data		X		X		As stated in API RP 1170 and 1115, core test data provide the geomechanical properties of salt and key units that are input into geomechanical models used to evaluate cavern stability, subsidence, and the operating pressures of storage caverns. API RP 1170 and 1115 require that cores be collected to evaluate elastic and strength properties of salt and non-salt deposits and creep of salt deposits. API RP 1170 and 1115 recommend that sufficient core should be cut to sample key lithologic units and interbeds in salt. Cylindrical specimens of salt and non-salt samples must be prepared for testing with procedures that meet or exceeds ASTM D4543. If a Brazilian indirect tension test is performed, it must be performed in a manner that meets or exceeds ASTM D3967. Triaxial compression tests must be performed in a manner that meets or exceeds ASTM D7012. A triaxial creep test must be performed in a manner that meets or exceeds ASTM D7070. At least three triaxial creep tests should be performed on similar salt specimens at different effective stresses to define creep response as a function of effective stress. There is no evidence that cores were collected during installation of Core Hole 1 for mechanical integrity testing nor indication that cores will be collected during well installation. The ODNR should require collection of cores for mechanical testing during installation of caverns with an interpretation of tests provided by a geotechnical engineer.	No response
In Situ Temperature	X		X			API RP 1170 and 1115 recommend the use of a temperature log in a borehole after drilling is completed to establish the in-situ distribution of temperature. Temperature logging should be delayed as long as possible (at least 3 to 5 days) to allow temperature equilibrium. Salt creep increases with temperature rise. It does not appear that use of a temperature log is planned.	No response
In Situ Stress		X		X	X	As stated in API RP 1170 and 1115, it is generally accepted that stress in salt units and non-salt units is isotropic and anisotropic, respectively. If reliable regional estimates of in situ stress are not available, the horizontal components of in situ stress should be established by hydraulic fracturing tests in non-salt units. Minifrac tests should be performed and interpretated with a procedure that meets or exceeds ASTM D4645. ODNR regulations also require estimation of the fracture gradient to ensure that injection does not initiate fractures. The operator states that the lithologic pressure was estimated at 6490 psig at a depth of 5470 feet with hydraulic fracture pressure estimated in the range of 9090 to 9640 psig at this depth. The	

						operator should review requirements for in situ stress estimation in API RP 1170 and 1115 and provide a written explanation to the ODNR demonstrating full compliance with this requirement.	
Geomechanical Modeling	X		X			API RP 1170 and 1115 recommend the use of numerical models that represent the geometries of caverns, their development history, operating conditions during gas or NGL storage, the geologic structure around the caverns, the mechanical properties of salt and nonsalt units, and preexisting conditions. The objective of numerical modeling is to determine key parameters to maintain the structural stability and mechanical integrity of the caverns. Geomechanical modeling should be performed to evaluate the effect of pressure cycling, brine compensation, and salt creep. It does not appear that geomechanical modeling is planned for this facility.	No response
Wellbore Installation and Design							
Drilling in Salt		X		X		Due to salt dissolution, API RP 1170 and 1115 stipulate use of a salt saturated solution when drilling through halite that will constitute part of the roof of a cavern. Chloride concentrations in drilling mud should be representative of saturated conditions when drilling through halite. Nonaqueous drilling fluids can also be utilized if highly soluble magnesium or potassium salt stringers are present. There is no discussion in the permit application regarding drilling methods. The operator should include a discussion of use of drilling fluids in the permit application.	No response
Lost Circulation	X		X			As discussed in API RP 1170 and 1115, lost circulation during drilling can result in loss of borehole stability, loss of pressure control, and in severe instances, loss of the well. API RP 1170 and 1115 recommend that operators prepare a detailed lost circulation plan prior to drilling to ensure a timely response. This is especially important given the proximity and history of subsurface mining activities in the area. A lost circulation plan was not submitted with the permit application.	No response
Borehole Diameters	X		X			API RP 1170 and 1115 recommend that borehole diameters be adequate for proper placement of cement in annuli and must be cemented to the surface. For large diameter casing used for cavern storage, borehole diameter should be at least 6 inches greater than the diameter of the next inner casing. From provided borehole schematics, 30-inch diameter surface casing will be placed within a 36-inch borehole; 20-inch intermediate casing will be placed within a 28-inch borehole; 16-inch contingency casing will be placed within a 20-inch borehole; and 13.375-inch casing will be placed within a 17.5-inch borehole. In terms of well integrity, the last cemented casing string is the most important since it comes in direct contact with product. In this case, where competent cement outside casing is most critical, there is only a 4.125-inch difference between the casing and borehole diameter resulting in only 2.06-inch annular space. ODNR should require greater annular space in this last casing string.	Insufficient response. ODNR states that Powhatan Salt Company LLC shall install 13-3/8-inch diameter casing in a 17½-inch borehole to a depth of approximately 6650 feet and cemented to the surface. Hence, no change to casing and borehole diameter in the lowest most string have been made.
Open-Hole Caliper Logs		X		X		API RP 1170 and 1115 stipulate than an excess cement volume be determined following an evaluation using an open-hole caliper log. There is	No response

						no indication in the permit applications that open-hole caliper logs will be utilized.	
Depth of Surface Casing	X		X		X	ODNR regulations require that surface casing must be at least 50 feet below the lowest USDW. Borehole schematics indicate surface casing to 340 feet. ODNR regulations mandate protection of USDWs. Evidence needs to be provided that this depth is below the deepest USDW.	Insufficient response. ODNR states that Powhatan Salt Company LLC shall: (1) install 30-inch diameter surface casing in a 36-inch diameter borehole to a depth of approximately 340 feet and cemented to the surface. No evidence is presented that this depth is below the deepest USDW.
Cement Outside Surface Casing		X		X	X	API RP 1170 and 1115 and ODNR regulations mandate that surface casing be cemented to the surface. The borehole schematic indicates that surface casing will be cemented to the surface.	Addressed in the permit applications
Collapse Strength of Surface Casing		X		X		API RP 1170 and 1115 require calculation of collapse strength of surface casing and pressures encountered during cementing of surface casing be calculated to ensure that the collapse strength of surface casing will not be exceeded. These calculations are not present in the permit application. The operator should provide these calculations to the ODNR.	No response
Cement Outside Intermediate Casing		X		X		API RP 1170 and 1115 require that if practical, intermediate casing be cemented to the surface. The borehole schematic indicates that intermediate and contingency casing will be cemented to the surface.	Addressed in the permit applications
Collapse and Burst Strength of Intermediate Casing		X		X		API RP 1170 and 1115 require that pressures encountered during cementing of intermediate casing be calculated to ensure that the collapse strength of casing will not be exceeded during cementing. Burst design for the top of intermediate casing must be based on the maximum operating pressure without allowance for pressure containment due to the cement sheath or hydrostatic head outside casing. Collapse strength at the bottom of casing must be based at a minimum on the cementing differential pressure to be encountered. Calculations of collapse and burst strength of intermediate casing are not provided in the permit application. The operator should provide these calculations to the ODNR.	No response
Cement Outside Production Casing	X		X			API RP 1170 and 1115 recommend when practical, production casing should be cemented with salt-saturated materials in halite and then cemented to the surface. The borehole schematic indicates that production casing will be cemented to the surface. However, the nature of materials is not described.	No response
Depth of Production Casing		X		X		API RP 1170 and 1115 require that production casing should be set below top of salt. If production casing is set above the salt, the rock forming the cavern roof must be nonporous and impermeable. The borehole schematics indicate that production casing will be set within salt.	Addressed in the permit applications
Pressure Testing of Production Casing Shoe		X		X		API RP 1170 and 1115 require that production casing be pressure tested before drilling out the plug or shoe. At least 10 feet of the salt below the casing shoe must be penetrated prior to the test. A minimum of 95% of the 120-hr compressive strength of cement should be achieved prior to pressure	Addressed in the permit applications

						testing. The test pressure at a minimum must be the maximum operating pressure but not exceed the yield pressure of the casing. The pressure should be maintained a minimum of 30 minutes. In the permit application, both the top of salt and production casing are estimated at 6600 feet while the illustration indicates that the casing is below the top of salt. In the permit application, it is stated that the production casing will be tested 24 to 96 hours after cementing by pressurizing the well to 75% of the calculated fracture pressure at the shoe, holding for one hour with less than 5% pressure loss.	
Collapse and Burst Design of Production Casing		X		X		API 1170 and 1115 require that burst strength of production casing be calculated using the maximum operating pressure or mechanical integrity testing (MIT) pressure without allowance for pressure containment due to the cement sheath or hydrostatic pressure outside of casing. The collapse strength should be based on full lithostatic load externally and atmospheric pressure internally. Calculations of collapse and burst strength of production casing are not included in permit applications. The operator should provide these calculations to the ODNR.	No response
Production Casing Logs	X		X			API 1170 and 1115 recommend utilization of a casing inspection log which uses either magnetic flux leakage or ultrasonic measurements to establish the production casing's wall thickness for future comparison to evaluate corrosion. There is no discussion in the permit application packages to monitor production casing thickness.	No response
Cement Application		X		X		API RP 1170 and 1115 stipulates that cement quality and testing meet or exceed API 10A and API 10F, respectively. API RP 1170 and 1115 recommend that laboratory testing be conducted on all proposed cements and actual mix water. Non-salt-saturated cements should include tests for 24-, 48-, and 72-hour compressive strengths at temperatures expected in the borehole. Salt-saturated cements used in halite should include tests for 24-, 48-, and 120-hour compressive tests at temperatures expected. No laboratory testing of cement mixtures is planned in the permit application. The operator should be required to submit a cement application plan to the ODNR.	No response
Casing Centralization		X		X	X	API RP 1170 and 1115 stipulates casing centralization to achieve proper placement of cement around casing. ODNR regulations on solution mining state that the Chief may require the use of centralizers on intermediate and production or long string casing. Centralizers are routinely used to center casing prior to cement application. However, in the absence of submittal of a drilling plan which should explicitly address this issue, it cannot be assumed that centralizers will be utilized.	Sufficient response. ODNR states that bow-string or rigid centralizers shall be used to provide sufficient casing standoff and faster effective circulation of cement to isolate critical zones including aquifers, flow zones, voids, loss circulation zones, and hydrocarbon bearing zones.
Spacers and Flushes	X		X			API RP 1170 and 1115 recommend the use of spacers and flushes ahead of the cement slurry to displace drilling fluids. Although this is common practice when installation oil and gas wells, a drilling plan was not submitted with the permit application specifying the use of spacers and flushes.	No response

Cement Evaluation Logs	X		X		X	API RP 1170 and 1115 recommend the use of cement evaluation tools to evaluate integrity of cement outside casing. ODNR regulations require use of a cement bond log or other log required by the chief to verify cement coverage outside production casing. The permit application states that a cement bond log will be run outside casing strings to verify cement integrity.	Addressed in permit applications. ODNR states that a cement bond log shall be run after the cementing of the 20-inch casing and the 13-3/8-inch casing. The cement bond log tool, at a minimum, shall be centralized and consist of a combination of an amplitude, variable density log (VDL)-time of travel bond curve.
Solution Well Mechanical Integrity Testing					X	ODNR regulations require mechanical integrity testing every five years. In its regulations, it is unclear whether ODNR requires mechanical integrity testing at the end of well construction prior to commencement of solution mining. This issue is of direct concern to the general public and thus should be included in the permit submission materials, so the public can have the opportunity to comment during the comment period. ODNR regulations state that, a solution mining well has mechanical integrity if: (1) There is no significant leak in the casing, tubing, or packer: and (2) There is no significant fluid movement into an underground source of drinking water through vertical channels adjacent to the well-bore.” One of the following methods shall be used to evaluate the absence of significant leaks in casing, tubing, or a packer: (1) monitoring of annulus pressure; or (2) pressure test with liquid or gas; or (3) a freshwater-brine interface test. One of the following methods may be used to detect fluid movement adjacent to the wellbore; (1) results of a temperature, noise, or cement bond log, (2) when solution well preclude the use of logs, use of cementing records demonstrating the presence of adequate cement to prevent fluid migration, and (3) if cementing records are used to evaluate fluid movement adjacent to the borehole procedures applicable to section 1501:9-7-09 for operation, monitoring, reporting, and recordkeeping are to be utilized.	Insufficient response. The ODNR states that each cemented casing shall be pressure tested in accordance with Ohio Adm.Code 1501:9-1-08(D)(3)(b) or pressure tested to at least 500 psi for 15 minutes with not more than 5% decline in pressure, whichever is at a greater pressure. The maximum operating pressure during solution mining specified in the original permit application was 1150 psig which is significantly greater than testing pressure. ODNR does not explicitly state the timing of mechanical integrity testing. Planned mechanical integrity testing does not address external (outside the casing) integrity.
Casing Seat Integrity Test	X		X			API RP 1170 and 1115 recommend that a casing seat integrity test be conducted after drilling and well completion but before solution mining. The test should be run at maximum allowable operating pressure (MAOP) and conducted with nitrogen or other nonmiscible gases or fluids. The permit application does not include a casing seat integrity test prior to solution mining.	No response
Solution Mining Operations							
Solution Model		X		X		API RP 1170 and 1115 stipulate the use of a solution mining model for the design and during the development of at least the first cavern. The solution mining model should be used to predict the geometries of the cavern shape during the phases of cavern development. A solution mining model should also be used to determine if and when cavern workovers may be required to shift the setting depths of the hanging strings to create the desired cavern shape. As stated in API RP 2270 and 1115, the solution mining model should	No Response

						be seen as a starting point for cavern development. Once solution mining starts, comparisons should be made to actual mining results. PSC should submit the results of solution modeling to support permit applications.	
Cavern Neck	X		X			As stated in API 1170 and 1115, the distance from the bottom of cemented casing to the cavern roof should be sufficient to prevent roof strains from affecting the integrity of the cemented casing and casing connections. Proper design of the uncased wellbore section and the cavern roof mitigates the stress and creep strain placed on the casing salt and casing connections, reducing the risk of casing damage or loss of integrity in the cement bond at the casing seat. API RP 1170 and 1115 recommend that the cavern neck (casing seat to cavern roof) be greater than one-half the diameter of the predicted, fully developed cavern. There is no description of the design of the cavern neck in permit applications. The operator should provide the ODNR with a description of proposed cavern necks.	No response
Cavern Roof and Blanket Monitoring		X		X		A salt roof must be left between the cavern top and the overburden to prevent weathering of the overburden (Bèrest 2017). As stated in API RP 1170 and 1115, during solution mining, it is critical that the roof of a cavern is prevented from dissolving (and thus compromising cavern stability) by placing and floating a blanket material which does not dissolve salt. After the roof is developed, API RP 1170 and 1115 stipulate that the blanket-water interface be periodically monitored with an interface log or similar method. During cavern excavation, the volume of the blanket is increased or decreased to help shape the cavity and prevent uncontrolled dissolution at the top of the cavern potentially leading to caverns having a much wider top than base which is structurally undesirable. Regulatory agencies generally now require that an adequate salt roof be maintained above caverns with downhole wireline logging (e.g. sonar) to periodically check the shape and sizes of caverns (Warren 2016). The permit applications indicate that a nitrogen blanket will be used to protect cavern roofs but there is no discussion of blanket monitoring. This is critical to maintain the roof of a salt cavern and should be included in permit applications even if product storage was not taking place. This discussion should be included with the permitting materials to ensure the structural integrity of the salt cavern will not compromised.	No response
Cavern Shape Monitoring		X		X		The presence of non-salt interlayers greatly increases the difficulty of cavern construction. Because of vertical and lateral stratigraphic variability in bedded salt deposits, it is difficult to construct caverns with regular shapes (Liu et al. 2020a, b) resulting in less reliable product storage compared to salt domes common along the Gulf Coast (Warren 2016). The most stable cavern shape for product storage resembles a giant carrot or cucumber embedded deep in a mass of salt. This ideal shape is impossible in bedded salt (Warren 2016). If a cavern has an irregular shape, stress concentrations and large deformations may appear in the wall rock which greatly increase the probability of failure necessitating more rigorous monitoring compared to	Sufficient response. ODNR states that beginning one year after commencement of solution mining operations and on or before December 1 every other year thereafter, Powhatan Salt Company LLC (Powhatan Salt) shall determine the boundaries of the solution mined caverns and voids associated with all three wells.

						salt domes (Liu et al. 2020a). In order to reduce the deformation of the wall rock, the roof of caverns must be designed as an arch (Liu et al. 2020a). Most solution-mined salt cavern collapses have been caused by roof instability and have resulted in subsequent brine leakage (Liu et al. 2020a). API RP 1170 and 1115 stipulate the use of periodic interface logs, such as sonar surveys to be performed to confirm the desired shape and volume of caverns during solution mining. Logically, a sonar survey should be performed at the end of solution mining. Maximum stability is achieved with a spherical cavern. However, an inverted cone shape with an arched roof is generally considered an acceptable alternative. Sonar surveys are not included in permit applications. Sonar surveys are critical in evaluating the shape of caverns during solution mining and should be included as a requirement in permit applications. Sonar surveys should be included with permit materials to monitor cavern geometry and eliminate possible subsidence risks.	ODNR states that Powhatan Salt shall submit a report, on or before December 1 each year the report is required, to the Division showing the boundaries of the solution mined caverns and voids associated with the Powhatan Salt Company LLC wells and describe the details of how the boundary determinations were made. Before determining the boundaries, Powhatan Salt shall submit in writing to, and obtain the approval of, the Division the method used to determine the boundaries. In addition, Powhatan Salt shall submit any documents necessary to substantiate the owner's legal right to conduct solution mining activities. The ODNR does not specify the use of sonar surveys but this requirement appears to satisfy cavern shape monitoring.
Pillar Distance	X		X			API RP 1170 and 1115 recommend that a P:D ratio greater than 1:1 where P equals the distance between two cavern boundaries and D equals the average of the maximum diameter of the two caverns. As stated in API RP 1170 and 1115, industry experience has shown that pillar widths of two to three times the average maximum diameter of adjacent caverns have satisfied mechanical modeling evaluations to determine safe cavern spacing for given pressure and operating scenarios. During the initial application process, there was concern of potential cavern interference between the proposed PSC caverns and existing caverns of the Westlake Facility in West Virginia. A conservative estimate of the long axis of caverns at the Westlake facility is 12,000 feet placing the northern extent of the cavity 1300 feet northwest of the northern most well (Eyermann 2017). The average width of the combined Field 1 and 3 caverns at the Westlake Facility is ~860 feet. The current distance between the Westlake caverns and the proposed PSC caverns is 11,600 feet with the Westlake caverns moving northward toward the PSC caverns at a rate ~ 16 feet/year. Based on this analysis, Eyermann (2017) concluded that the Westlake and PSC caverns could safely operate for 700 years. However, assuming that D = 860/2 or 430 feet for the Westlake caverns, a safe operating distance of 860 or 1290 feet is necessary for a P:D ratio of 2 to 3. Hence, in the absence of preferential pathways, there appears to be sufficient distance between the PSC and Westlake caverns. Of greater	No response

						concern is pillar spacing between caverns at the PSC facility itself. The permit applications do not include a discussion of planned P:D ratios or pillar space at all. Eyermann (2017) states that the average diameter of caverns at the PSC facility will be 300 feet. Hence, there must be a least 300 feet but preferably 600 to 900 feet of spacing between caverns. Using an approximate (mapping in ArcGIS) cavern diameter of 300 feet, it appears that spacing between neighboring caverns will be approximately 160 to 180 feet (P:D ratios of 0.53 and 0.60, respectively) (Figure 9). Thus, from this estimation, pillar distances between salt cavern 1 and salt cavern 2 and salt cavern 2 and salt cavern 3 do not appear to be sufficient. As such, information on anticipated pillar distances should be provided to the ODNR. If possible, geomechanical modeling should be used to determine adequate salt thickness between caverns.	
Separation Distance	X		X			API RP 1170 and 1115 recommend a S:D ratio greater than 2:1 where S equals the separation distance between the centers of two adjacent caverns and D equals the average of the maximum diameter of the two caverns. According to the permit materials, the distance between the centers of salt cavern 1 and salt cavern 2 and salt cavern 2 and salt cavern 3 appear to be 778 and 769 feet, respectively using ArcGIS. Thus, the S:D ratios for these caverns (~2.6) appear to satisfy the recommendations of API RP 1170 and 1115. However, permit applications do not include a discussion of S:D ratios.	No response
Source Water and Brine Monitoring		X		X		API RP 1170 and 1115 stipulate that the operator to measure the rate and salinity of water entering and brine leaving the cavern. This facilitates calculation of the volume and efficiency of the solution-mining process source water and resultant brine enables estimation of cavern growth. The brine should be checked for minerals, including the percentage of NaCL, KCL, and $MgCl_2$. Higher solubility salts KCl and $MgCl_2$ can undercut upper strata and cause strain or collapse. Permit applications indicate the water used for debrining will be sampled and analyzed quarterly. Brine will be sampled twice per day for specific gravity. The daily brine samples will be consolidated for more detailed chemical analysis on a monthly basis. In the permit applications, chemical analysis is presented for the source water which is the Ohio River, however the data presented generates both concerns and questions. Specifically, the concentration of arsenic is provided as 100 ppm (mg/L). This arsenic concentration is several orders of magnitude higher than nearby water quality measurements made by the U.S. Geological Survey. Measurements made at a station on the Ohio River (site number 395516080451501) on November 7, 2019 indicate an arsenic concentration of 0.46 ppb (µg/L). Hence, it is highly unlikely that the Ohio River has arsenic concentrations at 100 mg/L. If the units of this concentration were misreported as ppm, with the measured concentration being 100 ppb (µg/L) instead of 100 ppm, this concentration would still be exceeding high. This appears to be an example of sloppy reporting. Other elements are given in concentrations of GPL (grams per liter, grains per liter?). Grains per liter is a	No response

						measure of hardness. PSC should resubmit a table summarizing the quality of water that will be used for solution mining.	
Average and Maximum Injection Pressures					X	The ODNR requires specification of average and maximum injection pressures. The operator specified average and maximum pressures of 950 and 1150 psig, respectively. Are these pressures at the casing shoe or the surface? During solution mining there will likely be significant frictional head loss associated with movement down casing.	No response
Manifold Monitoring					X	ODNR regulations state that "solution mining projects may be monitored on a field or project basis, rather than an individual well basis, by manifold monitoring when such projects consist of more than one injection well, operating with a common manifold." It is unclear from the permit application packages whether injection at three solution mining wells will occur from a common manifold. Monitoring the solution mining process from a common manifold is incompatible with the rigor required for solution mining for utilization of NGL storage and at least for cavern roof and blanket monitoring is incompatible with requirements in API RP 1170 and 1115. PSC should make it clear in their applications that caverns will be monitored on an individual well basis.	No response
Workover Prior to Natural Gas Liquid Storage							
Inspection of Production Casing		X		X		API RP 1170 and 1115 stipulate inspection of production casing prior to natural gas or NGL storage. Wireline logs should be run that measure wall thickness, ovality, and internal/external anomalies. Since permit applications do not consider storage of product, permit applications do not include a discussion of a workover to configure the cavern for product storage including inspection of production casing. There does not appear to be another time when this would take place, creating an unacceptable regulatory void that could jeopardize public health and safety	No response
Full-Cavern Sonar Survey		X		X		API RP 1170 and 1115 stipulate running a full-cavern sonar survey to make a final verification of cavern geometries (shape, size, depths) and to ensure that there are no spatial features that could limit cavern storage. Since permit applications do not consider storage of product, the permit applications do not include full-cavern surveys prior to NGL storage. Again, there does not appear to be another time when this would take place, creating an unacceptable regulatory void that could jeopardize public health and safety	Sufficient response. ODNR states that beginning one year after commencement of solution mining operations and on or before December 1 every other year thereafter, Powhatan Salt Company LLC (Powhatan Salt) shall determine the boundaries of the solution mined caverns and voids associated with all three wells. ODNR states that Powhatan Salt shall submit a report, on or before December 1 each year the report is required, to the Division showing the boundaries of the solution mined caverns and voids associated with the Powhatan Salt

							Company LLC wells and describe the details of how the boundary determinations were made. Before determining the boundaries, Powhatan Salt shall submit in writing to, and obtain the approval of, the Division the method used to determine the boundaries. In addition, Powhatan Salt shall submit any documents necessary to substantiate the owner’s legal right to conduct solution mining activities. The ODNR does not specify the use of sonar surveys but this requirement appears to satisfy cavern shape monitoring.
Brine Strings		X		X		API RP 1170 and 1115 stipulate that brine strings of unknown quality cannot be used. The brine string should be new pipe with complete documentation. The use of new pipe for brine strings is not specified in permit applications. ODNR should require documentation demonstrating that new pipe will be used.	No response
Cavern MIT		X		X		API RP 1170 and 1115 stipulate that a cavern mechanical integrity test (MIT) be performed prior to being put in service. The test may be a nitrogen/brine interface test or an alternative equivalent test. ODNR regulations discuss requirements for MIT testing on well casing, not caverns, every five years. Since permit applications do not consider storage of product, a cavern MIT is not included in the permit applications. Again, there does not appear to be another time when this would take place, creating an unacceptable regulatory void that could jeopardize public health and safety.	No response
Operation							
Operating Flows for Product Storage					X	As in the CEC 2018 report, the site is planned to provide approximately 2 million barrels (bbls) of baseline storage capacity, with at least 25,000 bbls per day of load-in and load-out. Each storage well will have the capacity to separately store a minimum of 300,000 bbls.	Insufficient response. This information is presented in a support document not submitted in permit application packages. Verification of operating flows and product storage volumes should be required by the ODNR.
Operating Pressures for Product Storage		X			X	API RP 1170 and 1115 stipulate conversion of maximum and minimum operating pressures at the casing to the wellhead due to frictional head loss during operation. ODNR regulations require injection pressure and flow rate to be monitored on a semi-monthly basis unless daily metering of injected fluids is monitored. In the permit applications, it is stated that brine production and water injection volumes, flow rates and pressures will be recorded continuously in the control room. However, there is no description	No response

						of pressure and flow monitoring frequency or methodology of natural gas liquids in the permit application. This is a fundamental public safety consideration. Operating pressures for NGL storage should be specified in permit applications.	
Analysis of Injected Fluids					X	ODNR regulations require specification of the “nature” of the injected fluid. ODNR states that the nature of injected fluids must be monitored quarterly to yield representative data. ODNR also requires qualitative analysis and ranges in concentrations of all constituents of injected fluids unless the applicant requests confidentiality. Sample analysis of water to be used for debrining has been provided. There are no plans in the permit application for sampling or analysis of natural gas liquids to be injected.	No response
ESD Equipment and Procedures		X		X		Due to reduced compressibility but relatively low density of NGLs and immiscibility with water, caverns are operated by a brine compensation mechanism. As brine is injected through a central tube at the bottom of the cavern, an equivalent volume of produce is withdrawn through the annular space between the steel cemented casing and a central brine tube. For storage of NGLs, failure of an emergency shutdown (ESD) value would result in expulsion of NGLs in a liquid form. This liquid would evaporate on the ground surface and form a gas cloud denser than air. Accidental ignition of this gas would then result in an explosion as was the case in Brenham, Texas in 1992 killing 3 and injuring 21 people. This accident prompted the Texas Railroad Commission to mandate that NGL storage cavities by protected by a least two overfill detection and automatic shut-in methods (Warren 2016). API RP 115 stipulates that each outlet must have an emergency shutdown (ESD) valve (fail-close) installed adjacent to manual valves (wing valves). Each cavern must have an ESD system installed to isolate a cavern and wellhead from any attached piping in an emergency. ESD systems must be periodically tested to ensure that they perform as intended in the event of an emergency. Operators must develop emergency response plans to provide for the safe control or shutdown of a storage facility in the event of failure of other emergency conditions. Emergency shutdown procedures are not outlined in the permit application.	No response
Overpressure Monitoring	X		X			API RP 1170 and 1115 recommend that the pressure in a cavern be monitored at all times to ensure that the production casing shoe maximum pressure is not exceeded. Continuous pressure measurement during NGL storage is not outlined in the permit application.	No response
Bradenhead Monitoring	X		X			API RP 1170 and 1115 recommend that the cemented annulus between production casing and the next cemented casing should be monitored for pressure. Pressure increases could indicate a leak in production casing or a micro-annulus leak through cement from a cavern. Bradenhead monitoring should be standard in any NGL or gas storage operation and is not included in the permit applications.	No response

Contingency for Flooding						As illustrated in Figure 5, all 3 salt solution mining wells are within a 100-year floodplain. The operator needs to specify what contingencies are necessary in the event of flooding.	No response
Cavern Integrity Monitoring							
Cavern Integrity Monitoring Program		X		X		API 1170, 1171, and 1115 require that the integrity of the well and salt cavern system must be maintained and monitored. Once in operation and throughout its life, a cavern system must be monitored to ensure functional integrity. There must be a formal written integrity monitoring program that must contain, at a minimum, the following components: (1) identification of cavern system components to be monitored; (2) monitoring methods specifying the type of method and frequency of application; (3) cavern volume and growth monitoring; (4) analysis of data from inspections, reporting, and archiving of results; (5) periodic reviews of the monitoring program for effectiveness; and (6) subsidence monitoring. The permit application does not contain a formal written integrity monitoring program. This is absolutely critical for safe operation of NGL storage. PSC must include a cavern integrity monitoring program in permit applications or describe when a cavern integrity monitoring program will be provided to the ODNR.	No Response
Cavern Shape Monitoring		X		X		API 1170, 1171, and 1115 require cavern shape monitoring. This is especially important for NGL storage. Brine pumped into a cavern to compensate for displaced product must be less than saturated with respect to halite. While this prevents salt crystallization in access casing, it also leaches additional salt from cavern walls. Hence, regular product cycling using brine compensation increases the size of salt caverns necessitating the need for continual monitoring of cavern shape throughout the life of a facility (Warren 2016). Salt creep appears to be less critical for NGL storage compared to gas storage so volume loss over time is less of a concern (Warren 2016). Salt acts like a non-Newtonian fluid that will flow in response to deviatoric stress (Habibi, 2019). Some older salt caverns in the USA and Canada are now twice as large as when they were first filled due to brine compensation (Warren 2016). Uncontrolled enlargement of a storage cavern can evolve into a stability problem as the retreating salt roof and walls are increasingly susceptible to sloughing, caving, fusion, and associated damage to long string casing. As a result of numerous collapses, the State of Kansas now requires caverns created by solution wells to be acoustically monitored and a salt roof of at least 40 feet to be maintained (Warren 2016). Cavern expansion has led to accidents as some NGL storage facilities such as at Mineola, Texas in 1995. A subsurface blowout occurred when a salt wall separating two storage caverns storing propane had become so thin from enlargement due to brine compensation and product cycling that it cracked (Warren 2016). Pressure buildup led to a casing leak with escape of propane through soil as far as 100 feet from the well which ignited requiring an innovative well technique to extinguish the fire. This prompted the Texas	No response. The ODNR has now mandated cavern shape monitoring during and after solution mining but they do not directly specify the lifespan of this monitoring, and if it will continue during NGL storage operation.

						Railroad Commission to require an "acceptable" degree of enlargement prior to abandonment of a salt storage cavern (Warren 2016). PSC must include a cavern shape monitoring program in permit applications or describe when a cavern shape monitoring plan will be provided to the ODNR.	
Subsidence Monitoring		X			X	Some degree of subsidence of the land surface above a cavern is expected. From a storage perspective, subsidence is not a problem unless the roof span breaches and the rate of subsidence increases (Warren 2016). Responsible operators now conduct periodic or continuous subsidence monitoring to determine the rate of subsidence (Warren 2016). Automated subsidence monitoring is justified when there is a significant risk of environmental or property damage or when facilities are in close proximity to pipelines and other infrastructure (Warren 2016) as is the case here. ODNR regulations require a "brief description of existing or proposed monument grids and surveying method to be used in obtaining yearly measurements of second order accuracy for the detection of ground surface movement." ODNR requires that the permit applicant "describe monument types, construction, and emplacement."	Addressed in permit applications.
Groundwater Monitoring							
Installation of Monitoring Wells					X	The ODNR requires submittal of plans for meeting monitoring requirements for an USDW. The ODNR also requires installation of monitoring wells outside the physical influence of subsidence or potential catastrophic collapse. Since the installation of caverns will result in some level of subsidence at the ground surface, this should trigger a requirement for the installation of monitoring wells. Seven groundwater monitoring wells are installed along the southeast side of the proposed impoundment to store brine between March 21-27, 2018. While there is a mention of several observation wells that will be drilled by an affiliate in the future, no specific plan for monitoring USDWs at this facility is included in the permit applications. These monitoring wells are specific to the facility and separate from monitoring wells that will be installed to monitor impoundments. PSC should include a plan for monitoring well installation in permit applications.	No response

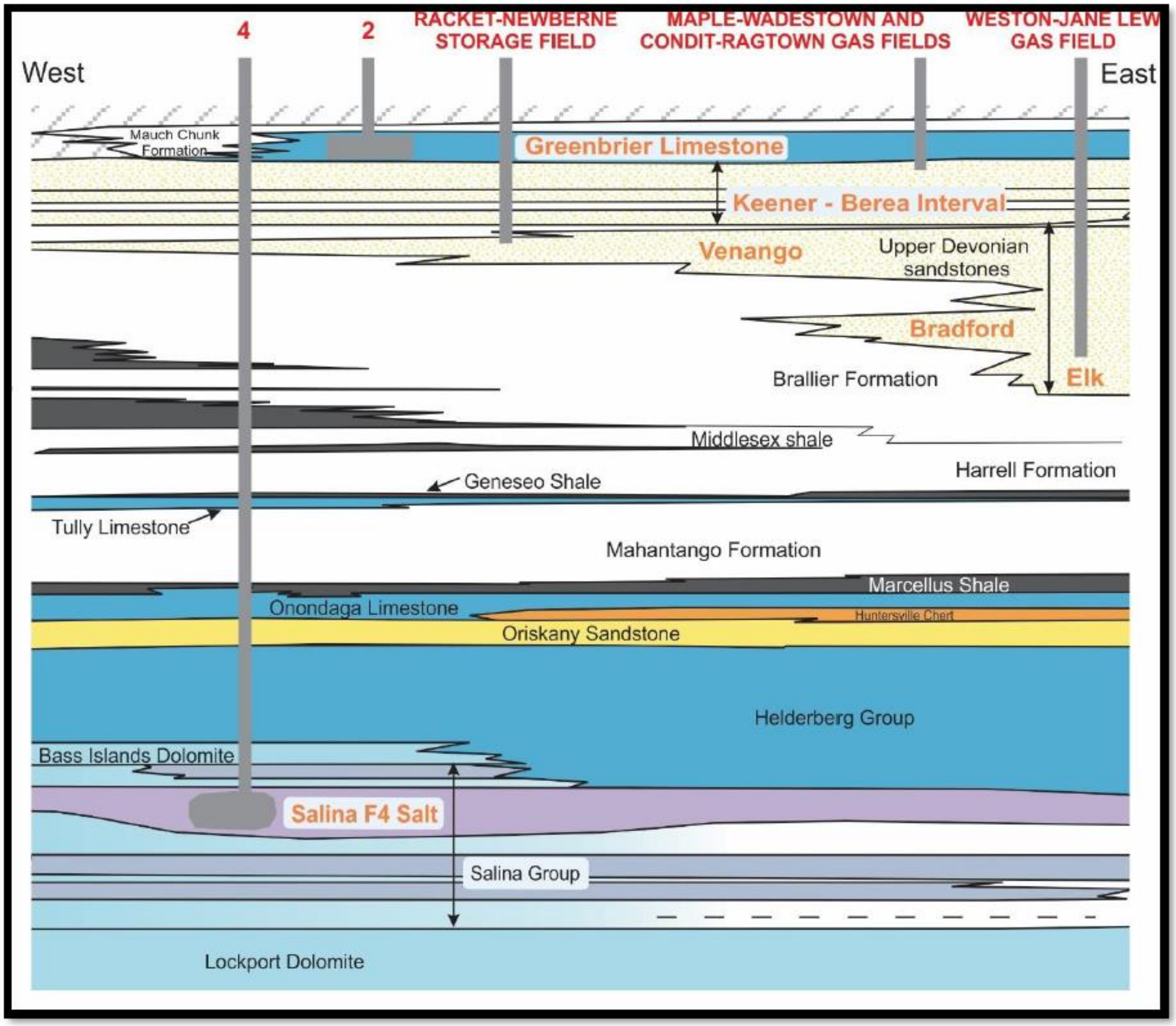

Figure 1. Conceptualization of NGL storage in the Salina F4 Salt unit and interbedded layers in the Salina Group. Figure from Carter et al. (2017).

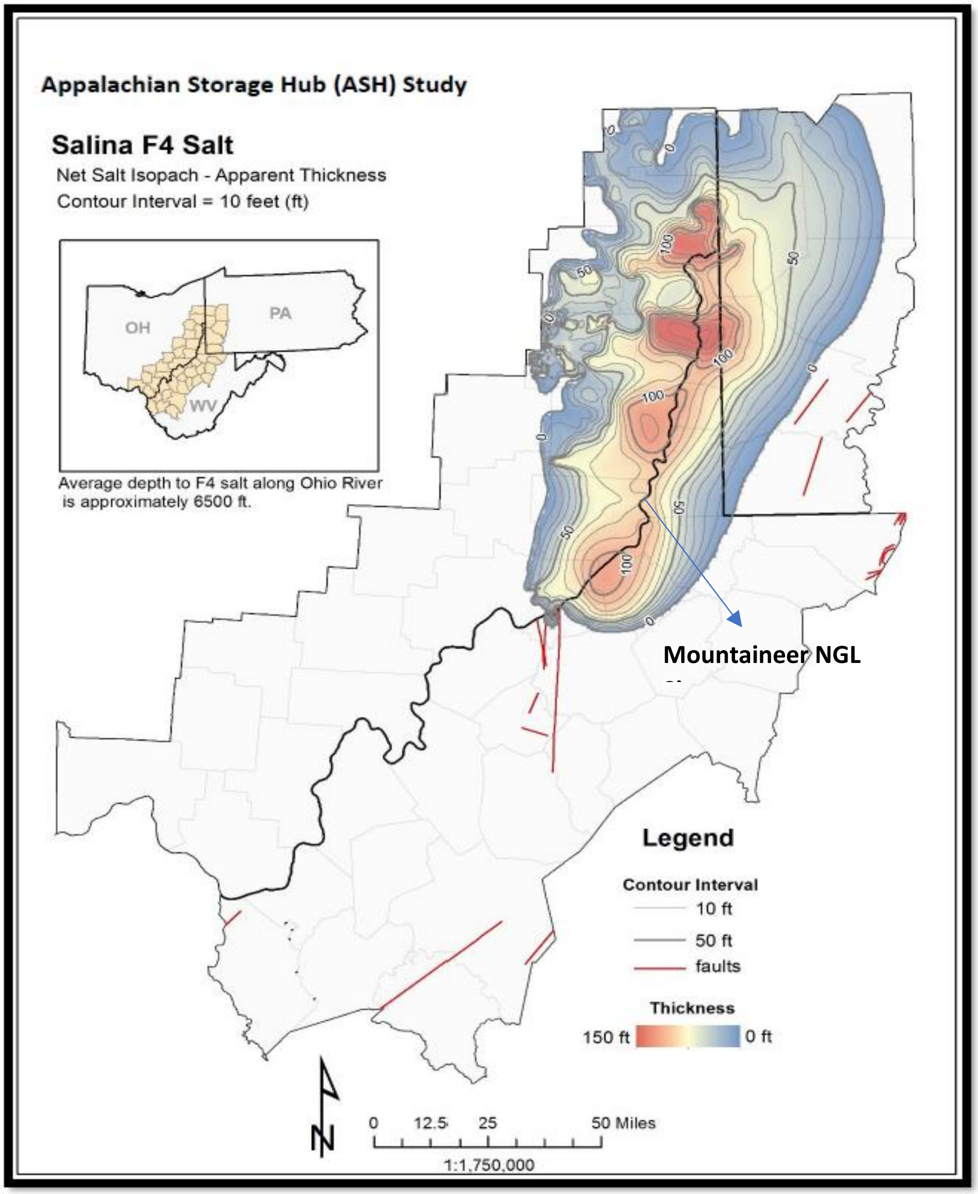

Figure 2. Net thickness of Salina F4 salt near Mountaineer NGL storage facility. This mapped interval is interpreted to be entirely comprised of salt above a persistent dolomite or anhydrite zone, and does not include the thickness any salt below the dolomite or anhydrite zone. Figure modified from Carter et al. (2017).

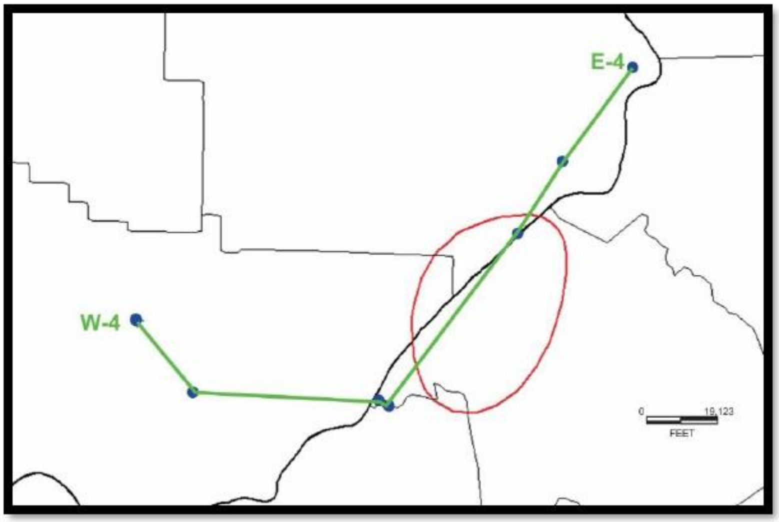

Figure 3. Location of cross section through the Salina F4 Salt near the Mountaineer NGL (directly northeast of borehole E-4). Red circle is isopach of 100-foot thickness of Salina F4 Salt. Figure from Carter et al. (2017).

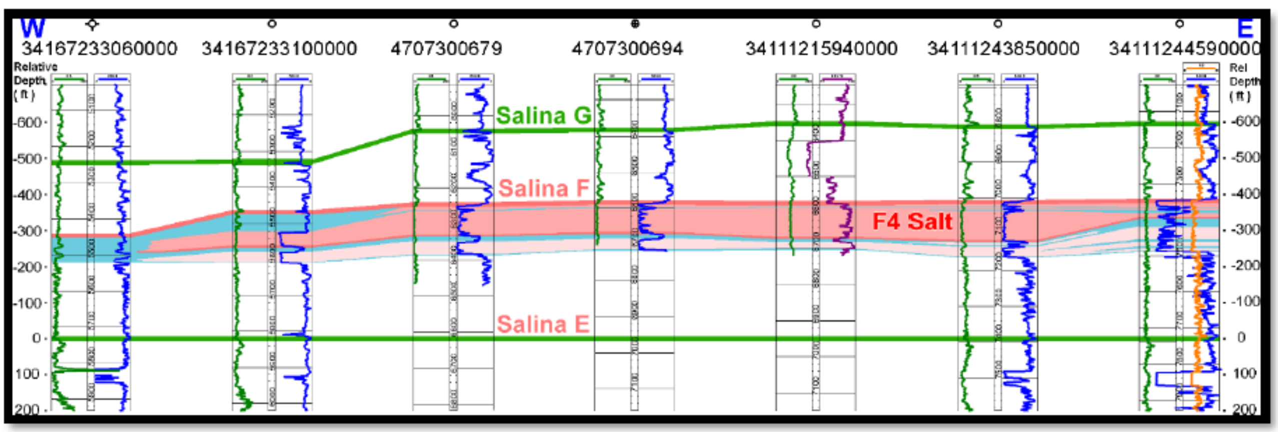

Figure 4. Cross section Salina Formation Sections E through G illustrating thinning of F4 Salt with outside of area deemed suitable for NGL storage. Figure from Carter et al. (2017).

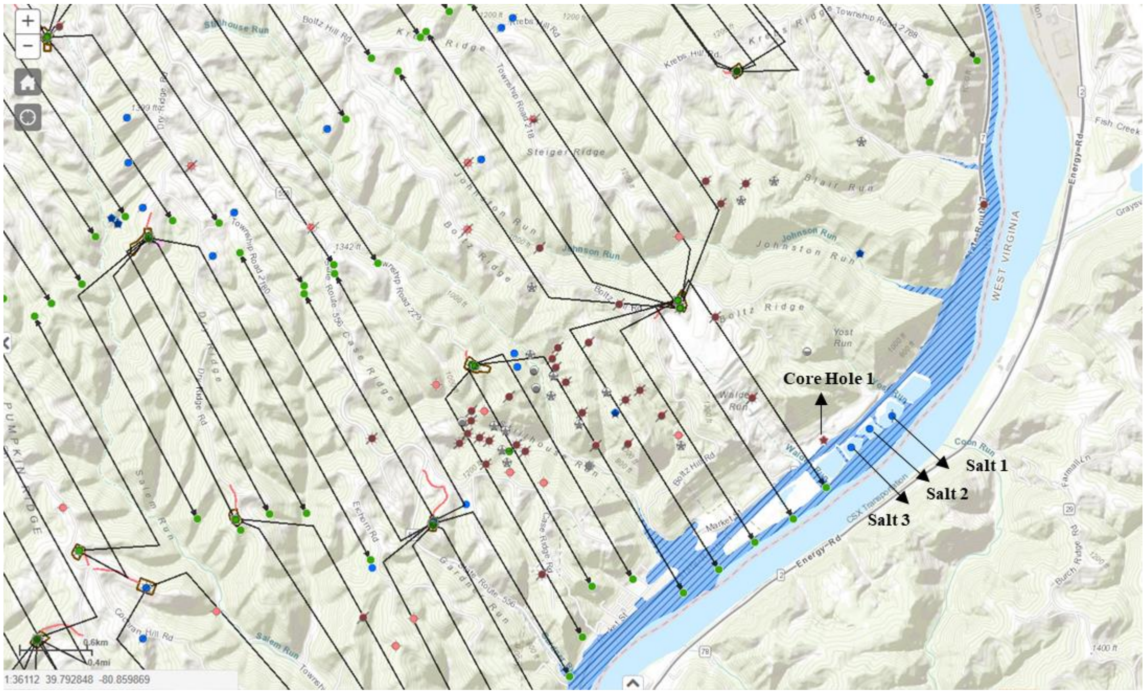

Figure 5. Modified screen shot from the ODNR Oil and Gas Well Viewer illustrating the locations of salt solution mining wells (Salt 1, Salt 2, Salt 3), location of Core Hole 1, horizontal extensions of hydraulically fractured oil and gas wells, and 100-year floodplain (shaded blue)

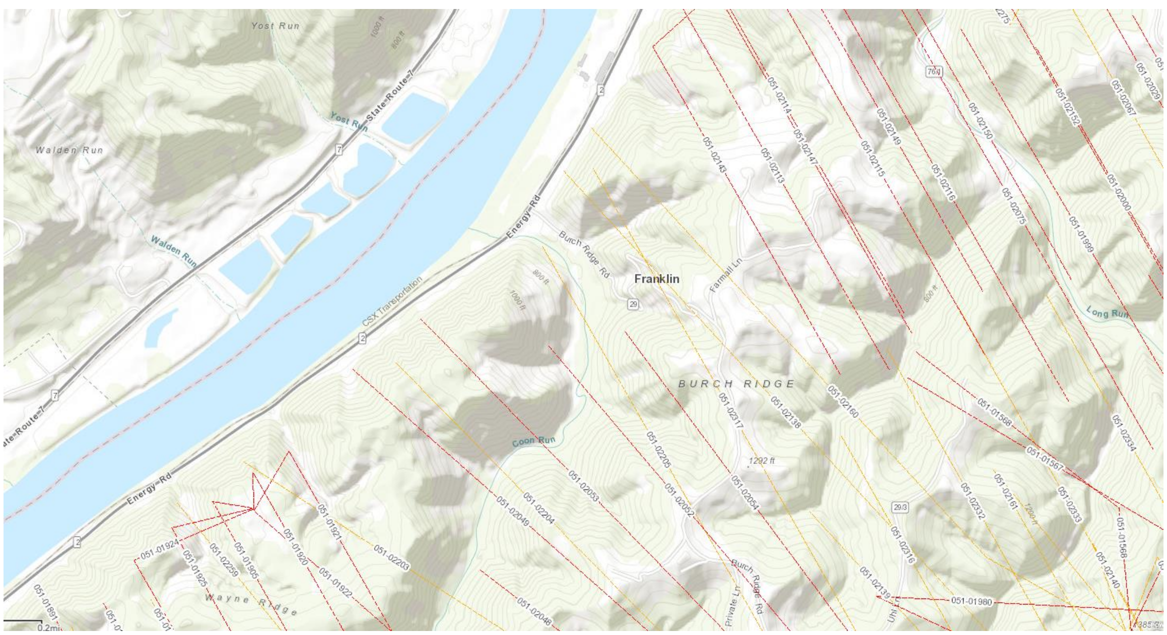

Figure 6. Screen shot from West Virginia Resource Management Plan Viewer illustrating the location of horizontal extents of hydraulically fractured wells in West Virginia near the Ohio River. Well numbers with associated depths as follows: 051-02049 (<3,000 ft), 051-02204 (“deep”), 051-02053 (<3,000 ft), 051-02205 (“deep”), 051-02138 (>3,000 ft), 051-02317 (“deep”), 051-02160 (>3,000 ft).

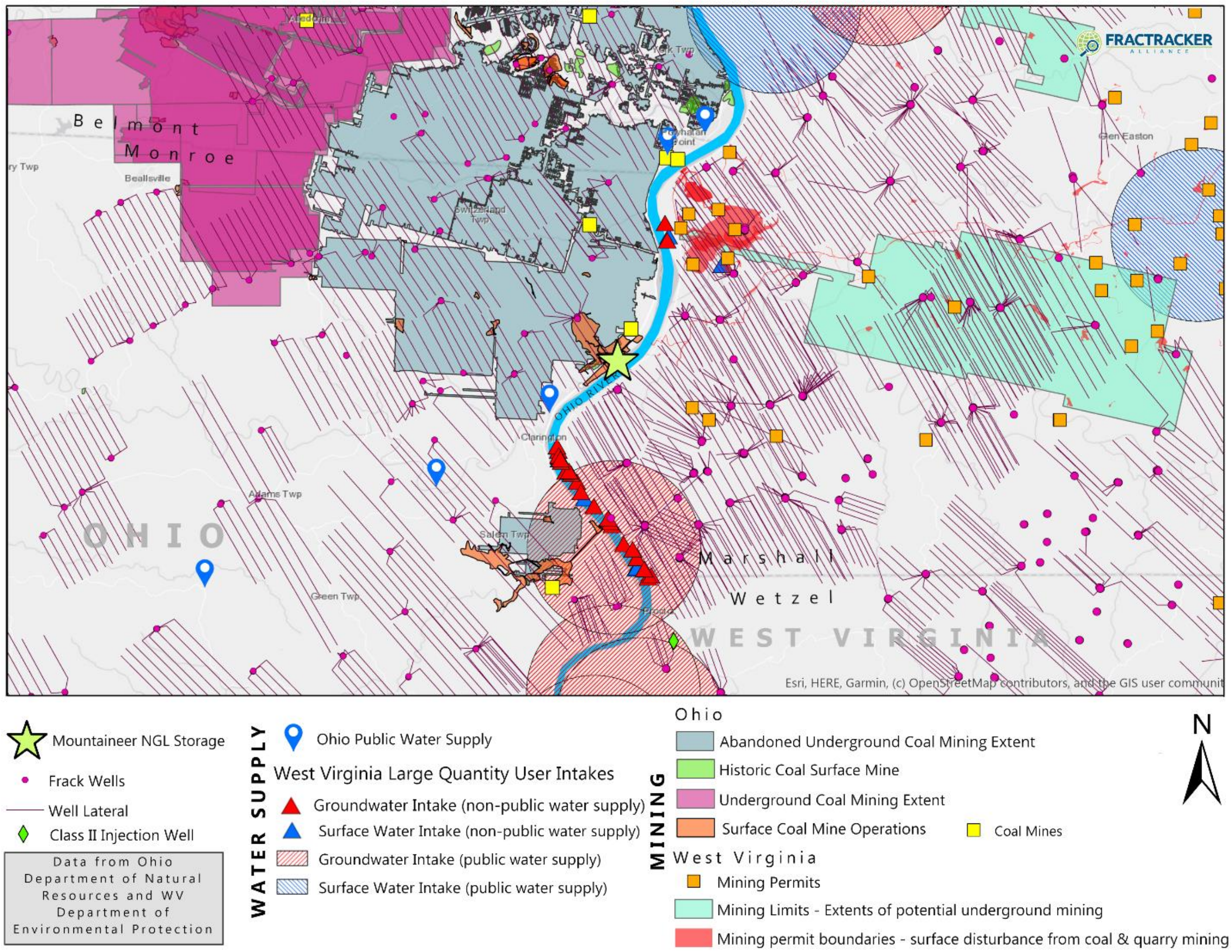

Figure 7. Overview of oil and gas development (hydraulic fracturing) and underground mining, and Class II injection wells in the vicinity of the Mountaineer NGL storage facility. Figure provided by Fracktracker Alliance.

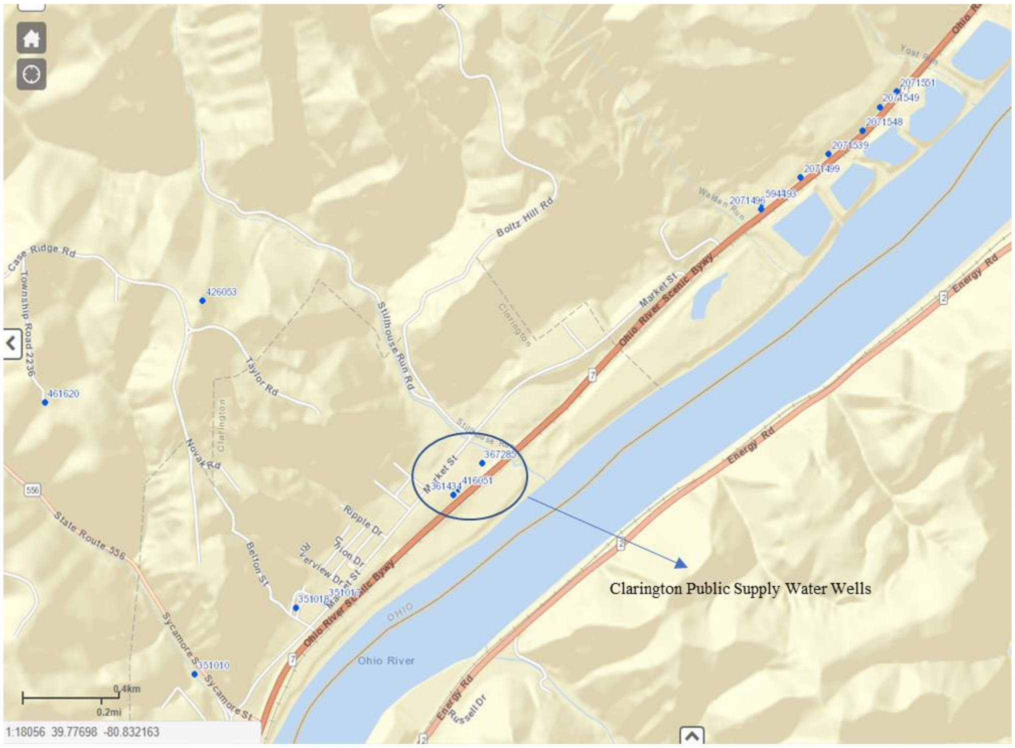

Figure 8. Modified screen shot from ODNR Water Wells Viewer illustrating the location of the Clarington Public Water wells relative to the salt solution mining well area.

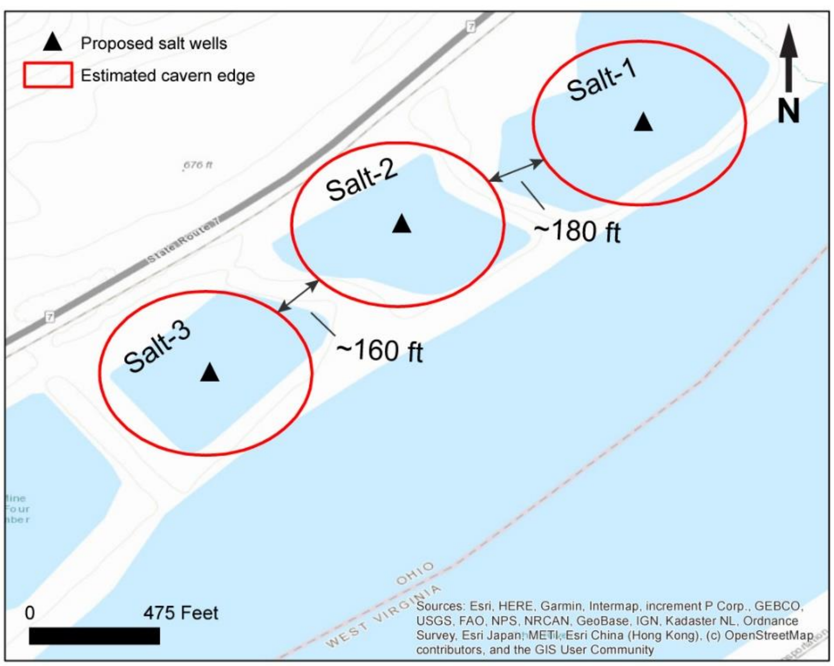

Figure 9. Approximate spacing of the proposed salt well caverns as determined in ArcGIS 10.8. Salt well locations were taken from the permit materials, and cavern edges were estimated by extending a 300 ft (the proposed cavern diameter) buffer from each well location.