Prediction of Seepage from the Clay Tailings Filter Stack (CTFS) at the Lithium Nevada Thacker Pass Mine, Northern Nevada

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LIGHTNING SUMMARY

The Nevada Division of Environmental Protection (NDEP) has issued a Water Pollution Control Permit for the Lithium Nevada Thacker Pass mine in northern Nevada. Although NDEP refers to the clay tailings filter stack (CTFS) as a “dry stack,” with a target geotechnical water content of 46%, it would probably have greater water content than any tailings storage facility ever constructed. Even so, 95% of the filtered tailings produced by Lithium Nevada have had geotechnical water contents in the range 47.1-86.7%. Although this should be a zero-discharge facility, seepage rates from the CTFS would be tens to thousands of gallons per minute and would continue for decades after closure with no provisions for management of the seepage.

EXECUTIVE SUMMARY

The Nevada Division of Environmental Protection (NDEP) has issued a Water Pollution Control Permit for the first 10-year phase of the Lithium Nevada Thacker Pass mine in northern Nevada, which is anticipated to be a 41-year mining project with five years of reclamation. The clay tailings would be filtered for partial removal of water and then permanently stored in a clay tailings filter stack (CTFS), which would be 190 feet high after 10 years and 400 feet high at the end of the final phase. The filtration of clay tailings is a new technology and there are no operating mines with filtered clay tailings anywhere in the world. Although NDEP has claimed that there are precedents, such as the Pumpkin Hollow mine in Nevada, all of the named precedents are either not in operation or processing hard-rock ores, rather than leaching metals from clay deposits, as at the Thacker Pass mine. The target geotechnical water content for maximum compaction of tailings within the CTFS is 46%. Although NDEP refers to the CTFS as a “dry stack,” the geotechnical water content of the tailings would be twice that of the tailings in a conventional tailings impoundment (23%), and would probably have the highest geotechnical water content of any tailings storage facility ever constructed. The permitted geotechnical water contents for the structural zone (constituting the dam or containment structure of the CTFS) are the range 40-52%, while the permitted geotechnical water contents for the non-structural zone are 34-58%. The permit requires the Thacker pass mine to be a zero-discharge facility.

Seepage analyses for the CTFS were carried out separately by NewFields and Piteau Associates. The analysis by NewFields assumed that tailings consolidation would take place, meaning that the weight of overlying tailings would further compact the underlying tailings, so that the lower portion of the CTFS would potentially be saturated. For a geotechnical water content of 49.1% and zero (or unspecified) precipitation, NewFields calculated an average seepage rate of 74 gpm without distinguishing between conditions during operation and after closure. No explanation has been provided as to how tailings consolidation was taken into
account or how the calculation was carried out. Piteau Associates used the HYDRUS software to calculate the long-term steady-state seepage from the CTFS after closure assuming an initial geotechnical water content of 46% and no tailings consolidation. For the base case (a closure cover consisting of a 12-inch layer of growth media underlain by a 12-inch layer of waste rock), Piteau Associates calculated a steady-state seepage of 0.02 gpm. The steady-state seepages for the sensitivity analyses ranged over three orders of magnitude, indicating that the prediction is highly dependent upon the input parameters. Piteau Associates found further that no seepage would occur for the first 1000 years after closure with the first seepage occurring when the saturation front reaches the base of the CTFS. NDEP essentially accepted the NewFields analysis in that the seepage would be directed to a reclaim pond (for recycling into the mining operation) with capacity for storing 74 gpm of seepage for seven days (together with sufficient capacity for storing stormwater from a 100-year, 24-hour storm). NDEP also essentially accepted the analysis by Piteau Associates in requiring no provision for storage, treatment or discharge of seepage after closure.

The objectives of this report were to answer the following questions:
1) Did either NewFields or Piteau Associates carry out correct seepage analyses?
2) Is current filter press technology capable of producing filtered tailings with the appropriate geotechnical water contents for the CTFS?
3) What will be the seepage rates through the CTFS during operation?
4) How long will seepage continue after closure of the CTFS?
5) What will be the seepage rate through the CTFS after closure?

Neither of the existing analyses provided sufficient input parameters or even the software used (in the case of the NewFields analysis), so that existing models could not simply be re-run with adjusted parameters. Since the analysis by NewFields included tailings consolidation, it was regarded as more accurate and as a starting point for adjustment of input parameters. Based on the average seepage rate of 74 gpm calculated for an initial geotechnical water content of 49.1%, it is certainly reasonable that seepage rates of hundreds of gallons per minute could be expected for higher geotechnical water contents. The results of the NewFields analysis were extrapolated to lower and higher geotechnical water contents using the Burdine equation for unsaturated hydraulic conductivity. Since various documents have stated tailings specific gravities of 2.93, 3.12, 3.20 and 3.28, as well as both a residual volumetric water content of 0.066 and a residual geotechnical water content of 19%, all calculations were carried out for all eight combinations. The calculations for average seepage rate and drainage time after closure were based upon the geotechnical water content at the time of closure and were independent of the analysis by NewFields. The post-closure calculations did not include precipitation (equivalent to a perfect closure cover), so that seepage rates and drainage times were minimum values.

A complication was that the Burdine equation is typically applied only to porous materials with a fixed structure that cannot have a water content that exceeds saturation. In the case of the CTFS at the Thacker Pass mine, the saturation geotechnical water contents would be 53.4%, 50.1%, 48.9% and 47.7% for tailings specific gravities equal to 2.93, 3.12, 3.20 and 3.28, respectively. Thus, tailings with geotechnical water contents up to 52% in the structural zone and 58% in the non-structural zone would be oversaturated (except in the structural zone for the lowest specific gravity), which would certainly be an unprecedented practice for filtered tailings stacks, since the tailings could not be compacted. The water in oversaturated tailings could find and create its own drainage pathways, thus greatly increasing the flux of water over the saturated
hydraulic conductivity. The preceding effect was accommodated by extending the Burdine equation to geotechnical water contents exceeding saturation.

The assertion by Piteau Associates that no seepage could occur until the bottom tailings were saturated is inconsistent with soil physics. The water stored in pores at volumetric water contents between the saturated volumetric water content and the field capacity is called the gravitational water. Thus, drainage under gravity will occur from unsaturated tailings stacks until the volumetric water content has fallen to the field capacity, at which point there is a balance between the gravitational forces that pull water downward and the capillary forces that prevent water from moving from pores into large open spaces (such as a drainage collection system). For a residual volumetric water content of 0.066, geotechnical field capacities were calculated as 47.5%, 44.6%, 43.5%, and 42.4% for tailings specific gravities of 2.93, 3.12, 3.20 and 3.28, respectively. For a residual geotechnical water content of 19%, geotechnical field capacities were calculated as 49.1%, 46.3%, 45.2%, and 44.1% for tailings specific gravities of 2.93, 3.12, 3.20 and 3.28, respectively. Thus, for a residual volumetric water content of 0.066 (assumed by Piteau Associates), except for the lowest specific gravity, drainage from the CTFS due to gravity should occur even for tailings at the target geotechnical water content of 46% (which was the only case considered by Piteau Associates). The inability of Piteau Associate to reproduce this result casts some doubt as to whether the HYDRUS software was used correctly. Even so, due to tailings consolidation, the base of the CTFS should be saturated, so that seepage should occur during operation and after closure until the CTFS has drained to field capacity.

Thus far, Lithium Nevada has carried out 93 tests of filtration of clay tailings for which the average solids content has been 60.8%, corresponding to a geotechnical water content of 64.6%, which is far higher than the target geotechnical water content (46%), the maximum geotechnical water content for tailings allowed in the structural zone (52%), and even the maximum geotechnical water content for tailings allowed in the non-structural zone (58%). Based on the standard deviation of the measurements (3.6% solids content), 95% of samples (the mean plus or minus two standard deviations) fall in the range 53.6-68.0% solids content (corresponding to geotechnical water contents of 47.1-86.7%), a considerable range that still does not include the target geotechnical water content (46%). Lithium Nevada measured the solids contents by drying the samples at 105°C, which is the standard procedure. Lithium Nevada has argued that the samples should have been dried at 45°C (which would have resulted in lower geotechnical water contents), since any water expelled above that temperature is not free water, but “structural water” that is part of the crystal structure. The justification for this argument is contained in a document that Lithium Nevada has marked as “Confidential.”

Seepage rates during operation were calculated to be in the range of tens to thousands of gallons per minute, depending upon the geotechnical water content and the residual water content, and to a lesser degree upon the tailings specific gravity. For the target geotechnical water content (46%), seepage rates ranged from 10 gpm for a residual geotechnical water content of 19% to 19 gpm for a residual volumetric water content of 0.066 (nearly independent of the tailings specific gravity). For the saturated geotechnical water content (ranging from 47.7 to 53.4%), seepage rates ranged from 30 gpm for a tailings specific gravity of 3.28 and a residual geotechnical water content of 19% to 881 gpm for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19%. For the maximum geotechnical water content in the structural zone (52%), seepage rates ranged from 243 gpm for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066 to 410 gpm for a residual geotechnical water content of 19% (nearly independent of the tailings specific gravity). For the maximum
geotechnical water content in the non-structural zone (58%), seepage rates ranged from 2297 gpm for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066 to 9215 gpm for a residual geotechnical water content of 19% (nearly independent of the tailings specific gravity). Since the permit allows all filtered tailings to be emplaced at the maximum geotechnical water content, a reclaim pond that can accommodate a seepage rate of only 74 gpm is entirely inadequate.

The time for the CTFS to drain to field capacity after closure ranged from a few years (within the planned reclamation period) to over a century, depending upon the geotechnical water content and tailings specific gravity, and to a lesser degree upon the residual water content. For the target geotechnical water content (46%), drainage times ranged from 17.6 years for a tailings specific gravity of 3.12 (nearly independent of the residual water content) to 86.2 years for a tailings specific gravity of 3.28 and residual volumetric water content of 0.066. For the saturated geotechnical water content (ranging from 47.7 to 53.4%), drainage times ranged from 3.2 years for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19% to 97.0 years for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066. For the maximum geotechnical water content in the structural zone (52%), drainage times ranged from 2.8 years for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19% to 105.6 years for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066. For the maximum geotechnical water content in the non-structural zone (58%), drainage times ranged from 3.5 years for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19% to 107.2 years for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066. The lack of provision for long-term seepage management after closure could be adequate, but it depends on key tailings characteristics that are still unknown, and, in any event, would still require a means for managing seepage during the reclamation period.

The average seepage rates from the CTFS during the time between closure and drainage to field capacity ranged from tens to thousands of gallons per minute, depending upon the geotechnical water content at the time of closure, the tailings specific gravity, and the residual water content. For the target geotechnical water content (46%), average seepage rates after closure ranged from 16 gpm for a tailings specific gravity of 3.28 and a residual geotechnical water content of 19% to 33 gpm for a tailings specific gravity of 3.20 and a residual volumetric water content of 0.066. For the saturated geotechnical water content (ranging from 47.7 to 53.4%), average seepage rates after closure ranged from 24 gpm for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066 to 692 gpm for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19%. For the maximum geotechnical water content in the structural zone (52%), average seepage rates after closure ranged from 48 gpm for a tailings specific gravity of 3.28 and a residual geotechnical water content of 19% to 523 gpm for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19%. For the maximum geotechnical water content in the non-structural zone (58%), average seepage rates after closure ranged from 84 gpm for a tailings specific gravity of 3.28 and a residual geotechnical water content of 19% to 1316 gpm for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19%. As above, since the permit allows all filtered tailings to be emplaced at the maximum geotechnical water content, even if seepage could be managed through the reclaim pond during the reclamation period, a reclaim pond that can accommodate a seepage rate of only 74 gpm is entirely inadequate.
The Fact Sheet that accompanies the permit from NDEP acknowledges that current filter press technology cannot produce the required geotechnical water contents and requires air drying as a mitigation. According to the Fact Sheet, “The tailings will be dewatered to approximately 61 percent dry basis (geotechnical) moisture content prior to being conveyed to the temporary tailings stockpile … From the stockpile, the material is hauled and placed in either the structural or nonstructural zone in a 12-inch thick lift and scarified to dry to the allowable moisture content.” Lithium Nevada has carried out laboratory evaporation experiments on filtered tailings and found 60% of remaining water lost after four days and 100% of remaining water lost after 22 days. The results also inexplicably show loss of 20% of remaining water after zero elapsed time and contradict other claims that 16.4% of the water in a filtered tailings sample is “structural water.” Even so, Lithium Nevada has not consistently met the required geotechnical water content coming from the filter presses (61%) and has produced a mean geotechnical water content that is considerably higher (64.6%). It is most important that there are no documents describing field experiments on air-drying of the filtered tailings, for which layer thickness should be a critical factor.

While creativity is generally considered to be a positive human endeavor, creativity is not an unmitigated good. There is another concept of “Reckless Creativity,” which has one or more of the following characteristics:

1) There is no scaffolding, meaning that the new innovation does not build upon previous innovations through a series of intermediate steps with proper testing and verification of each step.
2) One or more of the technologies required to carry out the innovation does not currently exist.
3) Predictions are based upon single input values or best-case scenarios without considering the range of possible inputs.
4) Although potential problems are recognized, they are quickly dismissed as irrelevant without justification.
5) Basic precautions are not taken that would be routine for previous innovations.
6) There is no consideration of the consequences of being wrong, that is, of the consequences of failure.

The Water Pollution Control Permit for the Lithium Nevada Thacker Pass mine fulfills all of the characteristics of Reckless Creativity. The recommendation of this report is that the Water Pollution Control Permit should be revoked at the present time.
OVERVIEW

The Nevada Division of Environmental Protection (NDEP) has issued a Water Pollution Control Permit for the first 10-year phase of the Lithium Nevada Thacker Pass mine in northern Nevada, which is anticipated to be a 41-year mining project with five years of reclamation (NDEP, 2022a-c). Sulfuric acid would be used to leach the lithium from a clay deposit that would be extracted from an open-pit mine. The clay tailings (clay that remains after the commodity of value has been removed) would be filtered for partial removal of water and then permanently stored in a clay tailings filter stack (CTFS), which would be 190 feet high after 10 years and 400 feet high at the end of the final phase. According to NDEP (2022b), “The CTFS will be constructed as a lined, zero discharge facility and covered with waste rock/growth media at closure; therefore, no degradation to groundwater is anticipated.”

Although the filtration and permanent stacking of clay tailings is a new technology and there are no operating or closed mines with filtered clay tailings storage facilities anywhere in the world, NDEP (2022c) has insisted that there are precedents. For example, in response to the public comment “To the best of our knowledge, there are no operating mines with this type of tailings dump. There are other similar proposals for lithium mines globally, but no data on how
these facilities have performed.” NDEP (2022c) replied, “There is one operating dry stacked tailings facility in Nevada at the Pumpkin Hollow Project. Two additional dry stacked tailings facilities have been proposed and approved in Nevada including at Mineral Ridge and Rhyolite Ridge. There are several other operating dry stacked tailings facilities including Greens Creek in Alaska, Pogo Gold Mine in Alaska, Bellekeno Mine in Canada, Minto Mine in Canada, Raglan Mine in Canada, and the Karara Mine in Australia.” However, of the mines listed by NDEP (2022c), except for the Rhyolite Ridge mine, none are mining lithium and all are filtering tailings from hard-rock ores, not from clay deposits (Mining Technology, 2010a-b; French et al., 2019; Hecla Mining Company, 2022; Minto Metals, 2022; Northern Star, 2022; Scorpio Gold Corporation, 2022). The Rhyolite Ridge mine cannot serve as a precedent because it has no operational history. Even so, the mining company website emphasizes that “Rhyolite Ridge is a geologically unique lithium-boron deposit that occurs within lacustrine sedimentary rocks … This mineralization style is different to the brine and pegmatite deposits that are the source of nearly all the lithium produced today and is also unlike lithium-claystone deposits found in the region [presumably referring to the Thacker Pass deposit]” (Ioneer, 2022). The significance of the use of the phrase “dry stack” by NDEP (2022c) to refer to filtered tailings storage will be discussed later in this report.

Since the CTFS is permitted only as a “zero discharge facility” (NDEP, 2022b), the prediction of seepage through the base of the CTFS is critical. Lithium Nevada contracted two seepage analyses, one by NewFields (2020, 2021) and one by Piteau Associates (2021a-b), both of which were included in permit applications. NewFields (2020, 2021) predicted seepage of 74 gpm through the CTFS without distinguishing between the operational and closure phases. Piteau Associates (2021a-b) did not address seepage during operation, but predicted no seepage for at least 1000 years after closure, followed by long-term steady-state seepage of 0.02 gpm. NDEP essentially accepted the seepage analysis by NewFields (2020, 2021) by requiring construction of a reclaim pond with capacity to store a seepage volume equivalent to 74 gpm over seven days plus the stormwater from a 24-hour event with return period of 100 years. The requirement of zero discharge would be maintained by recycling the water from the reclaim pond back into the mining operation. NDEP also essentially accepted the seepage analysis by Piteau Associates (2021a-b) by not requiring any provisions for management of seepage from the CTFS after closure. According to NDEP (2022b), “A conservative seepage calculation was completed [by NewFields] in order to size the Reclaim Pond which showed a maximum seepage rate of up to 74 gpm as a result of tailings consolidation. However, a more refined seepage analysis was later completed [by Piteau Associates] using Hydrus 1D which indicated seepage from the tailings material is not anticipated and infiltration would travel approximately 20 meters in 1,000 years. The Reclaim Pond will still be constructed with an operating capacity of 74 gpm for 7 days plus storage for the 100-year, 24-hour event … Under covered closure conditions, the resulting seepage is 0.01 percent of the Mean Annual Precipitation which translates to a total 0.02 gpm over the facility.” It should be noted that NewFields (2021) describes 74 gpm as the “estimated average seepage flow rate,” not the “maximum seepage rate” (NDEP, 2022b).

The objective of this report is to answer the following question: What is the predicted seepage through the clay tailings filter stack (CTFS) at the Lithium Nevada Thacker Pass mine both during operation and after closure? Before addressing the methodology for addressing the objective, I will first provide sufficient background information so that the argument is persuasive to readers who are not specialists in unsaturated flow or tailings storage facilities. This background information includes a tutorial on unsaturated flow, a review of filtered tailings
technology, a summary of the CTFS at the Thacker Pass mine, and the history of the seepage
analyses by NewFields and Piteau Associates. More fundamental information about unsaturated
flow is available in textbooks by Hillel (1980a-b), Charbeneau (2000), and Holtz et al. (2011),
while Klohn Crippen Berger (2017) is an excellent review of tailings management technologies,
including filtered tailings technologies. The approaches of the preceding references are largely
followed in the background information. Note that, throughout the tutorial, a body of tailings can
be regarded as a soil, that is, an unconsolidated mixture of solids, water and air.

**TUTORIAL ON UNSATURATED FLOW**

*Solids Content, Geotechnical Water Content and Volumetric Water Content*

A difficult aspect of reading the documents from Lithium Nevada and their consultants is
that the parameters solids content, geotechnical water content and volumetric water content are
variously used without stating the correspondences between the parameters and often without
clarifying whether “water content” refers to geotechnical water content or volumetric water
content. Since the permit (NDEP, 2022a-b) refers to geotechnical water content, in this report,
any mention of a solids content or volumetric water content will include the corresponding
geotechnical water content, and “water content” values will not be written without the qualifier
“geotechnical” or “volumetric.” For further clarity, all geotechnical water contents will be
written as percentages, while all volumetric water contents will be written in decimal form.

The geotechnical water content \( w \) of a mixture of solids, water and air is defined as

\[
w (\%) = 100 \times \frac{M_W}{M_S}
\]

where \( M_W \) is the mass of water and \( M_S \) is the mass of solids, while the solids content \( S \) of the
mixture is defined as

\[
S (\%) = 100 \times \frac{M_S}{M_W + M_S}
\]

In other words, the geotechnical water content is defined on a “dry” basis, while the solids
content is defined on a “wet” basis. Typically, the mass of air is not considered in mass-based
calculations, since it is much less than the masses of water or solids. Combining Eqs. (1)-(2)
yields the relationship between geotechnical water content and solids content

\[
w = 100 \left( \frac{100}{S} - 1 \right)
\]

It is most important to note that the geotechnical water content and the solids content do not sum
to 100%. For example, if a mixture of tailings and water contains 1 Mg of solids and 1 Mg of
water, then the solids content is 50%, while the geotechnical water content is 100%.

The volumetric water content \( \theta \) is defined as
\[
\theta = \frac{V_W}{V_W + V_A + V_S}
\]

where \(V_W\) is the volume of water, \(V_A\) is the volume of air, and \(V_S\) is the volume of solids, with the denominator being the total volume. The combined volumes of water and air are equal to the volume of voids, \(V_V\). Unlike mass-based calculations, volume-based calculations require inclusion of the volume of air. The saturated volumetric water content \(\theta_{sat}\), also called the porosity, is then defined as

\[
\theta_{sat} = \frac{V_V}{V_V + V_S}
\]

in which the denominator is still the total volume. Note that, as long as solids are present, the saturated volumetric water content must always be less than one.

The solids content, geotechnical water content and volumetric water content are all determined by comparing the weight of a soil or tailings sample before and after oven-drying. Standard oven temperatures are 105°C or 110°C, which are slightly above the boiling temperature of water in order to take into account the energy required to overcome the attraction between water in soil pores and the surfaces of solid particles. The standard drying temperature of 105°C was used in filter press experiments by Lithium Nevada (2021a-b), although not by all of their vendors. According to Lithium Nevada (2021a-b), “Once filter cakes are collected from each batch, composite samples are taken and dried in an oven at 105°C to determine the moisture content.” The significance of the drying temperature will be discussed further in the Results section.

The conversion of volumetric water content into its corresponding geotechnical water content requires a knowledge of \(G_S\), the specific gravity of the solid particles, where specific gravity is the ratio of the density of the solids to the density of water (1 Mg/m\(^3\)). Note that the specific gravity does not take into account any voids between the solid particles. The correspondence between volumetric water content and geotechnical water content is

\[
w = 100 \times \frac{\theta}{G_S(1 - \theta_{sat})}
\]

so that the correspondence between the saturated volumetric water content and the saturated geotechnical water content \(w_{sat}\) is

\[
w_{sat} = 100 \times \frac{\theta_{sat}}{G_S(1 - \theta_{sat})}
\]

Since the correspondence between volumetric water content and geotechnical water content does not seem to be readily available in textbooks, a derivation is given in Appendix A.
The matric potential (also called the soil water potential) refers to the energy per unit mass required to move a piece of water from its position in a soil pore to a large open space. Energy per unit mass can also be expressed as an equivalent height of water, as in the figure above. The relationship between volumetric water content and matric potential is called the soil water characteristic curve. As the volumetric water content decreases, water is present in smaller pores, so that the matric potential increases. Note that soils have a limiting volumetric water content called the residual or irreducible water content. Figure from Tuller and Or (2003).

**Soil Water Characteristic Curve**

It is a fundamental principal of soil physics that water spontaneously moves from a location where it has higher energy density (energy per unit mass) to a location where it has lower energy density. Energy is the ability to do work. For example, soil water is doing work when it dissolves soluble solid particles, such as salts. Water that is present within a small pore has limited capacity to do work because the water is partially bound to the surface of the solid particles that surround the pore. The smaller the pores, the more water is in contact with solid surfaces, thus reducing the ability of the water to do work. Therefore, water within soil will move spontaneously from larger to smaller pores, a phenomenon that is known as capillary effects. For example, if a water well is drilled above the water table (surface above which the pores are unsaturated), water will not enter the well, since it will not spontaneously move from pores (where is has lower energy density) into the large, open space of a well.

The soil water potential, also called the matric potential, is the energy required to move a unit mass of water from a location in soil into an unconfined body of free water. (Some
textbooks will define soil water potential as the energy required to move a unit mass of water from an unconfined body of free water to a location in soil, so that soil water potential is always negative.) The soil water potential can be expressed in energy density units (such as J/kg) or as the height of a column of water with the same gravitational potential energy (with units such as meters) or as the pressure at the base of the column of water (with units such as bars or MPa). The relationship between volumetric water content and soil water potential is called the soil water characteristic curve (see Fig. 1). Since soil water moves from larger to smaller pores, a soil with lower volumetric water content will have a higher soil water potential because water is present in smaller pores, thus requiring more energy for extraction (see Fig. 1). Note that, since a sandy soil has larger pores than a clayey soil, for a given volumetric water content, a clayey soil will have a larger soil water potential than a sandy soil (see Fig. 1).

Water can be extracted from soil by placing the soil in a pressure chamber, with more water being extracted as the pressure is increased. The remaining volumetric water content at a given pressure is simply given by the soil water characteristic curve, in which the pressure of the pressure chamber is equivalent to a particular matric potential (see Fig. 1). Typically, there is a limiting pressure, beyond which no further water can be extracted. The remaining water is called the residual volumetric water content or the irreducible volumetric water content and corresponds to the volumetric water content at the approximately vertical portions of the curves on the left-hand side of Fig. 1. In a similar way, there is a minimum pressure of the pressure chamber (equivalent to a minimum matric potential) required to extract any water from soil, which is commonly called the displacement pressure, corresponding to the approximately vertical portions of the curves on the right-hand side of Fig. 1.

The soil water characteristic curve is developed by pressure chamber experiments on undisturbed samples of soil or tailings, as described above. For numerical modeling, it is more convenient to replace the experimental curves with functional forms with adjustable parameters. The most common functional forms for matric potential $\Psi$ (expressed as a height of water) are the van Genuchten model

$$\Theta = \left(\frac{1}{1 + (\alpha \Psi)^N}\right)^M$$  \hspace{1cm} (8)

and the Brooks-Corey model

$$\Psi \leq \Psi_b: \Theta = 1$$

$$\Psi > \Psi_b: \Theta = \left(\frac{\Psi_b}{\Psi}\right)^\lambda$$ \hspace{1cm} (9)

where $M = 1 - 1/N$, $\Psi_b$ is the displacement pressure head (height of water equivalent to the displacement pressure) and the reduced saturation $\Theta$ is defined by

$$\Theta = \frac{\theta - \theta_r}{\theta_{sat} - \theta_r}$$ \hspace{1cm} (10)
where $\theta_r$ is the residual volumetric water content. An advantage of the Brooks-Corey model is its ease of interpretation, namely, a small value of $\lambda$ (much less than one) indicates a wide range of pore sizes (Charbeneau, 2000). For small volumetric water contents, the Brooks-Corey and van Genuchten models are identical if

$$\lambda = N - 1; \Psi_b = \frac{1}{\alpha}$$

(11)

Eq. (11) is useful for relating parameters of the two models, but for the entire range of volumetric water contents, a more exact relationship for $\lambda$ is (Charbeneau, 2000)

$$\lambda = \frac{M}{1 - M (1 - 0.5^{1/M})}$$

(12)

**Kinematic Flow and Unsaturated Hydraulic Conductivity**

The flow of water through an unsaturated soil or tailings pile is quite complex due to the competition between capillary forces (which pull water into smaller pores) and the gravitational forces (which pull water downwards). However, for large volumetric water contents, gravitational forces dominate over capillary forces. This state is called kinematic flow and is described by the relatively simple equation (Charbeneau, 2000)

$$q = K(\theta)$$

(13)

where $q$ is the downward flux of water (volume of water per unit area per unit time) and $K(\theta)$ is the unsaturated hydraulic conductivity. Eq. (13) would also apply if the soil water potential were uniform throughout the soil profile, thus eliminating any tendency for water to move from higher to lower soil water potential. For example, soil water potential would be uniform if all pores were the same size and with the same degree of saturation. Eq. (13) would further apply if the soil were saturated, thus eliminating capillary forces entirely. In that case, $K(\theta)$ would be equal to the saturated hydraulic conductivity $K_{sat}$.

In general, the unsaturated hydraulic conductivity is a very strong function of volumetric water content and can be orders of magnitude less than the saturated hydraulic conductivity. In a saturated soil, the flux of water is limited due to obstruction by solid particles and the tortuous pathways between the particles (see Fig. 2). In an unsaturated soil, in addition to the above effects, the unsaturated hydraulic conductivity is diminished by the drag by solid particles on water that is in close contact with the particles and the ability of air to impede the flow of water (see Fig. 2). A commonly-used model for unsaturated hydraulic conductivity is the Burdine equation (Charbeneau, 2000)

$$K(\theta) = K_{sat} \Theta^{(3 + 2/\lambda)} = K_{sat} \Theta^\epsilon$$

(14)
in which $\lambda$ refers to the parameter in the Brooks-Corey model (see Eq. (9)). As mentioned previously, a small value of $\lambda$ indicates a large range of pore sizes, which according to Eq. (13) implies a very strong dependence of unsaturated hydraulic conductivity on volumetric water content. This result should be expected because, at higher volumetric water contents, the soil water is present in larger pores, which facilitates the flux of water (see Fig. 2).

Figure 2. In a saturated soil (middle diagram), the flux of water (volume of water flowing per unit area per unit time) is equal to the saturated hydraulic conductivity. The flux is limited due to obstruction by solid particles and the tortuous pathways between the particles. The unsaturated hydraulic conductivity (right-hand diagram) is a strong function of water content and can be orders of magnitude less than the saturated hydraulic conductivity. In addition to the obstruction by solid particles and the tortuous pathways between the particles, the hydraulic conductivity is diminished by the drag by solid particles on water that is in close contact with the particles and the ability of air to impede the flow. In an unsaturated soil, the flux of water is typically even less than the unsaturated hydraulic conductivity because of the tendency of water to remain trapped in small pores (called capillary effects). In an oversaturated soil (left-hand diagram), water can flow through large channels or spaces without obstruction by solid particles. In this case, the flux can be much greater than even the saturated hydraulic conductivity. The last case is significant because many of the tailings in the clay tailings filter stack (CTFS) would be oversaturated. Although saturated geotechnical water contents would be 53.4%, 50.1%, 48.9% and 47.7% for tailings specific gravities equal to 2.93, 3.12, 3.20 and 3.28, respectively, tailings with geotechnical water contents as high as 52% would be allowed in the structural zone, while tailings with geotechnical water contents as high as 58% would be allowed in the non-structural zone. Figure from Sandra et al. (2021).
Figure 3. The water stored in pores at volumetric water contents between the saturated volumetric water content and the field capacity is called the gravitational water. Thus, drainage under gravity will occur from unsaturated soils or tailings stacks until the volumetric water content has fallen to the field capacity. At field capacity, there is a balance between the gravitational forces that pull water downward and the capillary forces that prevent water from moving from pores into large open spaces (such as a drainage collection system). According to Piteau Associates (2021a-b), “Seepage related to the drainage of in-situ water content during the first 1,000 years of emplacement was zero. Water content at the bottom of the CTFS was simulated to slowly increase as a result of unsaturated gravity drainage … However, pore water along the bottom of the CTFS will remain in tension with clay material until water content reaches field saturation conditions to overcome capillary tension and freely seep into the collection system.” Based upon the concept of field capacity, the above discussion by Piteau Associates (2021a-b) is not correct. Drainage from the CTFS will occur as long as the volumetric water content of the base of the stack exceeds the field capacity. For the CTFS, the field capacity equivalent to a soil water potential of 0.033 MPa (see figure above), the van Genuchten model parameters for clay tailings, and a residual volumetric water content of 0.066 (see Fig. 10b) is 0.543, corresponding to geotechnical water contents of 47.5%, 44.6%, 43.5%, and 42.4% for specific gravities of solid tailings of 2.93, 3.12, 3.20 and 3.28. Drainage would occur from the bottom of the stack for any geotechnical water content higher than the preceding field capacities, all of which are less than the target geotechnical water content of 46% (except for the lowest specific gravity of 2.93) and far less than the maximum geotechnical water contents in the structural zone (52%) and non-structural zone (58%). For comparison, the saturated geotechnical water contents are 53.4%, 50.1%, 48.9%, and 47.7%, for specific gravities for solid tailings of 2.93, 3.12, 3.20 and 3.28. Although it is not necessary for the bottom tailings to be saturated for drainage to occur, the bottom tailings will most likely become saturated due to tailings consolidation, a factor that was considered by NewFields (2020), but not by Piteau Associates (2021a-b). Finally, the inability of Piteau Associates (2021a-b) to predict drainage for unsaturated conditions within the CTFS casts doubt on their correct use of the HYDRUS software. Figure from Sandra et al. (2021a-b).
Field Capacity

The water stored in pores at volumetric water contents between the saturated volumetric water content and the field capacity is called the gravitational water (see Fig. 3). Thus, drainage under gravity will occur from unsaturated soils or tailings stacks until the volumetric water content has fallen to the field capacity. At field capacity, there is a balance between the gravitational forces that pull water downward and the capillary forces that prevent water from moving from pores into large open spaces (such as a drainage collection system). The field capacity is generally regarded as the volumetric water content corresponding to a soil water potential equal to 0.033 MPa, which is equivalent to a column of water of height 3.37 meters (Hillel, 1980b; Charbeneau, 2000; Sandra et al., 2021; see Fig. 3). (Note that Fig. 3 regards soil water potentials as negative values.) It should be noted that field capacity is not the same concept as residual volumetric water content (compare Figs. 1 and 3) and that field capacities tend to be much higher than residual volumetric water contents. For example, the mean field capacity for clay loam soils is 0.311, while the mean residual volumetric water content is 0.075 (Charbeneau, 2000).

REVIEW OF FILTERED TAILINGS TECHNOLOGY

Filtered tailings technology seeks to address two important problems in mining by partially dewatering the tailings before they are shipped to the tailings storage facility:

1) The water consumption can be reduced by recycling the water from the tailings back into the mining operation.
2) The likelihood of liquefaction of the tailings can be reduced by desaturating the tailings and then by compacting the tailings as they are stored in a filtered tailings storage facility.

In conventional tailings management, the tailings are shipped to the tailings storage facility from the ore processing plant with no dewatering, so that the geotechnical water content of the tailings is in the range 150-400%, although it can be as low as 67%. High-density thickened or paste tailings technology dewater the tailings to geotechnical water contents in the range 33-67% prior to export to the tailings storage facility, while filtered tailings technology dewater the tailings to geotechnical water contents less than about 20%. Conventional tailings behave like a wet slurry, while high-density thickened or paste tailings behave like a paste (as the name implies), and filtered tailings behave like a moist soil. The boundaries between the different tailings technologies depend upon the physical and chemical properties of the tailings, and is defined by physical behavior, not geotechnical water content. Other advantages of filtered tailings technology are reduction of the footprint of the tailings storage facility and facilitating the safe closure of the facility (Klohn Crippen Berger, 2017).

Although the response to public comments by NDEP (2022c) repeatedly refers to the CTFS as a “dry stack,” this is non-standard terminology. For example, according to NDEP (2022c), “With the facility being operated as a dry stacked facility, there is significantly less potential to degrade waters of the State … For the Thacker Pass Project the CTFS does not have a lower level of engineered containment with the incorporation of leak detection, being a dry stacked facility.” The tailings are not literally dry and, if they were, it would be impossible to properly compact them for safe storage. On their website, the consulting company Knight-Piésold includes a publication by employees of Knight-Piésold that states, “Regarding terminology, the rather misleading term dry stack is generally not a good engineering term since
the target moisture content coming from the filter plant is typically desired to be somewhere around the optimum moisture content based on the Proctor compaction procedure … Geotechnical engineers associate the optimum moisture content with moisture levels just below full saturation after compaction, thus terming such a facility as a dry stack is a misnomer. The present authors would encourage practitioners to abandon the use of the term dry stacking in favor of the more straightforward term, ‘filtered tailings.’ It is not desirable to unintentionally mislead the public at large with an industry term that is noticeably misused” (Ulrich and Coffin, 2017). With regard to the proposed Twin Metals mine, for which the mineral lease has since been cancelled, the Minnesota Department of Natural Resources (2021) asked, “Is characterizing the tailings filter cake as being ‘dry’ a common terminology for a product exhibiting a 13% to 16% moisture content?” Finally, the SME (Society for Mining, Metallurgy and Exploration) Tailings Management Handbook confirms that “The term dry stacking … is somewhat of a misnomer. Stacked tailings must be sufficiently dry to allow placement in stable and trafficable piles, but not so dry as to result in dust generation from prevailing wind” (Reemeyer, 2022). In this report, the tailings will be referred to as “filtered” rather than “dry,” except to quote from documents provided by NDEP, Lithium Nevada, or their consultants.

A simple comparison of the preceding water contents for the different categories of tailings overstates the reduction in water consumption that can be achieved by the transition from conventional to filtered tailings technology. The reason is that, within the tailings storage facility, the solid tailings will settle out of suspension so that the supernatant water can be recycled back into the mining operation. For example, a typical mill will export to the tailings storage facility 70 US tons of water for every 30 US tons of solid tailings (see Fig. 4). In a typical conventional tailings storage facility, of those 70 US tons of water, 7 US tons of water will remain entrained within the tailings for a geotechnical water content of 23.3%, while 63 US tons of water will be released at the tailings facility and recycled back into the mining operation (see Fig. 4). The progression from conventional to thickened to high-density thickened to paste tailings technology increases the proportion of water that is recycled through dewatering of the tailings prior to shipment to the tailings storage facility (“reclaimed during processing”) and decreases the proportion of water that is recycled out of the tailings storage facility (“released at tailings facility”) (see Fig. 4). However, the end result from a water consumption standpoint does not change, namely that typically, for every 30 US tons of solid tailings, 7 US tons of water remain permanently entrained within the tailings (see Fig. 4). The step change occurs in the transition to filtered tailings technology, in which, typically, no water can be recycled from the filtered tailings storage facility, while 5 US tons of water remain entrained within the tailings for every 30 US tons of solid tailings, for a geotechnical water content of 16.7% (see Fig. 4). In summary, the typical reduction in water consumption through the use of filtered tailings technology is 2 US tons of water for every 30 US tons of solid tailings, in comparison to any other tailings management technology (Klohn Crippen Berger, 2017).

An additional source of reduction in water consumption through filtered tailings technology is the reduction in evaporation through the elimination of a free water surface on top of the tailings. The evaporation from the tailings pond is highly variable and depends upon solar radiation, water temperature, and atmospheric factors, such as air temperature, relative humidity and wind speed, as well as the technologies that can be used to reduce evaporation. According to Spiller and Dunne (2017), “The amount of evaporation of water from the TSF [Tailings Storage Facility] may range from about 5% to more than 60% of the total water lost at a TSF.” On that basis, at the lower end of evaporation (5% of total water loss), for every 7 US tons of water
entrained within the tailings, another 0.4 US tons of water will be lost to evaporation. At the higher end of evaporation (60% of total water loss), for every 7 US tons of water entrained within the tailings, another 10.5 US tons of water will be lost to evaporation. Thus, the reduction in water consumption through a conversion to filtered tailings technology could be as high as 12.5 US tons of water for every 30 US tons of tailings if the conversion occurred from an existing or planned facility with extremely high evaporation and no other technologies for reducing evaporation. On the other hand, the tailings pond can also be a source of water through the capture of precipitation and surface runoff (Klohn Crippen Berger, 2017). Most case studies regarding conversions to filtered tailings technology have not explicitly taken into account any reduction in water consumption through reduction in evaporation from the tailings pond (e.g., Gagnon and Lind, 2017; Moreno et al, 2018).

Figure 4. In conventional tailings management, a slurry is pumped from the ore processing plant to the tailings storage facility with a typical mixture of 70 tons of water for 30 tons of solids, corresponding to a geotechnical water content of 233%. However, the water and tailings will separate at the facility, with the supernatant water recycled into the mining operation, minus the water lost by evaporation. Thus, within the stored tailings, it is common to find 7 tons of entrained water for 30 tons of solids, corresponding to a geotechnical water content of 23%. In filtered tailings stacks, water and tailings should not separate, leaving 5 tons of entrained water for 30 tons of solids, corresponding to a typical geotechnical water content of 17%. According to NDEP (2022c), “The Division disagrees that seepage may reach thousands of gallons per minute, as this rate of seepage is not realistic even for a conventional tailings impoundment with slurry deposition.” However, it should be noted that, even at the target geotechnical water content of 46%, the clay tailings filter stack (CTFS) at the Thacker Pass mine would have a geotechnical water content about twice that of the tailings in a conventional tailings storage facility (23%). To the best knowledge of the author, the CTFS would have the highest geotechnical water content of any tailings storage facility ever constructed. Figure from Klohn Crippen Berger (2017).
Filtered tailings technology reduces the likelihood of liquefaction of the tailings pile through desaturating the pore spaces between the tailings, reducing the overall quantity of water in the tailings storage facility, and compacting the tailings within the tailings storage facility. This compaction reduces the likelihood of liquefaction by putting the tailings into a dilative (as opposed to contractive) state in which they will expand rather than consolidate when they are sheared or disturbed. Most typically, filtered tailings storage facilities are constructed with an outer shell of compacted tailings (sometimes called the “structural zone”) surrounding an inner core of uncompacted or lightly compacted tailings (see Fig. 5). Although some recent mining project plans have claimed that filtered tailings do not require a dam, the structural zone fulfills the exact same function as a dam, that is, it is an engineered structure that prevents the flow of water or waste materials containing water. For example, with regard to its proposal for a copper mine in Minnesota, Twin Metals Minnesota (2022) wrote, “Dry stacking filtered tailings means there is no need for a dam – dam failure is impossible.” The response from the Minnesota Department of Natural Resources (2021) was that a dam is a “structure that impounds water and/or waste materials containing water” (emphasis in the original). Klohn Crippen Berger (2017) has also emphasized that a filtered tailings facility “still requires ‘structural zones’ (which perform like dams), made of compacted tailings for confinement” and “if filtered tailings are placed in a stand-alone facility (pile/stack), the outer slopes must maintain structural stability (similar to a dam or a waste dump), particularly under seismic loading conditions.” Finally, according to Safety First: Guidelines for Responsible Mine Tailings Management, “The structural zone of a filtered tailings facility is a type of tailings dam” (Morrill et al., 2020). Thus, it is misleading for NewFields (2020) to state that “the CTFS is not a water retaining structure, nor is it a dam.” The structural zone is a type of dam and it is difficult to understand how an engineered structure that contains material with a geotechnical water content of 46% could be described as “not a water retaining structure.”

The inner core of a filtered tailings storage facility is, in fact, a requirement for the storage of tailings that left the filter presses with too much water for adequate compaction. Crystal et al. (2018) have emphasized that target water contents for filtered tailings are rarely achieved. According to Crystal et al. (2018), “Commonly, projects are specifying (or promising) a target filter-cake moisture at the limit of the filter performance (including at the limit of the thickener’s ability to deliver feed at the required solids ratio). This has caused numerous examples where the operating performance does not consistently meet the target … Essentially, irrespective of site, ore body type, or filter press manufacturer, a 15% moisture content remains a typical target, while tracking of day-in and day-out moisture contents of filter cakes demonstrates that achievable moisture contents are often in the range of 17 to 18% when things are running smoothly and can be up to 20 to 23% when off-spec … ‘Targets’ may be cited or promised, but achievable filter cake moisture contents and the variability of the process are not generally within the tailings engineer’s control.” For example, Mexican gold and silver mines that use filtered tailings technology have achieved geotechnical water contents in the range 14-19% (Espinosa-Gomez et al., 2018). Even if the tailings leave the filter presses with the target geotechnical water content, they can still be rewetted by precipitation. Thus far, these filtered tailings storage facilities have mostly been small and mostly constructed in areas with arid climates (Klohn Crippen Berger, 2017). The partial restriction to arid regions has partly been motivated by the greater need to recycle water in regions with high water scarcity. However, an additional factor has been the challenges in achieving the appropriate water content for adequate compaction in wet climates. At the present time, the standard solution in both arid and wet climates is to set
aside an inner core (a region away from the outer slopes) for placement of tailings that cannot be adequately compacted. Crystal et al. (2018) continue, “The tailings engineer can, however, specify acceptable moisture contents for different areas of the dry stack, depending on stacking strategies. For example, external structural zones may have more stringent criteria than non-structural zones, for which reduced constraints may be allowed.”

Figure 3.5  Schematic of a Filtered Tailings Facility

Figure 5. Current filter press technology does not consistently produce filtered tailings with the appropriate geotechnical water content for adequate compaction. Even if tailings do leave the filter presses with the appropriate water content, they can be rewetted by precipitation. The standard solution for filtered tailings stacks is to place the tailings that are too wet or too dry for adequate compaction in the center of the facility in a non-structural zone, in which the tailings are either uncompacted or lightly compacted. The tailings with the appropriate water content for adequate compaction are then placed on the periphery, where they can be compacted to form a structural zone. The structural zone serves the same function as a dam for the non-structural zone. In the case of the clay tailings filter stack (CTFS) at the Thacker Pass mine (see Fig. 7), the non-structural zone would consist of clay tailings blended with salt with geotechnical water content in the range 34-58%. The structural zone would consist only of clay tailings with geotechnical water content in the range 40-52%. Figure from Klohn Crippen Berger (2017).

Because of its ability to reduce both the likelihood and the consequences of failure of tailings storage facilities, filtered tailings technology is currently regarded as the best available technology. According to the expert panel report on the failure of the tailings storage facility at the Mount Polley mine, “BAT [Best Available Technology] has three components that derive from first principles of soil mechanics: 1. Eliminate surface water from the impoundment. 2. Promote unsaturated conditions in the tailings with drainage provisions. 3. Achieve dilatant conditions throughout the tailings deposit by compaction … Filtered tailings technology embodies all three BAT components … There are no overriding technical impediments to more widespread adoption of filtered tailings technology.” The document Safety First: Guidelines for Responsible Mine Tailings Management also mandates “the use of Best Available Technology for tailings, in particular filtered tailings” (Morrill et al., 2020).

At the same time, it goes without saying that the use of filtered tailings technology cannot be a license for ignoring other aspects of safety. Even though Twin Metals Minnesota (2021)
writes, “Dry stacking filtered tailings means there is no need for a dam – dam failure is impossible,” failure is never impossible. In fact, a filtered tailings storage facility collapsed at the Pau Branco iron-ore mine in Brazil on January 8, 2022 (Angelo, 2022; Morrill, 2022; Petley, 2022; see Fig. 6). In fact, the use of filtered tailings technology can lead to complacency from an illusion of safety. According to Oboni and Oboni (2020), “Dewatered tailings would tend to bring the probability of failure towards the bottom of the historical range, provided, of course the dewatering is effective, and does not generate excessive risk taking based on its promises.” A related issue is the lack of guidance based on experience that always results from the adoption of a new technology. Again, according to Oboni and Oboni (2020), “The problem is that the possible alternatives to slurry deposition have not yet created the same body of knowledge that could support development of professional guidances and protocols of a quality equal to that for slurry deposition.” Further issues related to the adoption of new technologies will be developed in the Discussion section.

Figure 6. A 48-meter-high filtered tailings stack collapsed at the Pau Branco iron-ore mine in Brazil on January 8, 2022. Although filtered tailings are regarded as the Best Available Technology at the present time (Independent Expert Engineering Investigation and Review Panel, 2015; Morrill et al., 2020), the use of filtered tailings technology is not a license to ignore every other aspect of safety. Photo from Angelo (2022).

A key issue is that although filtered tailings may be unsaturated when deposited in the tailings storage facility, it is still necessary to prevent resaturation of the tailings in order to prevent future liquefaction. The problem is particularly acute since the target geotechnical water content for maximum compaction is typically only a few percentage points less than the saturated geotechnical water content. The pore spaces between the tailing particles can become resaturated simply by consolidation under the weight of additional overlying tailings, which reduces the volume of pores so that they become filled with water (Klohn Crippen Berger, 2017). In fact, it is not unusual for the lower one-third to one-half of a filtered tailings stack to be saturated, and the stability analysis for the CTFS was based on the assumption that the water
The table would be one-half of the height of the CTFS (NewFields, 2020; see Fig. 7). Water can also enter the filtered tailings storage facility through surface runoff, upward groundwater seepage, and direct precipitation onto the tailings. The above water sources require diversion canals that isolate the tailings storage facility from the rest of the watershed and appropriate drainage infrastructure for conveying any excess water out of the tailings.

**Figure 7.** Because of the tendency of overlying tailings to further compact the underlying tailings (called tailings consolidation), thus reducing the size of pores, so that unsaturated pores could become saturated, it is common for the phreatic surface (the surface below which all pores are saturated, also called the water table) to be one-third to one-half of the height of the filtered tailings stack. NewFields (2020) assumed that the phreatic surface would be one-half the height of the clay tailings filter stack (CTFS) as a worst-case scenario for the stability analysis. NewFields (2020) assumed that tailings consolidation would occur in their seepage analysis (see Fig. 9), although Piteau Associates (2021a-b) did not take tailings consolidation into account (see Figs. 10a-c and 11a-b). The above figure also illustrates the structural zone of the clay tailings filter stack (CTFS), which acts as the dam for the confinement of the non-structural zone (compare with Fig. 5). The non-structural zone would consist of clay tailings blended with salt with geotechnical water content in the range 34-58%. The structural zone would consist only of clay tailings with geotechnical water content in the range 40-52%. Figure from NewFields (2020).

It is important to point out that filtered tailings storage facilities have other possible failure mechanisms besides liquefaction. For example, surface runoff flowing over the structural zone could erode it away, thus exposing the uncompacted tailings that were behind the structural zone (see Fig. 5). Uneven settlement or failure of the foundation beneath the filtered tailings storage facility could cause failure of the entire structure. Finally, the structural zone (dam) could fail simply by sliding with no liquefaction or other flow behavior. According to Klohn Crippen
Berger (2017), due to the typical low water content of filtered tailings, “Failure, if it occurs, would likely be local slumping and consequences would be restricted to the local area (or the distance equivalent to roughly 10 times the height [of the tailings dam]) …” On the other hand, flow behavior of the tailings could develop if the tailings mixed with sufficient water after dam failure. The above quote continues, “… unless the material slumps into a water body … When large water ponds are located downstream of high-density thickened/paste facilities, cascading failures are possible and should be accounted for when developing the risk profile of tailings failure management” (Klohn Crippen Berger, 2017). On the above basis, drainage and runoff collection ponds should be located sufficiently far downstream from the tailings storage facility and excessive accumulation of water in these ponds should be avoided (Klohn Crippen Berger, 2017; see Fig. 5).

SUMMARY OF CLAY TAILINGS FILTER STACK AT THACKER PASS MINE

The materials intended for permanent storage in the CTFS include un-leached clay solids, neutralization solids, magnesium sulfate salt, and sodium/potassium salt (NDEP, 2021b). The neutralization solids and sulfate salts are all generated during the acid leaching process. According to a response from Lithium Nevada contained in NDEP (2021b), “The un-leached clay solids (clay solids) and neutralization solids will be combined in the process plant and conveyed to the CTFS. The combined material are ‘clay tailings.’” This report will follow the same convention in referring to the un-leached clay solids and the neutralization solids collectively as “clay tailings.” Newfields (2020) measured an optimum geotechnical water content of 46.0% for maximum compaction of tailings without salt (see Fig. 8a) and an optimum geotechnical water content of 45.3% for maximum compaction of tailings blended with salt (see Fig. 8b). According to Newfields (2020), “The addition of salt to the tailings decreases the LL [liquid limit] of the material, further reducing the workability at as produced moisture contents … Therefore, the recommendation is that the salts be handled separately from the tailings and placed in nonstructural zones within the CTFS facility.” The liquid limit is the geotechnical water content above which the tailings will flow as a viscous liquid (Holtz et al., 2011).

Based on the above results, the design for the CTFS includes a structural zone composed of clay tailings and a non-structural zone composed of tailings blended with sulfate salts (see Fig. 7), with the target geotechnical water content for both zones being 46% (NDEP, 2022b). As is typical, the non-structural zone would have a wider range of acceptable geotechnical water contents. According to NDEP (2022b), “The material placed in the structural zone must have the moisture content required to achieve structural stability (46 ± 6 percent) … If placed in the nonstructural zone, the material must have a moisture content of 46 ± 12 percent.” It is important to note that the above geotechnical water contents are far higher than what is typical for filtered tailings storage facilities (15-20%). In fact, the geotechnical water content would be twice as high as is typical for the tailings pile (excluding any overlying tailings pond) for even conventional tailings impoundments (see Fig. 4). Despite the persistent use of the phrase “dry stack” by NDEP (2022c), the CTFS at the Thacker Pass mine would probably have the highest geotechnical water content of any tailings storage facility that has ever been constructed.
Figure 8a. NewFields (2020) measured an optimum geotechnical water content of 46.0% for maximum compaction of tailings without salt, which became the target geotechnical water content for the clay tailings filter stack (CTFS). NewFields (2020) also measured a tailings specific gravity of 3.12. Other assumed and measured specific gravities in the same report (NewFields, 2020) were 2.93 (see Fig. 12a), 3.20 (see Fig. 12b), and 3.28 (see Fig. 8b). All calculations in this report were carried out for all four specific gravities (see Figs. 18a-d, 20a-d, and 21a-d). Figure from NewFields (2020).
NewFields (2020) measured an optimum geotechnical water content of 45.3% for maximum compaction of tailings blended with salt. NewFields (2020) also measured a tailings specific gravity of 3.28. Other assumed and measured specific gravities in the same report (NewFields, 2020) were 2.93 (see Fig. 12a), 3.12 (see Fig. 8a), and 3.20 (see Fig. 12b). All calculations in this report were carried out for all four specific gravities (see Figs. 18a-d, 20a-d, and 21a-d), although measurements for tailings with salt should apply only to the non-structural zone. Figure from NewFields (2020).

**Figure 8b.**
Figure 9. NewFields (2021) calculated a seepage rate of 74 gpm from the clay tailings filter stack (CTFS) at a geotechnical water content of 49.1%. No document from NewFields (2020, 2021) has explained how the calculation was carried out, how or whether meteorological variables (such as precipitation and evaporation) were taken into account, or clarifies whether the calculation applies to the operation or closure phase. According to NewFields (2020), “A seepage calculation was completed which showed a maximum seepage rate of up to 74 gpm could flow to the Reclaim Pond at ultimate facility buildout as a result of tailings consolidation. The seepage calculation is presented in Appendix E.” However, the calculation is not discussed in Appendix E of NewFields (2020) and nothing else explains how tailings consolidation was taken into account. In addition, no document reconciles the contradiction between 74 gpm as the “estimated average seepage flow rate” in the figure above (NewFields, 2021) and as the “maximum seepage rate” in the preceding quote (NewFields, 2020). A possible interpretation of the table above is that it was assumed that tailings consolidation caused saturation of the entire stack at a saturation geotechnical water content of 49.1%, at which the saturated hydraulic conductivity (saturated permeability) was $10^{-6}$ cm/s. Under those assumptions, the seepage rate would be equal to the saturated hydraulic conductivity multiplied by the area. The seepage rate would be unaffected by precipitation, which would only keep the pores saturated with any excess either ponding or becoming runoff. However, multiplying the hydraulic conductivity ($10^{-6}$ cm/s) by the area ($18 \times 10^6$ ft$^2$) yields a seepage rate of 265 gpm, not 74 gpm.
HISTORY OF SEEPAGE ANALYSES

Seepage Analysis by NewFields

NewFields (2021) calculated a seepage rate of 74 gpm from the CTFS at a geotechnical water content of 49.1% (see Fig. 9). The key feature of the calculation, the only feature mentioned in Newfields (2020), is that tailings consolidation was taken into account in the calculation. According to NewFields (2020), “A seepage calculation was completed which showed a maximum seepage rate of up to 74 gpm could flow to the Reclaim Pond at ultimate facility buildout as a result of tailings consolidation. The seepage calculation is presented in Appendix E.” However, the calculation is not discussed in Appendix E of NewFields (2020) and nothing else explains how tailings consolidation was taken into account. No document from NewFields (2020, 2021) has explained how the calculation was carried out, how or whether meteorological variables (such as precipitation and evaporation) were taken into account, why a geotechnical water content of 49.1% was chosen, or clarifies whether the calculation applies to the operation or closure phase. In addition, no document reconciles the contradiction between 74 gpm as the “estimated average seepage flow rate” (NewFields, 2021; see Fig. 9) and as the “maximum seepage rate” in the preceding quote (NewFields, 2020).

A possible interpretation of Fig. 9 is that it was assumed that tailings consolidation caused saturation of the entire stack at an assumed saturation geotechnical water content of 49.1%, at which the saturated hydraulic conductivity (saturated permeability) was $10^{-6}$ cm/s. Under those assumptions, the seepage rate would be equal to the flux multiplied by the area, and according to Eq. (13), the flux would be equal to the saturated hydraulic conductivity. The seepage rate would be unaffected by precipitation, which would only keep the pores saturated with any excess either ponding or becoming runoff. However, multiplying the hydraulic conductivity ($10^{-6}$ cm/s) by the area ($18 \times 10^6$ ft$^2$; see Fig. 9) yields a seepage rate of 265 gpm, not 74 gpm. Note that NewFields (2021) assumed the area of the base of the stack to be $18 \times 10^6$ ft$^2$ (413 acres), whereas Piteau Associates (2021-b) assumed a smaller area of 386 acres (see Fig. 9).

Seepage Analysis by Piteau Associates

Piteau Associates (2021a) used the HYDRUS software to calculate the seepage rate from the CTFS only after closure after 10 years of operation, corresponding to the first phase of the mining project and the only phase that has received a permit. After closure, the filtered tailings stack would be covered by a 12-inch layer of growth medium underlain by a 12-inch layer of waste rock. Piteau Associates (2021a) considered measurements of three samples of filtered tailings for the development of model parameters (see Fig. 10a). In its responses to NDEP, Lithium Nevada explained that “The 4-LFILTCAKE is the filter cake after acid leaching of the clay ore slurry and filtration. 4381-Blend is a blended sample of the clay solids and the neutralization solids which is the material from the acid leaching process and the pH neutralization and filtration process before being placed onto the clay tailings conveyor. 9-036-01 is a sample of the filter cake after acid leaching of the clay ore slurry and filtration” (NDEP, 2021b). The parameter $\Phi_{sat}$ is presumably the saturated volumetric water content (equivalent to the porosity), not the saturated geotechnical water content (see Fig. 10a). The hydraulic
conductivity is presumably the saturated hydraulic conductivity, although that is not stated (see Fig. 10a).

![Table 1](image)

**Table 1: Hydraulic summary of clay tailing samples**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>% Sand &amp; Gravel</th>
<th>% Silt</th>
<th>% Clay</th>
<th>USCS Classification</th>
<th>Hydraulic Conductivity (cm/s)</th>
<th>Φsat</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-LFILTCAKE-E05B-315</td>
<td>61.4</td>
<td>17.1</td>
<td>21.4</td>
<td>SM</td>
<td>8.3 x 10^{-7}</td>
<td>0.63</td>
<td>DBSA, 2019</td>
</tr>
<tr>
<td>4381-Blend</td>
<td>52.8</td>
<td>12.3</td>
<td>34.9</td>
<td>SM</td>
<td>4.8 x 10^{-6}</td>
<td>0.59</td>
<td>DBSA, 2019</td>
</tr>
<tr>
<td>19-036-01</td>
<td>16.5</td>
<td>28.4(^1)</td>
<td>54.8(^1)</td>
<td>ML</td>
<td>4.1 x 10^{-7}</td>
<td>0.59</td>
<td>Newfields, 2019</td>
</tr>
</tbody>
</table>

\(^1\) Projected from ratio of other samples

**Figure 10a.** Piteau Associates (2021a) considered measurements of three samples of filtered tailings for the development of model parameters. In its responses to the Nevada Division of Environmental Protection, Lithium Nevada explained that "The 4-LFILTCAKE is the filter cake after acid leaching of the clay ore slurry and filtration. 4381-Blend is a blended sample of the clay solids and the neutralization solids which is the material from the acid leaching process and the pH neutralization and filtration process before being placed onto the clay tailings conveyor. 9-036-01 is a sample of the filter cake after acid leaching of the clay ore slurry and filtration" (NDEP, 2021b). The parameter Φ\(_{\text{sat}}\) is presumably the saturated volumetric water content (equivalent to the porosity), not the saturated geotechnical water content. The hydraulic conductivity is presumably the saturated hydraulic conductivity, although that is not stated. The table above is identical to the equivalent table in Piteau Associates (2021b), except that Piteau Associates (2021b) includes an additional sample for a blend of filtered tailings and salt (see Fig. 11a). Table from Piteau Associates (2021a).

As input parameters for the HYDRUS software, Piteau Associates (2021a) assumed α = 0.6, N = 1.128, residual (or irreducible) volumetric water content θ\(_r\) = 0.066, saturated volumetric water content θ\(_{\text{sat}}\) = 0.61, saturated hydraulic conductivity \(K_{\text{sat}}\) = 1.2 x 10^{-6} cm/s, and an initial (at the time of closure) geotechnical water content of 46% (see Fig. 10b). The parameters α and N presumably correspond to the van Genuchten model for the soil water characteristic curve (see Eq. (8)), although this was never stated (see Fig. 10b). Note that the value of \(K_{\text{sat}}\) = 1.2 x 10^{-6} cm/s is very close to the hydraulic conductivity (permeability) of 10^{-6} cm/s that was chosen by NewFields (2021) for a geotechnical water content of 49.1% (compare Figs. 9 and 10b). The geotechnical water contents that correspond to the above volumetric water contents require an assumption for the tailings specific gravity and will be discussed in the Methodology section. For the sensitivity analysis, Piteau Associates (2021a) substituted the equivalent input parameters for a silt loam available in the HYDRUS database. It is unclear why a silt loam was chosen, since the textural classes of the first two samples (see Fig. 10a) considered by Piteau Associates (2021a) are sandy clay loams, while the textural class of the third sample (see Fig. 10a) is clay (USDA-NRCS, 2022).

Piteau Associates (2021a) calculated negligible seepage during the first 1000 years after closure. According to Piteau Associates (2021a), “Seepage related to the drainage of in-situ water content during the first 1,000 years of emplacement was zero. Water content at the bottom of the CTFS was simulated to slowly increase as a result of unsaturated gravity drainage … However, pore water along the bottom of the CTFS will remain in tension with clay material.
until water content reaches field saturation conditions to overcome capillary tension and freely seep into the collection system.” Piteau Associates (2021a) then calculated a long-term steady-state seepage of 0.02 gpm (see Fig. 10c) through the CTFS for the base case, which consisted of the above input parameters (see Fig. 10b) with a 12-inch cover layer of growth media underlain by a 12-inch layer of waste rock.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha$ (1/m)</th>
<th>$N$</th>
<th>$\theta_r$</th>
<th>$\theta_{sat}$</th>
<th>$K_{sat}$ (cm/s)</th>
<th>Initial Water Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth Media</td>
<td>0.74</td>
<td>1.342</td>
<td>0.021</td>
<td>0.424</td>
<td>$6.1 \times 10^{-6}$</td>
<td>23</td>
</tr>
<tr>
<td>Waste Rock</td>
<td>1.67</td>
<td>1.336</td>
<td>0.03</td>
<td>0.435</td>
<td>$6.8 \times 10^{-6}$</td>
<td>23</td>
</tr>
<tr>
<td>Clay Tailings</td>
<td>0.6</td>
<td>1.128</td>
<td>0.066</td>
<td>0.61</td>
<td>$1.2 \times 10^{-6}$</td>
<td>46¹</td>
</tr>
<tr>
<td>Alternate Clay Tailings</td>
<td>2</td>
<td>1.41</td>
<td>0.067</td>
<td>0.45</td>
<td>$1.2 \times 10^{-4}$</td>
<td>30</td>
</tr>
</tbody>
</table>

¹Projected water content of stacked clay tailings
²Selected soil material data from HYDRUS database

Figure 10b. As input parameters for the HYDRUS software, Piteau Associates (2021a-b) assumed $\alpha = 0.6$, $N = 1.128$, residual (or irreducible) volumetric water content $\theta_r = 0.066$, saturated volumetric water content $\theta_{sat} = 0.61$, saturated hydraulic conductivity $K_{sat} = 1.2 \times 10^{-6}$ cm/s, and an initial geotechnical water content of 46%. The parameters $\alpha$ and $N$ presumably correspond to the van Genuchten model for the soil water characteristic curve. For the sensitivity analysis, Piteau Associates (2021a-b) substituted the equivalent input parameters for a silt loam available in the HYDRUS database. It is unclear why a silt loam was chosen, since the textural classes of the first two samples (see Figs. 10a and 11a) considered by Piteau Associates (2021a-b) are sandy clay loams, while the textural class of the third sample (see Figs. 10a and 11a) is clay (USDA-NRCS, 2022). “Growth Media” and “Waste Rock” refer to the closure cover materials. Table from Piteau Associates (2021a-b).

Sensitivity analyses included the use of the input parameters for the silt loam from the HYDRUS database, the assumption of no transpiration, the reduction of potential evapotranspiration by 15%, and the use of only a 12-inch cover layer of growth media (without the underlying waste rock) (see Fig. 10c). The variation in predicted steady-state seepage rates over two orders of magnitude (as high as 2.42 gpm) emphasizes that the calculation is strongly dependent upon the choice of input parameters and conditions. All four sensitivity analyses considered alternative conditions separately, but not in combination. According to NDEP (2022c), “In the sensitivity analysis, all conditions are held steady, then one parameter is varied at a time to determine its impact potential. By varying multiple parameters concurrently, there would be no way to determine which variable resulted in a change to the model outcome” (NDEP, 2022c). However, often the greatest variation in predictions results from the interaction between input parameters. Thus, the standard practice in sensitivity analyses is to vary input parameters both separately and in combination in order to show a more realistic range in predictions.

Piteau Associates (2021b) updated the preceding calculation only by considering two additional sensitivity analyses. Although the properties of an additional tailings sample (composite salt / clay tailings) were considered (see Fig. 11a), they were not used to update any
of the input parameters (see Fig. 10b). The additional sensitivity analyses were the use of only the growth media and waste rock with no underlying tailings (cover only) and doubling the mean annual precipitation. The steady-state seepage was still 0.02 gpm for the base case (see Fig. 11b). The variation in predicted steady-state seepage rates now ranged over three order of magnitude (up to 12.7 gpm for doubling the annual precipitation and 15.2 gpm for cover only), which further emphasizes that the calculation is strongly dependent upon the choice of input parameters and conditions (see Fig. 11b). As in Piteau Associates (2021a), all six sensitivity analyses considered alternative conditions separately, but not in combination, so that there was no way to assess the interactions among input parameters and conditions.

Table 3  Summary of Infiltration Results

<table>
<thead>
<tr>
<th>Simulation / Sensitivity</th>
<th>Cumulative 1D Seepage (m)</th>
<th>Average Seepage Rate (in/yr)</th>
<th>Average Seepage Rate (% MAP)</th>
<th>Facility Seepage Rate (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>0.02</td>
<td>0.001</td>
<td>0.01%</td>
<td>0.02</td>
</tr>
<tr>
<td>Alternate Clay Tailings</td>
<td>1.0</td>
<td>0.056</td>
<td>0.46%</td>
<td>1.12</td>
</tr>
<tr>
<td>No Transpiration</td>
<td>2.2</td>
<td>0.121</td>
<td>0.99%</td>
<td>2.42</td>
</tr>
<tr>
<td>Reduced Evaporation</td>
<td>0.14</td>
<td>0.008</td>
<td>0.06%</td>
<td>0.15</td>
</tr>
<tr>
<td>12-inch Cover</td>
<td>0.68</td>
<td>0.038</td>
<td>0.31%</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Figure 10c. Piteau Associates (2021a) used the HYDRUS software to calculate a long-term (post-closure) steady-state seepage of 0.02 gpm through the clay tailings filter stack (CTFS) for the base case, which consisted of the input parameters shown in Fig. 10a, with a 12-inch cover layer of growth media underlain by a 12-inch layer of waste rock. Sensitivity analyses included the use of the input parameters for the silt loam from the HYDRUS database, the assumption of no transpiration, the reduction of potential evapotranspiration by 15%, and the use of only a 12-inch cover layer of growth media (without the underlying waste rock). The variation in predicted steady-state seepage rates over two orders of magnitude emphasizes that the calculation is strongly dependent upon the choice of input parameters and conditions. All four sensitivity analyses considered alternative conditions separately, but not in combination. According to the Nevada Division of Environmental Protection, “In the sensitivity analysis, all conditions are held steady, then one parameter is varied at a time to determine its impact potential. By varying multiple parameters concurrently, there would be no way to determine which variable resulted in a change to the model outcome” (NDEP, 2022c). However, often the greatest variation in predictions results from the interaction between input parameters. Thus, the standard practice in sensitivity analyses is to vary input parameters both separately and in combination in order to show a more realistic range in predictions. Piteau Associates (2021a) considered seepage through the CTFS only after closure and not during operation. According to Piteau Associates (2021a), “Seepage related to the drainage of in-situ water content during the first 1,000 years of emplacement was zero. Water content at the bottom of the CTFS was simulated to slowly increase as a result of unsaturated gravity drainage … However, pore water along the bottom of the CTFS will remain in tension with clay material until water content reaches field saturation conditions to overcome capillary tension and freely seep into the collection system.” The above discussion by Piteau Associates (2021a) is not correct because drainage from the CTFS will occur as long as the volumetric water content of the base of the stack exceeds the field capacity (see Fig. 3). The inability of Piteau Associates (2021a) to predict drainage for unsaturated conditions within the CTFS casts doubt on their correct use of the HYDRUS software. Although it is not necessary for the bottom tailings to be saturated for drainage to occur, the bottom tailings will most likely become saturated due to tailings consolidation, a factor that was considered by NewFields (2020), but not by Piteau Associates (2021a). The equivalent table in Piteau Associates (see Fig. 11b) has the same results, but with additional sensitivity analyses. Table from Piteau Associates (2021a).
Table 1 Hydralic summary of clay tailing samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>% Sand &amp; Gravel</th>
<th>% Silt</th>
<th>% Clay</th>
<th>USCS Classification</th>
<th>Hydraulic Conductivity (cm/s)</th>
<th>Φsat</th>
<th>Type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-LFILTCAKE-E05B-315</td>
<td>61.4</td>
<td>17.1</td>
<td>21.4</td>
<td>SM</td>
<td>8.3 x 10^-7</td>
<td>0.63</td>
<td>Clay Tailings</td>
<td>DBSA, 2019</td>
</tr>
<tr>
<td>4381-Blend</td>
<td>52.8</td>
<td>12.3</td>
<td>34.9</td>
<td>SM</td>
<td>4.8 x 10^-6</td>
<td>0.59</td>
<td>Clay Tailings</td>
<td>DBSA, 2019</td>
</tr>
<tr>
<td>19-036-01</td>
<td>16.5</td>
<td>83.5</td>
<td></td>
<td>ML</td>
<td>4.1 x 10^-7</td>
<td>0.59</td>
<td>Clay Tailings</td>
<td>Newfields, 2019</td>
</tr>
<tr>
<td>19-057-02C</td>
<td>35.4</td>
<td>64.6</td>
<td></td>
<td>ML</td>
<td>1.2 x 10^-7</td>
<td>0.45</td>
<td>Composite Salt / Clay Tailings</td>
<td>Newfields, 2019</td>
</tr>
</tbody>
</table>

1. This is percentage of Silt and Clay combined
2. Saturated Porosity ($Φ_{sat}$)

Figure 11a. Piteau Associates (2021b) considered measurements of four samples of filtered tailings for the development of model parameters. In its responses to the Nevada Division of Environmental Protection, Lithium Nevada explained that “The 4-LFILTCAKE is the filter cake after acid leaching of the clay ore slurry and filtration. 4381-Blend is a blended sample of the clay solids and the neutralization solids which is the material from the acid leaching process and the pH neutralization and filtration process before being placed onto the clay tailings conveyor. 9-036-01 is a sample of the filter cake after acid leaching of the clay ore slurry and filtration. 19-057-02C is a sample of the filter cake and salts blended at a ratio of 81.4% clay tailings and 18.6% salt as measured by dry weight which is the same ratio that is being produced in the process plant” (NDEP, 2021b). The parameter $Φ_{sat}$ is presumably the saturated volumetric water content (equivalent to the porosity), not the saturated geotechnical water content. The hydraulic conductivity is presumably the saturated hydraulic conductivity, although that is not stated. It is unclear how the saturated volumetric content for the composite salt / clay tailings ($Φ_{sat} = 0.45$) was or ever could be used, since it would be equivalent to saturated geotechnical water contents of 27.9%, 26.2%, 25.6%, and 24.9% for specific gravities of 2.93 (see Fig. 12a), 3.12 (see Fig. 8a), 3.20 (see Fig. 12b), and 3.28 (see Fig. 8b), respectively. A specific gravity of 3.28 (see Fig. 8b) is probably most relevant, since that measurement was also carried out on a blend of clay tailings and salt. The above saturated geotechnical water contents would all be far less than the target geotechnical water content (46%), the minimum geotechnical water content for the structural zone (40%), and even the minimum geotechnical water content for the non-structural zone (34%). The table above is identical to the equivalent table in Piteau Associates (2021a), except that Piteau Associates (2021a) does not include the sample of composite salt / clay tailings (see Fig. 10a). Table from Piteau Associates (2021b).
Figure 11b. Piteau Associates (2021b) used the HYDRUS software to calculate a long-term (post-closure) steady-state seepage of 0.02 gpm through the clay tailings filter stack (CTFS) for the base case, which consisted of the input parameters shown in Fig. 11a, with a 12-inch cover layer of growth media underlain by a 12-inch layer of waste rock. Sensitivity analyses included the use of the input parameters for the silt loam from the HYDRUS database, the assumption of no transpiration, the reduction of potential evapotranspiration by 15%, the use of only a 12-inch cover layer of growth media (without the underlying waste rock), the use of only the growth media and waste rock with no underlying tailings, and doubling the mean annual precipitation. The variation in predicted steady-state seepage rates over three orders of magnitude emphasizes that the calculation is strongly dependent upon the choice of input parameters and conditions. All six sensitivity analyses considered alternative conditions separately, but not in combination. According to the Nevada Division of Environmental Protection, “In the sensitivity analysis, all conditions are held steady, then one parameter is varied at a time to determine its impact potential. By varying multiple parameters concurrently, there would be no way to determine which variable resulted in a change to the model outcome” (NDEP, 2022c). However, often the greatest variation in predictions can result from the interaction between input parameters. Thus, the standard practice in sensitivity analyses is to vary input parameters both separately and in combination in order to show a more realistic range in predictions. Piteau Associates (2021b) considered seepage through the CTFS only after closure and not during operation. According to Piteau Associates (2021b), “Seepage related to the drainage of in-situ water content during the first 1,000 years of emplacement was zero. Water content at the bottom of the CTFS was simulated to slowly increase as a result of unsaturated gravity drainage … However, pore water along the bottom of the CTFS will remain in tension with clay material until water content reaches field saturation conditions to overcome capillary tension and freely seep into the collection system.” The above discussion by Piteau Associates (2021b) is not correct because drainage from the CTFS will occur as long as the volumetric water content of the base of the stack exceeds the field capacity (see Fig. 3). The inability of Piteau Associates (2021b) to predict drainage for unsaturated conditions within the CTFS casts doubt on their correct use of the HYDRUS software. Although it is not necessary for the bottom tailings to be saturated for drainage to occur, the bottom tailings will most likely become saturated due to tailings consolidation, a factor that was considered by NewFields (2020), but not by Piteau Associates (2021b). The equivalent table in Piteau Associates (2021a; see Fig. 10c) has the same results, but with only the first four sensitivity analyses. Table from Piteau Associates (2021b).

<table>
<thead>
<tr>
<th>Simulation / Sensitivity</th>
<th>Cumulative 1D Seepage (m)</th>
<th>Average Seepage rate (in/yr)</th>
<th>Average Seepage rate (% MAP)</th>
<th>Facility Seepage rate (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
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<td>0.001</td>
<td>0.01%</td>
<td>0.02</td>
</tr>
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<td>1.0</td>
<td>0.056</td>
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<tr>
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<tr>
<td>Reduced Evaporation</td>
<td>0.14</td>
<td>0.008</td>
<td>0.06%</td>
<td>0.15</td>
</tr>
<tr>
<td>12-inch Cover</td>
<td>0.68</td>
<td>0.038</td>
<td>0.31%</td>
<td>0.15</td>
</tr>
<tr>
<td>Cover Only</td>
<td>13.6</td>
<td>0.76</td>
<td>6.26%</td>
<td>15.2</td>
</tr>
<tr>
<td>Precipitation x 2(^1)</td>
<td>11.3</td>
<td>0.64</td>
<td>5.22%</td>
<td>12.7</td>
</tr>
</tbody>
</table>

\(^1\)Sensitivity meant to represent, among other properties, north facing slopes with greater precipitation and/or snow drifts.
Response of NDEP to Seepage Analyses

As explained in the Overview section, NDEP essentially accepted the seepage analysis by Newfields (2021) in requiring a reclaim pond with a capacity to store a seepage rate of 74 gpm for seven days and also accepted the seepage analysis by Piteau Associates in not requiring any provision for post-closure treatment and discharge of seepage water. However, in its responses to public comments, NDEP (2022c) clearly indicated that it regarded the analysis by Piteau Associates (2021a-b) as superior, despite the fact that only the seepage analysis by NewFields (2020, 2021) took tailings consolidation into account. In response to a question regarding the source of 74 gpm as a criterion for the reclaim pond, NDEP (2022c) wrote, “The calculation [of 74 gpm by NewFields] was not originally provided as it was essentially superseded by the 21 September Piteau Model [Piteau Associates, 2021b] … The 74 gpm … included several conservative factors including a higher permeability … Since this original calculation, a more refined seepage analysis was completed by Piteau.” In other words, NDEP (2022c) decided that the analysis by Piteau Associates (2021a-b) was superior because the analysis by NewFields (2020, 2021) was too conservative in that it included a higher permeability (hydraulic conductivity). However, the quote is stating incorrect information. Piteau Associates (2021a-b) assumed a saturated hydraulic conductivity of $K_{sat} = 1.2 \times 10^{-6}$ cm/s (see Fig. 10b), while NewFields (2020, 2021) assumed a hydraulic conductivity of $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9), so that NewFields (2020, 2021) was actually less conservative than Piteau Associates (2021a-b) in assuming a lower hydraulic conductivity.

Again in response to public comments, NDEP (2022c) defended the choice by Piteau Associates (2021a-b) to calculate the seepage rate only for the target geotechnical water content of 46% (see Fig. 10b). According to NDEP (2022c), “A range of moisture contents was not analyzed because the clay tailings are required to be dried, stacked at near optimal moisture content [the target geotechnical water content of 46%], and compacted by the approved engineered design, thus the materials are unsaturated upon placement and are not anticipated to produce any meaningful seepage.” The above quote is inconsistent with the Fact Sheet accompanying the permit that allows tailings with geotechnical water contents in the range 40-52% in the structural zone and tailings with geotechnical water contents in the range 34-58% in the non-structural zone (NDEP, 2022b). Since Lithium Nevada has the authorization to fill the structural zone entirely with tailings with geotechnical water content of 52% and to fill the non-structural zone entirely with tailings with geotechnical water content of 58%, the target geotechnical water content of 46% is completely irrelevant, and the seepage analysis should have been carried out at the limits of authorization, not at the target.

In light of the above defense by NDEP of the analysis by Piteau Associates (2021a-b), the precise language in the Water Pollution Control (NDEP, 2022a), as opposed to the accompanying Fact Sheet (NDEP, 2022a) is quite mysterious. According to NDEP (2022a), “The moisture content of the clay tailings material placed in the structural zone shall not exceed 46 percent until additional seepage analysis is submitted and approved by the Division in accordance with Part I.B.8. The moisture content of the clay tailings material placed in the non-structural zone shall not exceed 46 percent until additional seepage analysis is submitted and approved by the Division in accordance with Part I.B.8.” Of course, it makes no sense for the maximum geotechnical water content to be set equal to the target geotechnical water content. NDEP (2022c) partially clarifies, “Furthermore, WPCP NEV2020104 Part I.B.8 states within 120 days of the effective date of the Permit, the Permittee shall submit for review and approval.
an additional sensitivity analysis of the moisture content effect on seepage rate.” However, nothing clarifies why additional sensitivity analysis is needed or why the defense of the use of only the target geotechnical water content (which is found in the same document) is no longer adequate. It is most important that NDEP is apparently not requiring the consideration of tailings consolidation, which NewFields (2020) stated as the key feature of their model.

**METHODOLOGY**

Based on the preceding background, the objective of this report can be subdivided into the following questions:

1) Did either NewFields or Piteau Associates carry out correct seepage analyses?
2) Is current filter press technology capable of producing filtered tailings with the appropriate geotechnical water contents for the CTFS?
3) What will be the seepage rates through the CTFS during operation?
4) How long will seepage continue after closure of the CTFS?
5) What will be the seepage rate through the CTFS after closure?

The original concept for this report was that the seepage models by NewFields (2020, 2021) and Piteau Associates (2021a-b) would be re-run with a greater range of input parameters, especially with a greater range of geotechnical water contents. That concept quickly proved unworkable because neither NewFields (2020, 2021) and Piteau Associates (2021a-b) provided sufficient information about their models. NewFields (2020, 2021) did not clarify how tailings consolidation was taken into account or what software was used, which was likely a proprietary or in-house software. Piteau Associates (2021a-b) used the 1-D version of the HYDRUS software, which is available for free download. Although some key parameters were provided (see Table 10b), Piteau Associates (2021a-b) did not provide all of the input parameters that would be needed for re-running the software, even for the purpose of verifying their calculations. For example, none of the meteorological input parameters were provided. With regard to the sensitivity analysis based on doubling the precipitation (see Fig. 11b), Piteau Associates (2021b) stated “The frequency of rainy days remained the same with double the magnitude,” although without ever stating the assumed frequency of rainy days. Other important missing information are the assumed functional dependence of the unsaturated hydraulic conductivity upon the volumetric water content and the assumed tailings specific gravity that would be needed to convert between volumetric and geotechnical water contents. In this respect, Fig. 10b from Piteau Associates (2021a-b) is difficult to interpret because nothing tells the reader how the initial (at the time of closure) geotechnical water content of 46% compares with the saturated volumetric water content \( \theta_{sat} = 0.61 \).

The alternative concept, which was followed in this report, was to predict the seepage rate during operation by accepting the result by NewFields (2020, 2021) of a seepage rate of 74 gpm at a geotechnical water content of 49.1%. The seepage analysis by NewFields (2020, 2021) was regarded as more accurate than that of Piteau Associates (2021a-b) because only the analysis by NewFields took into account the key feature of tailings consolidation. Further comparison between the seepage analyses by NewFields (2020, 2021) and Piteau Associates (2021a-b) will be provided in the Results section. The result by NewFields (2020, 2021) was then extrapolated to the range of geotechnical water contents 34-58%, which would encompass both the structural zone and the non-structural zone. The extrapolation was carried out by re-stating Eq. (13) as
\[
\frac{Q(w)}{Q^*(w^*)} = \frac{K(w)}{K^*(w^*)}
\]  

(15)

where \( Q(w) \) is the seepage rate at a given geotechnical water content and \( K(w) \) is the hydraulic conductivity at the same geotechnical water content. The starred parameters refer to the analysis by NewFields (2020, 2021) in that \( Q^* \) is the reference seepage rate of 74 gpm at the reference geotechnical water content \( w^* \) of 49.1%, corresponding to the reference hydraulic conductivity \( K^* \) of \( 10^{-6} \) cm/s (see Fig. 9). The hydraulic conductivity function was assumed to be the Burdine equation (see Eq. (14)). Note that, as stated, Eq. (14) uses \( K = K_{sat} \) at \( \theta = \theta_{sat} \) as the reference hydraulic conductivity, but any given hydraulic conductivity for a given volumetric water content could substituted in the following manner

\[
K(\theta) = K^* \left( \frac{\theta}{\theta^*} \right)^{(3+2/\lambda)} = K^* \left( \frac{\theta}{\theta^*} \right)^{\varepsilon}
\]  

(16)

where \( \Theta^* \) is the reference reduced saturation (see Eq. (10)). The Brooks-Corey parameter \( \lambda \) was calculated as \( \lambda = 0.128 \) from Eq. (11) using the van Genuchten parameter \( N = 1.128 \) (see Fig. 10b). The use of Eq. (12) resulted in the same value to three significant digits. Note that the very small value of \( \lambda \) indicates a wide range of pore sizes in the clay tailings. The saturated volumetric water content \( \theta_{sat} \) was assumed to be 0.61 (as was assumed by Piteau Associates (2021a-b; see Fig. 10b). Two values were considered for the residual water content, which were either the residual volumetric water content \( \theta_r = 0.066 \) assumed by Piteau Associates (2021a-b; see Fig. 10b) or the residual geotechnical water content of 19% assumed by NewFields (2020; see Fig. 9). All input parameters assumed in the analysis in this report are listed in Table 1.

### Table 1. Input parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geotechnical water content</td>
<td>34-58%</td>
</tr>
<tr>
<td>Saturated volumetric water content ( \theta_{sat} )</td>
<td>0.61</td>
</tr>
<tr>
<td>Residual volumetric water content ( \theta_r )</td>
<td>0.06, 19%(^1)</td>
</tr>
<tr>
<td>Tailings specific gravity</td>
<td>2.93, 3.12, 3.20, 3.28</td>
</tr>
<tr>
<td>Van Genuchten parameter ( N )</td>
<td>1.128</td>
</tr>
<tr>
<td>Van Genuchten parameter ( \alpha ) (m(^{-1}))</td>
<td>0.6</td>
</tr>
<tr>
<td>Soil water potential at field capacity (MPa)</td>
<td>0.033</td>
</tr>
<tr>
<td>Reference hydraulic conductivity ( K^* ) (cm/s)(^2)</td>
<td>( 10^{-6} )</td>
</tr>
<tr>
<td>Reference geotechnical water content ( w^* )(^2)</td>
<td>49.1%</td>
</tr>
<tr>
<td>Reference seepage rate ( Q^* ) (gpm)(^3)</td>
<td>74</td>
</tr>
<tr>
<td>Height of clay tailings filter stack ( L ) (ft)</td>
<td>190</td>
</tr>
<tr>
<td>Base area of clay tailings filter stack ( A ) (acres)</td>
<td>386</td>
</tr>
</tbody>
</table>

\(^1\)The value 19% is a residual geotechnical water content.

\(^2\)The reference hydraulic conductivity \( K^* \) is the hydraulic conductivity at the reference geotechnical water content \( w^* \).

\(^3\)The reference seepage rate \( Q^* \) is the seepage rate occurring at the reference hydraulic conductivity \( K^* \) and reference geotechnical water content \( w^* \).
Figure 12a. NewFields (2020) stated a tailings specific gravity of 2.93 as a design criterion for the clay tailings filter stack (CTFS). The assumed specific gravity was not justified and measurements in the same report stated tailings specific gravities of 3.12 (see Fig. 8a), 3.20 (see Fig. 12b), and 3.28 (see Fig. 8b). All calculations in this report were carried out for all four specific gravities (see Figs. 18a-d, 20a-d, and 21a-d). Table from NewFields (2020).
Figure 12b. NewFields (2020) measured a specific gravity of 3.20 for the filtered tailings without salt. Other assumed and measured specific gravities in the same report (NewFields, 2020) were 2.93 (see Fig. 12a), 3.12 (see Fig. 8a), and 3.28 (see Fig. 8b). All calculations in this report were carried out for all four specific gravities (see Figs. 18a-d, 20a-d, and 21a-d). Figure from NewFields (2020).
At this point, it is necessary to consider the appropriate value for the tailings specific gravity, which is required to convert between volumetric and geotechnical water contents. NewFields (2020) stated a tailings specific gravity of 2.93 as a design criterion for the CTFS and stated that that measurement was obtained in their laboratory (see Fig. 12a). However, that same document reported measurements of tailings specific gravities of 3.12 (see Fig. 8a), 3.20 (see Fig. 12b), and 3.28 (see Fig. 8b). Since nothing in NewFields (2020) reconciles the various measurements of tailings specific gravity, all calculations in this report were carried out for the eight combinations of four tailings specific gravities (2.93, 3.12, 3.20 and 3.28) and two residual water contents (residual volumetric water content of 0.066 and residual geotechnical water content of 19%). Since the highest tailings specific gravity of 3.28 was measured only for tailings blended with salt, those results from this report should be regarded as applicable only to the non-structural zone. The residual volumetric water content of 0.066 corresponds to residual geotechnical water contents of 5.8%, 5.4%, 5.3%, and 5.2% for tailings specific gravities of 2.93, 3.12, 3.20 and 3.28, respectively.

It is most important to compare the geotechnical water contents of tailings stored in the CTFS with the saturation geotechnical water content. The saturated volumetric water content $\theta_{sat}$ of 0.61 corresponds to geotechnical water contents of 53.4%, 50.1%, 48.9%, and 47.7% for tailings specific gravities of 2.93, 3.12, 3.20, and 3.28, respectively. As is typical, the saturated geotechnical water contents are a few percentage points above the target geotechnical water content for maximum compaction (46%). Along these lines, it is unclear how the saturated volumetric content of $\theta_{sat} = 0.45$ for the composite salt / clay tailings (see Fig. 11a) was or ever could be used, since it would be equivalent to saturated geotechnical water contents of 27.9%, 26.2%, 25.6%, and 24.9% for specific gravities of 2.93, 3.12, 3.20, and 3.28, respectively. A specific gravity of 3.28 (see Fig. 8b) is probably most relevant, since that measurement was also carried out on a blend of clay tailings and salt. The above saturated geotechnical water contents would all be far less than the target geotechnical water content (46%), the minimum geotechnical water content for the structural zone (40%), and even the minimum geotechnical water content for the non-structural zone (34%). In fact, Piteau Associates (2021b) does not appear to have taken into account the measured $\theta_{sat} = 0.45$, but assumed $\theta_{sat} = 0.61$ for all calculations.

The obvious complication is that, for possible saturated geotechnical water contents of 53.4%, 50.1%, 48.9%, and 47.7%, the maximum allowed geotechnical water content in the structural zone (52%) and the maximum allowed geotechnical water content in the non-structural zone (58%) exceed the saturated geotechnical water content. The only exception would be that the maximum allowed geotechnical water content in the structural zone (52%) would be less than the saturated geotechnical water content (53.4%) at the lowest tailings specific gravity (2.93). In other words, except for the single exception, the filtered tailings in the CTFS would be oversaturated (see Fig. 2), which would be an unprecedented practice for filtered tailings storage facilities. Oversaturated tailings would have a hydraulic conductivity substantially greater than the saturated hydraulic conductivity because the water inside and outside of the tailings pores would find and create its own large channels and spaces through which it could flow without obstruction by solid particles (see Fig. 2). A similar concept was expressed by NDEP (2021a) in writing to Lithium Nevada, “Because of the fine nature of the material to be stacked on the CTFS, it is possible for preferential pathways to develop and for drainage pipes to get blinded off. Please provide a plan for any blinding issues that may occur.” It is not clear whether Lithium Nevada ever responded to the concern expressed by NDEP (2021a). In fact, oversaturated tailings should lead to rapid seepage of water in the both the upward and downward directions.
In this respect, it is not clear how the storage of oversaturated tailings could be reconciled with
the requirement of the Water Pollution Control Permit that prohibits “ponding on the surface of
the facility” (NDEP, 2022b).

The complication in the analysis of this report is that the Burdine equation, and every
other equation for unsaturated hydraulic conductivity, assumes that the soil or tailings stack has a
fixed structure (fixed arrangement of solid particles), so that the water content cannot exceed the
saturated water content and the hydraulic conductivity cannot exceed the saturated hydraulic
conductivity. However, as mentioned above, the excess water in an oversaturated tailings stack
has the ability to break down the structure as the water creates its own seepage pathways. In the
absence of any reasonable alternative, the Burdine equation was still used, while allowing water
contents to exceed the saturated water content. For this reason, results at very high geotechnical
water contents, such as the maximum allowed geotechnical water contents in the non-structural
zone (58%) should be regarded with caution.

The calculation of seepage rates at geotechnical water contents exceeding the target
géotechnique water is carried out in this report because such geotechnical water contents are
allowed in the Water Pollution Control Permit (NDEP, 2022b). However, this is almost an
academic exercise because the CTFS could not actually be constructed out of oversaturated
tailings. Oversaturated tailings could not be compacted and any attempt to compact them would
result in material with very low shear strength. This same point was made by NewFields (2020)
in writing, “Currently, tailings without salt are produced at a moisture content that is in excess of
the liquid limit and approximately 15 percent above optimum moisture content. Materials
produced at this moisture content are difficult to handle and result in very low material
strengths” (see Fig. 13). Further consideration of the physical stability of the CTFS is beyond the
scope of this report.

After closure, the CTFS will drain until the volumetric water content has dropped to
the field capacity. The field capacity was calculated using the van Genuchten model with parameters
\( N = 1.128 \) and \( \alpha = 0.6 \, \text{m}^{-1} \) and saturated volumetric water content \( \theta_{\text{sat}} = 0.61 \) (see Fig. 10b and
Eqs. (8) and (10)). For a residual volumetric water content of 0.066, the field capacity was
calculated as 0.543, corresponding to geotechnical field capacities of 47.5%, 44.6%, 43.5%, and
42.4% for tailings specific gravities of 2.93, 3.12, 3.20, and 3.28, respectively. For a residual
geotechnical water content of 19% (for which the corresponding residual volumetric water
content depends upon the tailings specific gravity), geotechnical field capacities were calculated
as 49.1%, 46.3%, 45.2%, and 44.1% for tailings specific gravities of 2.93, 3.12, 3.20, and 3.28,
respectively. Expressions for the time required for the closed tailings stack to drain to field
capacity \( t_{\text{FC}} \) and the average seepage rate \( \bar{Q} \) during the period between closure \( (t = 0) \) and the
cessation of drainage \( (t = t_{\text{FC}}) \) are derived in Appendix B. The assumptions were kinematic flow
(see Eq. (13)), a uniform volumetric water content \( \theta \) at the time of closure, and the Burdine
equation (see Eq. (14)) for unsaturated hydraulic conductivity. The assumption of kinematic flow
(equivalent to neglecting capillary effects) is consistent with the assumption that volumetric
water content exceeds field capacity, but becomes less appropriate as the volumetric water
content approaches field capacity. Precipitation was not included (equivalent to a perfect closure
cover) so that the time to drain to field capacity and the average seepage rate are minimum
values. The post-closure drainage calculations included the reference hydraulic conductivity \( K^* \)
\( (10^{-6} \, \text{cm/s}) \) at the reference geotechnical water content \( w^* \) (49.1%) (see Fig. 9), but were
independent of the reference seepage rate \( Q^* \) during operation. The expressions are
\[ t_{FC} = \frac{L(\theta^* - \theta_r)^\varepsilon}{K^*(\varepsilon - 1)} \left\{ \frac{1}{(\theta_{FC} - \theta_r)^{\varepsilon-1}} - \frac{1}{(\theta_0 - \theta_r)^{\varepsilon-1}} \right\} \] (17)

and

\[ \bar{Q} = \frac{AL(\theta_0 - \theta_{FC})}{t_{FC}} \] (18)

where \( \theta^* \) is the reference volumetric water content (corresponding to the reference geotechnical water content for a given tailings specific gravity), \( L \) is the height of the CTFS, \( A \) is the area of the base of the CTFS, \( \theta_{FC} \) is field capacity, and \( \theta_0 \) is volumetric water content at the time of closure.

**RESULTS**

**Evaluation of Seepage Analyses by NewFields and Piteau Associates**

It has already been mentioned that the seepage analysis by NewFields must be the more accurate analysis, since it takes into consideration the consolidation of the tailings, the process by which the underlying tailings are further compacted by the overlying tailings, so that unsaturated tailings could potentially be resaturated. A critique of the analysis by NewFields (2020, 2021) is that it considered only a single geotechnical water content (49.1%). A related critique is that there is a lack of transparency in that the reader cannot take their model and re-run it with adjusted parameters, such as higher geotechnical water contents. Since the Water Pollution Control Permit allows geotechnical water contents as high as 52% and 58% in the structural zone and non-structural zone, respectively, Lithium Nevada would have the authorization to store all filtered tailings at the preceding maximum allowed geotechnical water contents. Thus, the correct procedure would have been to calculate the seepage rate at the maximum allowed geotechnical water contents. The analysis by Piteau Associates (2021a-b) had the same shortcoming in that the seepage rate was calculated only for tailings stored with the target geotechnical water content of 46% (see Fig. 10b). Piteau Associates (2021a-b) explained this choice by writing “It should be noted that clay tailings will be dried and stacked at near optimum moisture content, thus the materials are unsaturated upon placement and are not anticipated to produce any meaningful seepage. The purpose of this exercise is to validate the concept.” As explained above, the “optimum moisture content” has no relevance to seepage prediction and the software should have been run at the maximum allowed geotechnical water contents.

The key conclusion by Piteau Associates (2021a-b) was “Seepage related to the drainage of in-situ water content during the first 1,000 years of emplacement was zero. Water content at the bottom of the CTFS was simulated to slowly increase as a result of unsaturated gravity drainage … However, pore water along the bottom of the CTFS will remain in tension with clay material until water content reaches field saturation conditions to overcome capillary tension and freely seep into the collection system.” The additional implication is that no seepage would occur during operation because the base of the CTFS would not become saturated until well after closure. However, the conceptual understanding by Piteau Associates is incorrect and inconsistent with basic principles of soil physics. As explained in the tutorial, gravity is acting on
soil water even if the pores are unsaturated. Capillary forces are acting to retain the water within pores, but for volumetric water contents that exceed the field capacity, gravitational forces will dominate over capillary forces. Thus, even an unsaturated soil will drain until the volumetric water content has dropped to the field capacity (see Fig. 3).

In the case of the CTFS, for a residual volumetric water content of 0.066 (which was assumed by Piteau Associates (2021a-b); see Fig. 10b), geotechnical field capacities were calculated as 47.5%, 44.6%, 43.5%, and 42.4% for tailings specific gravities of 2.93, 3.12, 3.20 and 3.28, respectively. Therefore, even the target geotechnical water content (46%) would exceed the field capacity, except for the lowest tailings specific gravity (2.93). On that basis, the use of HYDRUS should have predicted seepage from the base of the CTFS long before the base became saturated. The fact that the use of HYDRUS by Piteau Associates (2021a-b) produced results consistent with their conceptual misunderstanding and inconsistent with soil physics casts doubt upon their correct use of the software.

In response to public comments that the free 1-D version of the HYDRUS software was not used correctly and, moreover, could not be used to simulate horizontal cracking that could convey water from the interior to the outside of the CTFS, NDEP (2022c) replied, “Hydrus 1D is listed on the BMRR [Bureau of Mining Regulation and Reclamation] guidance document titled ‘LISTING OF ACCEPTED CODES FOR GROUNDWATER AND GEOCHEMICAL MODELING AT MINE SITES’ and is the preferred draindown model in analyzing draindown from tailings impoundments.” The above response is disturbing because, although the 1-D version of HYDRUS is free, it has no provisions for taking into account tailings consolidation, which is probably the most important effect. Since the base of the CTFS will likely be saturated even during operation, the incorrect statement by Piteau Associates (2021a-b) that “pore water along the bottom of the CTFS will remain in tension with clay material until water content reaches field saturation conditions” is completely irrelevant. Therefore, it is more likely that seepage will be continuous throughout operation and closure until the CTFS has drained to its field capacity. In summary, unless further evidence or clarification can be provided, the analysis by Piteau Associates (2021a-b) should be regarded as both incorrect and irrelevant.

**Ability to Achieve Target Geotechnical Water Contents**

According to NDEP (2022c), “The filtering of tailings material has been tested on a pilot scale to confirm success … The ability of the filter presses to consistently meet the target water content for the filtered tailings is described in the document titled, ‘Filterability of LNC Neutralized Clay Slurry V2’ [Lithium Nevada, 2021b].” However, a detailed look at the results of filter press experiments by Lithium Nevada (2021a-b) and their vendors and consultants reveals a different story. The filtered tailings received by NewFields (2020) from Lithium Nevada for testing purposes had geotechnical water contents of 59.3% for tailings without salt and 60.9% for tailings with salt (see Fig. 13). Lithium Nevada (2021a-b) has reported on 93 tests of filtration of clay tailings for which the average solids content has been 60.8%, corresponding to a geotechnical water content of 64.6% (see Fig. 14). The above measurements of geotechnical water contents for filtered tailings were far higher than the target geotechnical water content (46%), the maximum geotechnical water content for tailings allowed in the structural zone (52%), and even the maximum geotechnical water content for tailings allowed in the non-structural zone (58%).
Filtered tailings received by NewFields from Lithium Nevada for testing purposes had geotechnical water contents of 59.3% for tailings without salt and 60.9% for tailings with salt. The geotechnical water contents were far higher than the target geotechnical water content (46%), the maximum geotechnical water content for tailings allowed in the structural zone (52%), and even the maximum geotechnical water content for tailings allowed in the non-structural zone (58%). The liquid limit is the geotechnical water content above which the tailings will flow as a viscous liquid. According to NewFields (2020), “Currently, tailings without salt are produced at a moisture content that is in excess of the liquid limit and approximately 15 percent above optimum moisture content. Materials produced at this moisture content are difficult to handle and result in very low material strengths. The addition of salt to the tailings decreases the LL of the material, further reducing the workability at as-produced moisture contents.” Figure from NewFields (2020).

The statistics for the filter press experiments carried out by Lithium Nevada (2021a-b) are stated in a literally correct, but misleading manner. According to Lithium Nevada (2021a-b), “On average, filter cakes are measured to contain 61% solids, with the 95% confidence interval ranging to 60% to 61.5% solids.” The above confidence interval refers to the confidence that the measured mean is the true mean, that is, there is 95% confidence that the true mean is the range 60.0-61.5% solids content (corresponding to geotechnical water contents of 62.6-66.7%) (see Fig. 14). Based on the standard deviation of the measurements (3.6% solids content), 95% of samples (the mean plus or minus two standard deviations) fall in the range 53.6-68.0% solids content (corresponding to geotechnical water contents of 47.1-86.7%), a considerable range that still does not include the target geotechnical water content (46%) (see Fig. 14).

The results of filter press experiments by one vendor were only slightly better and still not even close to the target geotechnical water content. Unidentified Vendor 1 carried out 11 tests of filtration of clay tailings for which the average solids content was 62.0% (Lithium Nevada, 2021a-b), corresponding to a geotechnical water content of 61.3%, which is again far higher than the target geotechnical water content (46%), the maximum geotechnical water content for tailings allowed in the structural zone (52%), and even the maximum geotechnical water content for tailings allowed in the non-structural zone (58%) (see Fig. 15a). Based on the standard deviation of the measurements (1.4% solids content), 95% of samples (the mean plus or minus two standard deviations) fall in the range 59.2-64.8% solids content (corresponding to geotechnical water contents of 54.2-69.0%), which is again a considerable range that still does not include the target geotechnical water content (46%) (see Fig. 15a).
Figure 14. Lithium Nevada has carried out 93 tests of filtration of clay tailings for which the average solids content has been 60.8%, corresponding to a geotechnical water content of 64.6%, which is far higher than the target geotechnical water content (46%), the maximum geotechnical water content for tailings allowed in the structural zone (52%), and even the maximum geotechnical water content for tailings allowed in the non-structural zone (58%). According to Lithium Nevada (2021a-b), “On average, filter cakes are measured to contain 61% solids, with the 95% confidence interval ranging to 60% to 61.5% solids.” The above confidence interval refers to the confidence that the measured mean is the true mean, that is, there is 95% confidence that the true mean is the range 60.0-61.5% solids content (corresponding to geotechnical water contents of 62.6-66.7%). Based on the standard deviation of the measurements (3.6% solids content), 95% of samples (the mean plus or minus two standard deviations) fall in the range 53.6-73.8% solids content (corresponding to geotechnical water contents of 47.1-86.7%), a considerable range that still does not include the target geotechnical water content (46%). Figure from Lithium Nevada (2021a-b).

On the other hand, another vendor seemed to achieve adequate geotechnical water contents. Unidentified Vendor 2 carried out 21 tests of filtration of clay tailings for which the average solids content was 68.7% (Lithium Nevada, 2021a-b), corresponding to a geotechnical water content of 45.7%, which is nearly equal to the target geotechnical water content (46%) (see Fig. 15b). Based on the standard deviation of the measurements (2.6% solids content), 95% of samples (the mean plus or minus two standard deviations) fall in the range 63.5-73.8% solids content (corresponding to geotechnical water contents of 35.5-57.5%) (see Fig. 15b). There has been no explanation as to how Vendor 2 was able to achieve results superior to those of
Vendor 1, since both “vendors were able to achieve higher squeeze pressures in their testing,” as opposed to the pilot scale filter press at Lithium Nevada that “operates at a squeeze pressure of 200 psig [200 psi above atmospheric pressure]” (Lithium Nevada, 2021a-b).

Figure 15a. Unidentified Vendor 1 carried out 11 tests of filtration of clay tailings for which the average solids content was 62.0%, corresponding to a geotechnical water content of 61.3%, which is far higher than the target geotechnical water content (46%), the maximum geotechnical water content for tailings allowed in the structural zone (52%), and even the maximum geotechnical water content for tailings allowed in the non-structural zone (58%). Based on the standard deviation of the measurements (1.4% solids content), 95% of samples (the mean plus or minus two standard deviations) fall in the range 59.2-64.8% solids content (corresponding to geotechnical water contents of 54.2-69.0%), a considerable range that still does not include the target geotechnical water content (46%). According to Lithium Nevada (2021a-b), “the filter cake moisture was determined [by Vendors 1 and 2] by drying at 60°C versus 105°C at the LNC [Lithium Nevada Corporation] facility.” Therefore, it is difficult to evaluate the relationship between the results obtained by Vendor 1 and those obtained by Lithium Nevada. Figure from Lithium Nevada (2021a-b).

A difficult aspect of comparing the results of filter press experiments by Lithium Nevada and their vendors is that, while Lithium Nevada used the standard drying temperature (105°C), the vendors used a much lower drying temperature. A lower drying temperature will expel less water during oven-drying, thus resulting in a lower measurement for the geotechnical water content. According to Lithium Nevada (2021a-b), “the filter cake moisture was determined [by Vendors 1 and 2] by drying at 60°C versus 105°C at the LNC [Lithium Nevada Corporation]"
Of course, the above difference in drying temperature does not explain why Vendor 2 achieved adequate results, while Vendor 1 did not. NewFields (2020) does not state what drying temperature was used to obtain their measured geotechnical water contents (see Fig. 13).

**Figure 6: Descriptive statistics for filter cake moisture data, Vendors 1 and 2**

*Figure 15b.* Unidentified Vendor 2 carried out 21 tests of filtration of clay tailings for which the average solids content was 68.7%, corresponding to a geotechnical water content of 45.7%, which is nearly equal to the target geotechnical water content (46%). Based on the standard deviation of the measurements (2.6% solids content), 95% of samples (the mean plus or minus two standard deviations) fall in the range 63.5-73.8% solids content (corresponding to geotechnical water contents of 35.5-57.5%). According to Lithium Nevada (2021a-b), “the filter cake moisture was determined [by Vendors 1 and 2] by drying at 60°C versus 105°C at the LNC [Lithium Nevada Corporation] facility.” Therefore, it is difficult to evaluate the relationship between the results obtained by Vendor 2 and those obtained by Lithium Nevada. There has been no explanation as to how Vendor 2 was able to achieve results superior to those of Vendor 1, since both “vendors were able to achieve higher squeeze pressures in their testing,” as opposed to the pilot scale filter press at Lithium Nevada that “operates at a squeeze pressure of 200 psig [200 psi above atmospheric pressure]” (Lithium Nevada, 2021a-b). Figure from Lithium Nevada (2021a-b).
Figure 16. Lithium Nevada contracted an engineering services company to determine the solids contents of samples obtained from filter presses at the Lithium Nevada facility by drying the samples at a range of temperatures. As expected, it was found that drying temperatures lower than the standard (105°C) resulted in higher measured solids contents. According to Lithium Nevada (2021a-b), “The hypothesis is that two forms of water are in the clay; structural water which is bound in the crystal structure of the material, and free water which is representative of moisture on particle surfaces and in pores … It was concluded that 45°C be used as the reference temperature, as it is thought to better represent free water rather than structural water … Thus, it is likely that the ‘real’ percent solids of filter cakes [see Fig. 14] are closer to 70% solids.” The above argument is apparently justified in a “Confidential” document entitled “Clay Tailings Filter Stack Design Review Summary Report” (see Fig. 17). It was not explained why Lithium Nevada contracted an engineering services company for this study, since measurements of solids contents are relatively simple and Lithium Nevada must have the necessary equipment (a drying oven and a balance) to obtain their own measurements of solids contents (see Fig. 14). Although not stated by Lithium Nevada (2021a-b), the difference between a solids content of 70% as measured after drying at 45°C (corresponding to a geotechnical water content of 49.1%) and a solids content of 63% after drying at 105°C (corresponding to a geotechnical water content of 58.7%) implies that 16.4% of the water in a filtered tailings sample is “structural water,” while 83.6% is “free water.” Figure from Lithium Nevada (2021a-b).

The first version of “Filterability of LNC Neutralized Clay Slurry” (Lithium Nevada, 2021a) includes a memo from the US Sales Manager for Aqseptence Group (also called Diemme Filtration), which is not present in the second version (Lithium Nevada, 2021b), and which reports on further filter press experiments on clay tailings provided by Lithium Nevada. According to the memo, “It has come to our attention that there are questions surrounding the
scale up from a filter press test unit to a commercial-sized filter press. Namely, there is concern that the commercial unit will not achieve the same results as the lab unit … More often than not, the commercial unit will exceed the targeted values established on the test unit. It is with confidence that we can say that the parameters achieved with the laboratory test filter press will be repeated in our commercial filter presses …” (Lithium Nevada, 2021a). Of course, the memo does not provide evidence that the commercial filter press will achieve the same results as the lab filter press, but only asserts that it will happen. The memo continues, “In 20 separate tests, we achieved a minimum filter cake solids of 64.9% (wt basis, 60 deg C oven dry) to a maximum of 73.7% with an average of 69.4%” (Lithium Nevada, 2021a), corresponding to minimum, average, and maximum geotechnical water contents of 35.7%, 44.1%, and 54.1%, respectively. The preceding geotechnical water contents appear to be adequate, but, as with Vendor 2, it is difficult to compare results obtained at two different drying temperatures (105°C by Lithium Nevada and 60°C by their vendors).

To some degree, Lithium Nevada (2021a-b) addressed the discrepancies in drying temperatures by contracting an engineering services company to measure the geotechnical water contents of samples obtained from filter presses at the Lithium Nevada facility by drying the samples at a range of temperatures. It was not explained why Lithium Nevada contracted an engineering services company for this study, since measurements of geotechnical water contents are relatively simple and Lithium Nevada must have the necessary equipment (a drying oven and a balance) to obtain their own measurements of geotechnical water contents (see Fig. 14). As expected, it was found that drying temperatures lower than the standard (105-110°C) resulted in lower measured geotechnical water contents or higher solids contents (see Fig. 16). According to Lithium Nevada (2021a-b), “The hypothesis is that two forms of water are in the clay; structural water which is bound in the crystal structure of the material, and free water which is representative of moisture on particle surfaces and in pores … It was concluded that 45°C be used as the reference temperature, as it is thought to better represent free water rather than structural water … Thus, it is likely that the ‘real’ percent solids of filter cakes [see Fig. 14] are closer to 70% solids [geotechnical water content of 42.9%].” The above argument is apparently justified in a “Confidential” document entitled “Clay Tailings Filter Stack Design Review Summary Report” (see Fig. 17). In fact, out of the seven references in Nevada (2021b), four are labeled “Confidential” (see Fig. 17). It is not clear in what sense these documents are confidential, since all of the confidential documents were prepared for LNC (Lithium Nevada Corporation) and are, presumably, owned by LNC. Although not stated by Lithium Nevada (2021a-b), the difference between a solids content of 70% as measured after drying at 45°C (corresponding to a geotechnical water content of 49.1%) and a solids content of 63% after drying at 105°C (corresponding to a geotechnical water content of 58.7%) (see Fig. 16) implies that 16.4% of the water in a filtered tailings sample is “structural water,” while 83.6% is “free water.”

The Fact Sheet (NDEP, 2022b) that accompanies the Water Pollution Control Permit does not explicitly state the drying temperature that should be used for measurement of the geotechnical water content. However, the Fact Sheet does state that “the material placed in the structural zone must have the moisture content required to achieve structural stability (46 ± 6 percent) and must be compacted at 95% of Modified Maximum Dry Density (MDD) as determined by ASTM D1557 … If placed in the nonstructural zone, the material must have a moisture content of 46 ± 12 percent and compacted at 85 percent of MMDD as determined by ASTM D1557” (NDEP, 2022b). The procedure ASTM D1557 requires the use of a
“thermostatically controlled oven, capable of maintaining a uniform temperature of 230 ± 9°F (110 ± 5°C) throughout the drying chamber” (ASTM, 2012). In other words, the target geotechnical water content of 46% (geotechnical water content at which maximum compaction can be achieved) was determined based on geotechnical water contents that were obtained by oven-drying the tailings samples at 110°C (see Figs. 8a-b). NewFields (2020) also confirmed that “two moisture-unit weight relationship tests using the modified Proctor method (ASTM D1557) were completed on bulk samples of tailings, one without salt and one with salt.”


Figure 17. The seven references in Lithium Nevada (2021b) include four “Confidential” documents, including the document entitled “Clay Tailings Filter Stack Design Review Summary Report” that justifies the conclusion that solids contents of samples from filter presses should be measured by drying at 45°C instead of the standard drying temperature (105°C) (see Fig. 16). It is not clear in what sense these documents are confidential, since all of the confidential documents were prepared for LNC (Lithium Nevada Corporation) and are, presumably, owned by LNC. List of references from Lithium Nevada (2021b).

In summary, Lithium Nevada has, thus far, been unable to produce filtered clay tailings with geotechnical water contents even close to the target geotechnical water content of 46% (see Fig. 14). This situation is not improved by adjusting the drying temperature, since the target geotechnical water content (46%) was determined based on a drying temperature of 110°C, which is even higher than the drying temperature of 105°C used by Lithium Nevada (2021a-b). Therefore, the ability of an unidentified Vendor 2 (Lithium Nevada, 2021a-b) and the Aqseptence Group (Lithium Nevada, 2021a) to achieve adequate geotechnical water contents at a drying temperature of 60°C is completely irrelevant. The implications of issuing a Water Pollution Control Permit for a technology that does not exist will be addressed in the Discussion section.

**Prediction of Seepage from CTFS during Operation and Closure**

Seepage rates during operation were calculated to be in the range of tens to thousands of gallons per minute, depending upon the initial (at the time of placement in the CTFS)
geotechnical water content and residual geotechnical water content of the tailings, and to a lesser degree upon the tailings specific gravity (see Figs. 18a-d). For the target geotechnical water content (46%), seepage rates ranged from 10 gpm for a residual geotechnical water content of 19% to 19 gpm for a residual volumetric water content of 0.066 (nearly independent of the tailings specific gravity). For the saturated geotechnical water content (ranging from 47.7 to 53.4%), seepage rates ranged from 30 gpm for a tailings specific gravity of 3.28 and a residual geotechnical water content of 19% to 881 gpm for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19%. For the maximum geotechnical water content in the structural zone (52%), seepage rates ranged from 243 gpm for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066 to 9215 gpm for a residual geotechnical water content of 19% (nearly independent of the tailings specific gravity). For the maximum geotechnical water content in the non-structural zone (58%), seepage rates ranged from 2297 gpm for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066 to 9215 gpm for a residual geotechnical water content of 19% (nearly independent of the tailings specific gravity). Since the Water Pollution Control Permit allows all filtered tailings to be emplaced at the maximum geotechnical water content, a reclaim pond that can accommodate a seepage rate of only 74 gpm is entirely inadequate.

In the response to public comments, NDEP (2022c) wrote “The Division disagrees that seepage may reach thousands of gallons per minute, as this rate of seepage is not realistic even for a conventional tailings impoundment with slurry deposition.” The statement by NDEP (2022c) is not correct. According to the textbook Geotechnical Engineering of Mine Waste Storage Facilities, “For an unlined storage [in a conventional tailings impoundment], R [seepage recharge] will typically be governed by the permeability to seepage of the tailings, rather than the foundation strata, and typically would be of the order of 1 m/y (or 1 Mg/m²y) …” (Blight, 2010). Multiplying the above flux by an area of 386 acres (Piteau Associates, 2021a-b) results in a seepage rate of 785 gpm, so that seepage rates of thousands of gallons per minute are not out of the realm of possibility for conventional tailings storage facilities. In any event, as mentioned earlier, even at the target geotechnical water content (46%), the CTFS would have geotechnical water content twice as high as the tailings in a conventional tailings impoundment (see Fig. 4). In fact, the CTFS would probable have the highest geotechnical content of any tailings storage facility ever constructed. Of course, the CTFS would contain even more water if tailings were stored in the structural zone at the maximum allowed geotechnical water content of 52% and in the non-structural zone at the maximum allowed geotechnical water content of 58%. On the above basis, seepage rates of thousands of gallons per minute from the CTFS certainly are realistic.

It is worth comparing the predicted seepage rates (see Figs. 18a-d) with the rate at which water is added to the CTFS. Based on the storage of 63,552,290 metric tons of tailings over 10 years (NewFields, 2020; see Fig. 9), the rate of addition of water to the CTFS was calculated as 1085-1851 gpm for geotechnical water contents in the range 34-58% (see Fig. 19). On that basis, calculated seepage rates on the order of hundreds of gallons per minute (see Figs. 18a-d) can easily be accommodated by the rate of water addition and seepage from the CTFS will probably be continuous. On the other hand, calculated seepage rates on the order of thousands of gallons per minute (see Figs. 18a-d) will probably be pulsed with drainage to field capacity after tailings are added, followed by cessation of drainage until the next addition of tailings.
Figure 18a. The seepage from the clay tailings filter stack (CTFS) during operation was extrapolated for a range of initial geotechnical water contents using the Burdine equation for relative hydraulic conductivity and the assumption that the seepage would be 74 gpm at an initial geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 2.93 for the solid particles (see Fig. 12a), saturated volumetric water content $\theta_{sat} = 0.61$, and the van Genuchten parameter $N = 1.128$ (see Fig. 10b). For a residual geotechnical water content of 5.8% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted seepage was 19 gpm at the target geotechnical water content (46%), 247 gpm at the maximum geotechnical water content for the structural zone (52%), 428 gpm at the saturated geotechnical water content (53.4%), and 2402 gpm for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted seepage was 10 gpm at the target geotechnical water content (46%), 410 gpm at the maximum geotechnical water content for the structural zone (52%), 881 gpm at the saturated geotechnical water content (53.4%), and 9215 gpm for the maximum geotechnical water content for the non-structural zone (58%).
The seepage from the clay tailings filter stack (CTFS) during operation was extrapolated for a range of initial geotechnical water contents using the Burdine equation for relative hydraulic conductivity and the assumption that the seepage would be 74 gpm at an initial geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.12 for the solid particles (see Fig. 8a), saturated volumetric water content $\theta_{sat} = 0.61$, and the van Genuchten parameter $N = 1.128$ (see Fig. 10b). For a residual geotechnical water content of 5.4% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted seepage was 19 gpm at the target geotechnical water content (46%), 114 gpm at the saturated geotechnical water content (50.1%), 245 gpm at the maximum geotechnical water content for the structural zone (52%), and 2341 gpm for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted seepage was 10 gpm at the target geotechnical water content (46%), 139 gpm at the saturated geotechnical water content (50.1%), 410 gpm at the maximum geotechnical water content for the structural zone (52%), and 9215 gpm for the maximum geotechnical water content for the non-structural zone (58%).
Figure 18c. The seepage from the clay tailings filter stack (CTFS) during operation was extrapolated for a range of initial geotechnical water contents using the Burdine equation for relative hydraulic conductivity and the assumption that the seepage would be 74 gpm at an initial geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.20 for the solid particles (see Fig. 12b), saturated volumetric water content $\theta_{sat} = 0.61$, and the van Genuchten parameter $N = 1.128$ (see Fig. 10b). For a residual geotechnical water content of 5.3% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted seepage was 19 gpm at the target geotechnical water content (46%), 67 gpm at the saturated geotechnical water content (48.9%), 244 gpm at the maximum geotechnical water content for the structural zone (52%), and 2318 gpm for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted seepage was 10 gpm at the target geotechnical water content (46%), 64 gpm at the saturated geotechnical water content (48.9%), 410 gpm at the maximum geotechnical water content for the structural zone (52%), and 9215 gpm for the maximum geotechnical water content for the non-structural zone (58%).
Figure 18d. The seepage from the clay tailings filter stack (CTFS) during operation was extrapolated for a range of initial geotechnical water contents using the Burdine equation for relative hydraulic conductivity and the assumption that the seepage would be 74 gpm at an initial geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.28 for the solid particles (see Fig. 8b), saturated volumetric water content $\theta_{sat} = 0.61$, and the van Genuchten parameter $N = 1.128$ (see Fig. 10b). For a residual geotechnical water content of 5.2% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted seepage was 19 gpm at the target geotechnical water content (46%), 40 gpm at the saturated geotechnical water content (47.7%), 243 gpm at the maximum geotechnical water content for the structural zone (52%), and 2297 gpm for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted seepage was 10 gpm at the target geotechnical water content (46%), 30 gpm at the saturated geotechnical water content (47.7%), 410 gpm at the maximum geotechnical water content for the structural zone (52%), and 9215 gpm for the maximum geotechnical water content for the non-structural zone (58%).
Figure 19. Based on the storage of 63,552,290 metric tons of tailings over 10 years (see Fig. 9), the rate of addition of water to the clay tailings filter stack (CTFS) was calculated as 1085-1851 gpm for geotechnical water contents in the range 34-58%. On that basis, calculated seepage rates on the order of hundreds of gallons per minute (see Figs. 18a-d) can easily be accommodated by the rate of water addition and seepage from the CTFS will probably be continuous. On the other hand, calculated seepage rates on the order of thousands of gallons per minute (see Figs. 18a-d) will probably be pulsed with drainage to field capacity after tailings are added, followed by cessation of drainage until the next addition of tailings.
Figure 20a. The time for the clay tailings filter stack (CTFS) to drain to field capacity after closure was calculated for a range of geotechnical water contents at the time of closure using the Burdine equation for relative hydraulic conductivity and the assumption that the hydraulic conductivity would be $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 2.93 for the solid particles (see Fig. 12a), saturated volumetric water content $\theta_{sat} = 0.61$, the van Genuchten parameters $N = 1.128$ and $\alpha = 0.6$ (see Fig. 10b), and stack height $L = 190$ feet. For a residual geotechnical water content of 5.8% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted time was 8.5 years at the maximum geotechnical water content for the structural zone (52%), 9.1 years at the saturated geotechnical water content (53.4%), and 9.9 years for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted time was 2.8 years at the maximum geotechnical water content for the structural zone (52%), 3.2 years at the saturated geotechnical water content (53.4%) and 3.5 years for the maximum geotechnical water content for the non-structural zone (58%).
Figure 20b. The time for the clay tailings filter stack (CTFS) to drain to field capacity after closure was calculated for a range of geotechnical water contents at the time of closure using the Burdine equation for relative hydraulic conductivity and the assumption that the hydraulic conductivity would be $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.12 for the solid particles (see Fig. 8a), saturated volumetric water content $\theta_{sat} = 0.61$, the van Genuchten parameters $N = 1.128$ and $\alpha = 0.6$ (see Fig. 10b), and stack height $L = 190$ feet. For a residual geotechnical water content of 5.4% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted time was 17.6 years at the target geotechnical water content (46%), 34.2 years at the saturated geotechnical water content (50.1%), 36.0 years at the maximum geotechnical water content for the structural zone (52%), and 37.6 years for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted time was 17.6 years at the target geotechnical water content (46%), 19.6 years at the saturated geotechnical water content (50.1%), 21.0 years at the maximum geotechnical water content for the structural zone (52%), and 21.7 years for the maximum geotechnical water content for the non-structural zone (58%).
Figure 20c. The time for the clay tailings filter stack (CTFS) to drain to field capacity after closure was calculated for a range of geotechnical water contents at the time of closure using the Burdine equation for relative hydraulic conductivity and the assumption that the hydraulic conductivity would be $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.20 for the solid particles (see Fig. 12b), saturated volumetric water content $\theta_{sat} = 0.61$, the van Genuchten parameters $N = 1.128$ and $\alpha = 0.6$ (see Fig. 10b), and stack height $L = 190$ feet. For a residual geotechnical water content of 5.3% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted time was 43.5 years at the target geotechnical water content (46%), 58.0 years at the saturated geotechnical water content (48.9%), 62.4 years at the maximum geotechnical water content for the structural zone (52%), and 64.0 years for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted time was 19.4 years at the target geotechnical water content (46%), 41.5 years at the saturated geotechnical water content (48.9%), 45.2 years at the maximum geotechnical water content for the structural zone (52%), and 45.9 years for the maximum geotechnical water content for the non-structural zone (58%).
The time for the clay tailings filter stack (CTFS) to drain to field capacity after closure was calculated for a range of geotechnical water contents at the time of closure using the Burdine equation for relative hydraulic conductivity and the assumption that the hydraulic conductivity would be $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.28 for the solid particles (see Fig. 8b), saturated volumetric water content $\theta_{sat} = 0.61$, the van Genuchten parameters $N = 1.128$ and $\alpha = 0.6$ (see Fig. 10b), and stack height $L = 190$ feet. For a residual geotechnical water content of 5.2% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted time was 86.2 years at the target geotechnical water content (46%), 97.0 years at the saturated geotechnical water content (47.7%), 105.6 years at the maximum geotechnical water content for the structural zone (52%), and 107.2 years for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted time was 69.3 years at the target geotechnical water content (46%), 87.2 years at the saturated geotechnical water content (47.7%), 95.8 years at the maximum geotechnical water content for the structural zone (52%), and 96.5 years for the maximum geotechnical water content for the non-structural zone (58%).
Figure 21a. The average seepage rate from the clay tailings filter stack (CTFS) between closure and when the stack has drained to field capacity was calculated for a range of geotechnical water contents (at the time of closure) using the Burdine equation for relative hydraulic conductivity and the assumption that the hydraulic conductivity would be $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 2.93 for the solid particles (see Fig. 12a), saturated volumetric water content $\theta_{sat} = 0.61$, the van Genuchten parameters $N = 1.128$ and $\alpha = 0.6$ (see Fig. 10b), stack height $L = 190$ feet, and area $A = 386$ acres. For a residual geotechnical water content of 5.8% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted seepage rate was 273 gpm at the maximum geotechnical water content for the structural zone (52%), 336 gpm at the saturated geotechnical water content (53.4%), and 552 gpm for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted seepage rate was 523 gpm at the maximum geotechnical water content for the structural zone (52%), 692 gpm at the saturated geotechnical water content (53.4%) and 1316 gpm for the maximum geotechnical water content for the non-structural zone (58%).
The average seepage rate from the clay tailings filter stack (CTFS) between closure and when the stack has drained to field capacity was calculated for a range of geotechnical water contents (at the time of closure) using the Burdine equation for relative hydraulic conductivity and the assumption that the hydraulic conductivity would be $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.12 for the solid particles (see Fig. 8a), saturated volumetric water content $\theta_{sat} = 0.61$, the van Genuchten parameters $N = 1.128$ and $\alpha = 0.6$ (see Fig. 10b), stack height $L = 190$ feet, and area $A = 386$ acres. For a residual geotechnical water content of 5.4% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted seepage rate was 90 gpm at the saturated geotechnical water content (50.1%), 114 gpm at the maximum geotechnical water content for the structural zone (52%), and 197 gpm for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted seepage rate was 109 gpm at the saturated geotechnical water content (50.1%), 151 gpm at the maximum geotechnical water content for the structural zone (52%), and 299 gpm for the maximum geotechnical water content for the non-structural zone (58%).
Figure 21c. The average seepage rate from the clay tailings filter stack (CTFS) between closure and when the stack has drained to field capacity was calculated for a range of geotechnical water contents (at the time of closure) using the Burdine equation for relative hydraulic conductivity and the assumption that the hydraulic conductivity would be $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.20 for the solid particles (see Fig. 12b), saturated volumetric water content $\theta_{sat} = 0.61$, the van Genuchten parameters $N = 1.128$ and $\alpha = 0.6$ (see Fig. 10b), stack height $L = 190$ feet, and area $A = 386$ acres. For a residual geotechnical water content of 5.3% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted seepage rate was 33 gpm at the target geotechnical water content, 53 gpm at the saturated geotechnical water content (48.9%), 78 gpm at the maximum geotechnical water content for the structural zone (52%), and 129 gpm for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 9), the predicted seepage rate was 24 gpm at the target geotechnical water content (46%), 51 gpm at the saturated geotechnical water content (48.9%), 86 gpm at the maximum geotechnical water content for the structural zone (52%), and 158 gpm for the maximum geotechnical water content for the non-structural zone (58%).
The average seepage rate from the clay tailings filter stack (CTFS) between closure and when the stack has drained to field capacity was calculated for a range of geotechnical water contents (at the time of closure) using the Burdine equation for relative hydraulic conductivity and the assumption that the hydraulic conductivity would be $10^{-6}$ cm/s at a geotechnical water content of 49.1% (see Fig. 9). Additional assumptions were a specific gravity of 3.28 for the solid particles (see Fig. 8b), saturated volumetric water content $\theta_{sat} = 0.61$, the van Genuchten parameters $N = 1.128$ and $\alpha = 0.6$ (see Fig. 10b), stack height $L = 190$ feet, and area $A = 386$ acres. For a residual geotechnical water content of 5.2% (corresponding to residual volumetric water content of 0.066; see Fig. 10b), the predicted seepage rate was 24 gpm at the target geotechnical water content, 32 gpm at the saturated geotechnical water content (47.7%), 53 gpm at the maximum geotechnical water content for the structural zone (52%), and 85 gpm for the maximum geotechnical water content for the non-structural zone (58%). For a residual geotechnical water content of 19% (see Fig. 8), the predicted seepage rate was 16 gpm at the target geotechnical water content (46%), 24 gpm at the saturated geotechnical water content (47.7%), 48 gpm at the maximum geotechnical water content for the structural zone (52%), and 84 gpm for the maximum geotechnical water content for the non-structural zone (58%).
The time for the CTFS to drain to field capacity after closure ranged from a few years (within the planned reclamation period) to over a century, depending upon the geotechnical water content and tailings specific gravity, and to a lesser degree upon the residual water content (see Figs. 20a-d). For the target geotechnical water content (46%), drainage times ranged from 17.6 years for a tailings specific gravity of 3.12 (nearly independent of the residual water content) to 86.2 years for a tailings specific gravity of 3.28 and residual volumetric water content of 0.066. For the saturated geotechnical water content (ranging from 47.7 to 53.4%), drainage times ranged from 3.2 years for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19% to 97.0 years for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066. For the maximum geotechnical water content in the structural zone (52%), drainage times ranged from 2.8 years for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19% to 105.6 years for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066. For the maximum geotechnical water content in the non-structural zone (58%), drainage times ranged from 3.5 years for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19% to 107.2 years for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066. The lack of provision for long-term seepage management after closure could be adequate, but it depends on key tailings characteristics that are still unknown, and, in any event, would still require a means for managing seepage during the reclamation period.

The average seepage rates from the CTFS during the time between closure and drainage to field capacity ranged from tens to thousands of gallons per minute, depending upon the geotechnical water content at the time of closure, the tailings specific gravity, and the residual water content (see Figs. 21a-d). For the target geotechnical water content (46%), average seepage rates after closure ranged from 16 gpm for a tailings specific gravity of 3.28 and a residual geotechnical water content of 19% to 33 gpm for a tailings specific gravity of 3.20 and a residual volumetric water content of 0.066. For the saturated geotechnical water content (ranging from 47.7 to 53.4%), average seepage rates after closure ranged from 24 gpm for a tailings specific gravity of 3.28 and a residual volumetric water content of 0.066 to 692 gpm for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19%. For the maximum geotechnical water content in the structural zone (52%), average seepage rates after closure ranged from 48 gpm for a tailings specific gravity of 3.28 and a residual geotechnical water content of 19% to 523 gpm for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19%. For the maximum geotechnical water content in the non-structural zone (58%), average seepage rates after closure ranged from 84 gpm for a tailings specific gravity of 3.28 and a residual geotechnical water content of 19% to 1316 gpm for a tailings specific gravity of 2.93 and a residual geotechnical water content of 19%. As above, since the permit allows all filtered tailings to be emplaced at the maximum geotechnical water content, even if seepage could be managed through the reclaim pond during the reclamation period, a reclaim pond that can accommodate a seepage rate of only 74 gpm is entirely inadequate.

**DISCUSSION**

It should go without saying that it is highly problematic for a governmental agency to issue a permit for a project for which the required technologies do not exist. In the case of the clay tailings filter stack (CTFS) for the Thacker Pass lithium mine, the following key technologies do not exist:
1) There is no technology for producing filtered clay tailings with the target geotechnical water content.

2) There is no technology for constructing a filtered tailings stack out of oversaturated tailings.

3) There is no technology for maintaining a zero-discharge facility when predicted seepage rates range from tens to thousands of gallons per minute with drainage continuing for a few years to over a century after closure.

The Nevada Division of Environmental Protection (NDEP) has at least recognized the non-existence of the first technology in allowing the production of relatively wet tailings from the filter presses as long as the tailings undergo sufficient air-drying before compaction and storage in the CTFS. According to the Water Pollution Control Permit, “The tailings will be dewatered to approximately 61 percent dry basis (geotechnical) moisture content prior to being conveyed to the temporary tailings stockpile located in Cell 0 of the facility. From the stockpile, the material is hauled and placed in either the structural or nonstructural zone in a 12-inch thick lift and scarified to dry to the allowable moisture content” (NDEP, 2022a). Even so, Lithium Nevada has not consistently met the above required geotechnical water content coming from the filter presses (61%) and has produced a mean geotechnical water content that is considerably higher (64.6%).

Lithium Nevada (2021a-b) has also recognized a role for air-drying in producing filtered tailings with the target geotechnical water content and has measured the loss of water from filtered tailings due to evaporation at room temperature (22°C) (see Fig. 22). According to Lithium Nevada (2021a-b), “From Figure 8 [Fig. 16 in this report], the filter cake is measured to contain ~72% solids at 22°C, thus every kilogram of cake contains 0.28 kg moisture. According to Figure 9 [Fig. 22 in this report] then, after 4 days of air drying at room temperature, it is expected that 60% of that moisture would evaporate, or ~0.17 kg moisture.” Although not stated by Lithium Nevada (2021a-b), by extrapolation, filtered tailings with a geotechnical water content of 64.6% (see Fig. 14) would reduce to a geotechnical water content of 25.8% (loss of 60% of available water) after four days of air drying, which would be far drier than the minimum geotechnical water contents for either the structural zone (40%) or the non-structural zone (34%). Lithium Nevada (2021a-b) does not clarify how slightly more than 20% of available water was lost after zero elapsed time (see Fig. 22). Lithium Nevada (2021a-b) also does not clarify how to reconcile the loss of 100% of total water after 22 days of evaporation with the implication from the experiments on the effect of drying temperature that 16.4% of the water in a filtered tailings sample is “structural water which is bound in the crystal structure of the material” (Lithium Nevada, 2021a-b) (see Figs. 16 and 22). It is most important that Lithium Nevada has provided no information as to how the results in Fig. 22 could be applied to a field situation in which the principal controlling variable would be the thickness of the layer of filtered tailings that was exposed to the atmosphere. Based on the above critique, it should be concluded that there is no technology for producing wet tailings from the filter presses and then air-drying them in the field to the target geotechnical water content.
Figure 22. Lithium Nevada measured the loss of water from filtered tailings due to evaporation at room temperature (22°C). According to Lithium Nevada (2021a-b), “From Figure 8 [Fig. 16 in this report], the filter cake is measured to contain ~72% solids at 22°C, thus every kilogram of cake contains 0.28 kg moisture. According to Figure 9 [above] then, after 4 days of air drying at room temperature, it is expected that 60% of that moisture would evaporate, or ~0.17 kg moisture.” Although not stated by Lithium Nevada (2021a-b), by extrapolation, filtered tailings with a geotechnical water content of 64.6% (see Fig. 14) would reduce to a geotechnical water content of 25.8% (loss of 60% of available water) after four days of air drying, which would be far drier than the minimum geotechnical water contents for either the structural zone (40%) or the non-structural zone (34%). Lithium Nevada (2021a-b) does not clarify how slightly more than 20% of available water was lost after zero elapsed time. Lithium Nevada (2021a-b) also does not clarify how to reconcile the loss of 100% of total water after 22 days of evaporation with the implication from the experiments on the effect of drying temperature that 16.4% of the water in a filtered tailings sample is “structural water which is bound in the crystal structure of the material” (Lithium Nevada, 2021a-b). It is most important that Lithium Nevada has provided no information as to how the results in the figure above could be applied to a field situation in which the controlling variable would be the thickness of the layer of filtered tailings that was exposed to the atmosphere. Despite the preceding concerns, it has been assumed by NDEP that any excess water in the filtered tailings could be remedied by evaporation. According to NDEP (2022b), “From the stockpile, the material is hauled and placed in either the structural or nonstructural zone in a 12-inch thick lift and scarified to dry to the allowable moisture content.” Figure from Lithium Nevada (2021a-b).

There is no denying that the design of the filtered tailings storage facility for the Thacker Pass lithium mine is highly creative. At the same time, while creativity is generally considered to be a positive human endeavor, creativity is not an unmitigated good. In fact, there is another
concept of “Reckless Creativity,” which is prejudicial to human welfare. For example, a proposal to immediately replace all automobiles in Reno with driverless vehicles would be a type of Reckless Creativity. Reckless Creativity has one or more of the following characteristics:

1) There is no scaffolding, meaning that the new innovation does not build upon previous innovations through a series of intermediate steps with proper testing and verification of each step.
2) One or more of the technologies required to carry out the innovation does not currently exist.
3) Predictions are based upon single input values or best-case scenarios without considering the range of possible inputs.
4) Although potential problems are recognized, they are quickly dismissed as irrelevant without justification.
5) Basic precautions are not taken that would be routine for previous innovations.
6) There is no consideration of the consequences of being wrong, that is, of the consequences of failure.

The plan for the filtered tailings storage facility at the Thacker Pass mine fulfills all of the characteristics of Reckless Creativity. This does not mean no version of the proposed tailings facility could ever be permitted, but this plan should not be permitted at this place at this time.

The first characteristic is fulfilled because the plan comes as a quantum leap without intermediate steps. Each designer of filtered tailings storage facilities and the mining industry as a whole needs to gain experience with the safe construction and operation of filtered tailings stacks that store clay tailings at ever-increasing heights and tailings production rates. It would be reassuring if there were already an operating lithium mine with a filtered tailings stack that stored clay tailings with a height of, say, 152 feet (80% of the planned height of the stack at the Thacker Pass mine) or with a tailings production rate of 13,290 metric tons per day (80% of the planned tailings production rate at the Thacker Pass mine). However, nothing close to either of those exist at the present time. I am not aware of any operating lithium mine that uses filtered tailings technology. I am not aware of any operating mine of any kind that uses filtered tailings technology with clay tailings. I am not aware of any operating mine of any kind that stores filtered tailings with such a high geotechnical water content. Even if such filtered tailings storage facilities have emerged recently (either clay tailings or very wet filtered tailings or tailings from lithium extraction), it still requires time for the mining industry to learn how to design, construct and operate such facilities at ever-increasing heights and tailings production rates. In particular, the designers of each new filtered tailings storage facility need to learn from the mistakes of previous facilities. In summary, it is disturbing that the analysis by NewFields (2020) does not present any history of their concept for a new type of tailings storage facility. Of course, any history should include an emphasis on how they have learned from that history.

The second characteristic is fulfilled because at least three key technologies are nonexistent. It bears repeating that there is no technology for producing filtered clay tailings with the target geotechnical water content, there is no technology for constructing a filtered tailings stack out of oversaturated tailings, and there is no technology for maintaining a zero-discharge facility when predicted seepage rates range from tens to thousands of gallons per minute with drainage continuing for a few years to over a century after closure. The third characteristic is fulfilled because the seepage analyses on which NDEP is relying were carried out under the assumption that all tailings would have the target geotechnical water content, which is only the best-case scenario. The problematic nature of the reliance on that single input value is emphasized by the
sensitivity analyses carried out by Piteau Associates (2021b), in which varying other parameters (but not the initial geotechnical water content) resulted in seepage rates varying over three orders of magnitude, thus demonstrating the extreme dependence on the input parameters. The fact that doubling the precipitation resulted in an increase in the predicted seepage rate by a factor of 635 (see Fig. 1b) should show the importance of the geotechnical water content of the tailings.

The fourth characteristic is fulfilled because the Water Pollution Control Permit implicitly recognizes that there is no technology for producing clay tailings from the filter presses with the target geotechnical water content of 46%. Thus, the permit requires only production of tailings from the filter presses with a geotechnical water content of 61%, followed by drying in the sun to obtain the target geotechnical water content. However, there is no documentation of experiments on the field-drying of clay tailings. On that basis, there is no knowledge as to the time required to dry the tailings or the maximum thickness of the layers of tailings or the air temperature, relative humidity or wind speed required to adequately dry the tailings.

The fifth characteristic is fulfilled because there is no attention to the Observational Method, which is the basis for nearly every other mining project. The Global Industry Standard on Tailings Management (GISTM) defines the Observational Method as “a continuous, managed, integrated, process of design, construction control, monitoring and review that enables previously defined modifications to be incorporated during or after construction as appropriate. All of these aspects must be demonstrably robust. The key element of the Observational Method is the proactive assessment at the design stage of every possible unfavourable situation that might be disclosed by the monitoring programme and the development of an action plan or mitigative measure to reduce risk in case the unfavourable situation is observed. This element forms the basis of a performance-based risk management approach.” The GISTM then requires that “Full implementation of the Observational Method shall be adopted for non-brittle failure modes [failure modes that will be preceded by some warning so that there is time to carry out the preplanned actions]” (ICMM-UNEP-PRI, 2020). Member Companies of the International Council on Mining & Metals (ICMM) are required to fully implement the GISTM by August 2023 (ICMM, 2020). Lithium Nevada is not a Member Company, but it is noteworthy that Association Members include the International Lithium Association (ILiA), the USA-based National Mining Association (NMA), and the USA-based Society for Mining, Metallurgy and Exploration (SME) (ICMM, 2022).

Unlike nearly every other mining project, Lithium Nevada does not appear to have any preplanned actions ready for execution in the event of adverse observations, such as unanticipated seepage from the CTFS, nor does NDEP require them to have such preplanned actions. Instead, there are only intentions to carry out more analyses. According to the response by NDEP to public comments, “If the Division determines the facility is not being operated as designed, additional analysis and permit modifications, if necessary, will be required … If it becomes apparent through the routine monitoring, reporting and inspections … that there is a wide range of moisture contents, the model, closure plan, and ET Cell capacity can be updated accordingly … If it is apparent that more waste rock is being placed than anticipated, revision to stability and seepage analysis will be required” (NDEP, 2022c). Of course, “more analyses” and similar activities do not constitute preplanned actions. According to Independent Expert Engineering Investigation and Review Panel (2015), “The Observational Method is useless without a way to respond to the observations.”
The sixth characteristic is fulfilled because there has been absolutely no consideration of any kind of the consequences of failure of the clay tailings filter stack (CTFS). Failure could include overtopping of the reclaim pond or the entry of seepage water from the CTFS into groundwater or surface water. Of course, failure could include the slumping or total collapse of the CTFS. There has been no consideration of the potential loss of human lives, the potential impacts on aquatic or wildlife habitat, the potential impacts on livestock, the potential economic losses, or any other kinds of impacts. The rigorous analysis of the consequences of failure, however unlikely, are standard practice in high-risk industries, such as aviation, pipelines and nuclear power. Instead, the analysis by NewFields (2020) simply dismisses the possibility of failure by writing “the CTFS is not a water retaining structure, nor is it a dam.” That sentence is equivalent to stating that the concept of failure is meaningless because the CTFS does not really have any performance objectives. Simply writing the preceding sentence should be sufficient cause to reject the plan.

CONCLUSIONS

The chief conclusions of this report can be summarized as follows:

1) Although the Nevada Division of Environmental Protection (NDEP) refers to the clay tailings filter stack (CTFS) as a “dry stack,” the geotechnical water content would be twice that of the tailings in conventional tailings impoundment (23%), and would probably have the highest geotechnical water content of any tailings storage facility ever constructed.

2) The seepage analysis by Piteau Associates using the freely available HYDRUS software predicted no seepage during operation and for more than 1000 years after closure, followed by a steady-state seepage of 0.02 gpm. This analysis did not include the key feature of tailings consolidation, according to which underlying tailings would be further compacted by the weight of overlying tailings, potentially leading to resaturation of the base of the CTFS.

3) The assertion by Piteau Associates that no seepage could occur until the bottom tailings were saturated is inconsistent with soil physics, according to which drainage will occur until the volumetric water content has decreased to the field capacity, at which point gravitational forces are balanced by capillary forces. The inability of Piteau Associate to reproduce this basic result from soil physics casts some doubt as to whether the HYDRUS software was used correctly.

4) Since the seepage analysis by NewFields, which predicted a seepage rate of 74 gpm, included tailings consolidation, it should be regarded as more accurate and as a starting point for adjustment of input parameters.

5) The Water Pollution Control Permit allows geotechnical water contents up to 52% and 58% in the structural and non-structural zones, respectively. Since the saturation geotechnical water contents would be 53.4%, 50.1%, 48.9% and 47.7% for tailings specific gravities equal to 2.93, 3.12, 3.20 and 3.28, respectively, oversaturated tailings could be stored within the CTFS. This would be an unprecedented practice since oversaturated tailings could not be compacted without substantial loss of shear strength.

6) Thus far, Lithium Nevada has carried out 93 tests of filtration of clay tailings for which the average geotechnical water content has been 64.6%, which is far higher than the target geotechnical water content (46%), the maximum geotechnical water content for tailings allowed in the structural zone (52%), and even the maximum geotechnical water content for
tailings allowed in the non-structural zone (58%). Based on the standard deviation of the measurements, 95% of samples fall in the range of geotechnical water contents of 47.1-86.7%, which does not even include the target geotechnical water content (46%).

7) Seepage rates during operation and closure were calculated to be in the range of tens to thousands of gallons per minute, depending upon the geotechnical water content at the time of emplacement in the CTFS or the time of closure, the residual geotechnical water content, and the tailings specific gravity.

8) The time for the CTFS to drain to field capacity after closure ranged from a few years to over a century, depending upon the geotechnical water content at the time of closure, the residual geotechnical water content, and the tailings specific gravity.

9) Based on the above, the plan for a reclaim pond that can accommodate up to 74 gpm of seepage during operation with no provision for management of seepage water after closure should be regarded as entirely inadequate.

10) The provision in the Water Pollution Control Permit that allows for production of tailings from the filter presses with geotechnical water content of 61% followed by air-drying to a geotechnical water content within the allowable range has not been tested in the field.

RECOMMENDATIONS

The recommendation of this report is that the Water Pollution Control Permit for the Lithium Nevada Thacker Pass mine (NEV2020104) should be revoked.

ABOUT THE AUTHOR

Dr. Steven H. Emerman has a B.S. in Mathematics from The Ohio State University, M.A. in Geophysics from Princeton University, and Ph.D. in Geophysics from Cornell University. Dr. Emerman has 31 years of experience teaching hydrology and geophysics, including teaching as a Fulbright Professor in Ecuador and Nepal, and has 70 peer-reviewed publications in these areas. Dr. Emerman is the owner of Malach Consulting, which specializes in evaluating the environmental impacts of mining for mining companies, as well as governmental and non-governmental organizations. Dr. Emerman has evaluated proposed and existing tailings storage facilities in North America, South America, Europe, Africa, Asia and Oceania, and has testified on tailings storage facilities before the U.S. House of Representatives Subcommittee on Indigenous Peoples of the United States, the European Parliament, the United Nations Permanent Forum on Indigenous Issues, and the United Nations Environment Assembly. Dr. Emerman is the Chair of the Body of Knowledge Subcommittee of the U.S. Society on Dams and one of the authors of Safety First: Guidelines for Responsible Mine Tailings Management.

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APPENDIX A: DERIVATION OF WATER CONTENT RELATIONSHIPS

The standard geotechnical phase diagram is a useful tool for visualizing the conversion between geotechnical and volumetric water contents. Figure from Wikimedia Commons (2010).

The purpose of this appendix is to derive an expression for the volumetric water content $\theta$, given the geotechnical water content $w$, the saturated volumetric water content $\theta_{sat}$, the density of water $\rho_w$ (1 Mg/m$^3$) and the density of the solid particles $\rho_S$. The geotechnical phase diagram (see Fig. A1) is a useful tool for visualizing parameter conversions and is explained in great detail by Holtz et al. (2011). Assume that the mass of solids is $M_S$. Recalling that $w$ is a percentage, the mass of water $M_W$ is then given by

$$M_W = \frac{wM_S}{100} \quad (A1)$$

which completes the mass side (right-hand side) of the geotechnical phase diagram (see Fig. A1). The next step is to consider the volume side (left-hand side) of the geotechnical phase diagram. The volume of water $V_W$ is given by

$$V_W = \frac{wM_S}{100\rho_w} \quad (A2)$$

while the volume of solids $V_S$ is given by

$$V_S = \frac{M_S}{\rho_S} \quad (A3)$$
The missing piece in the geotechnical phase diagram is the volume of air $V_A$. Since the saturated volumetric water content $\theta_{sat}$ is the ratio of the volume of voids ($V_A + V_W$) to the total volume ($V_A + V_W + V_S$),

$$\theta_{sat} = \frac{V_A + \frac{wM_S}{100\rho_W}}{V_A + \frac{wM_S}{100\rho_W} + \frac{M_S}{\rho_S}}$$

(A4)

Eq. (A4) can be rearranged to solve for $V_A$, yielding

$$V_A = \frac{\theta_{sat} \frac{M_S}{\rho_S} - \frac{wM_S}{100\rho_W} (1 - \theta_{sat})}{(1 - \theta_{sat})}$$

(A5)

All of the pieces of the geotechnical phase diagram are now present. Combining

$$\theta = \frac{V_W}{V_A + V_W + V_S}$$

(A6)

with Eqs. (A2), (A3) and (A5) and simplifying then yields the required relationships

$$\theta = \frac{wG_S}{100} (1 - \theta_{sat})$$

(A7)

$$w = 100 \times \frac{\theta}{G_S(1 - \theta_{sat})}$$

(A8)

where $G_S$ is the specific gravity of solids (ratio of the density of solids to density of water).
The purpose of this appendix is to derive expressions for the time required for a closed tailings stack to drain to field capacity \( t_{FC} \) and the average seepage rate \( \overline{Q} \) during the period between closure \((t = 0)\) and the cessation of drainage \((t = t_{FC})\). The assumptions are kinematic flow (see Eq. (13)), a uniform volumetric water content \( \theta \) at the time of closure, and the Burdine equation (see Eq. (14)) for unsaturated hydraulic conductivity. The assumption of kinematic flow (equivalent to neglecting capillary effects) is consistent with the assumption that volumetric water content exceeds field capacity, but will become less appropriate as the volumetric water content approaches field capacity. Precipitation will not be included (equivalent to a perfect closure cover) so that the time to drain to field capacity and the average seepage rate will be minimum values.

Combining the kinematic flow equation

\[
q = K(\theta) \quad (B1)
\]

with conservation of mass

\[
q = -L \frac{d\theta}{dt} \quad (B2)
\]

and the Burdine equation

\[
K(\theta) = K_{sat} \left( \frac{\theta - \theta_r}{\theta_{sat} - \theta_r} \right)^\varepsilon \quad (B3)
\]

yields the differential equation

\[
-L \frac{d\theta}{dt} = K_{sat} \left( \frac{\theta - \theta_r}{\theta_{sat} - \theta_r} \right)^\varepsilon \quad (B4)
\]

where \( q \) is downwards flux of water, \( K(\theta) \) is hydraulic conductivity as a function of volumetric water content, \( K_{sat} \) is saturated hydraulic conductivity, \( L \) is height of the tailings stack, \( \theta_{sat} \) is saturated volumetric water content, \( \theta_r \) is residual volumetric water content, and \( \varepsilon = 3 + 2/\lambda \), where \( \lambda \) is the exponent in the Brooks-Corey model for the soil water characteristic curve (see Eq. (9)). Integrating Eq. (B4) with the initial condition (time of closure) \( \theta = \theta_0 \) at \( t = 0 \) then yields

\[
t = \frac{L(\theta_{sat} - \theta_r)\varepsilon}{K_{sat}(\varepsilon - 1)} \left\{ \frac{1}{(\theta - \theta_r)^{\varepsilon - 1}} - \frac{1}{(\theta_0 - \theta_r)^{\varepsilon - 1}} \right\} \quad (B5)
\]

and
\[ t_{FC} = \frac{L(\theta_{sat} - \theta_r)\varepsilon}{K_{sat}(\varepsilon - 1)} \left\{ \frac{1}{(\theta_{FC} - \theta_r)\varepsilon^{-1}} - \frac{1}{(\theta_0 - \theta_r)\varepsilon^{-1}} \right\} \]  

(B6)

where \( \theta_{FC} \) is field capacity. For this report, it is convenient to rewrite Eq. (B6) so that it applies when the unsaturated hydraulic conductivity \( K^* \) is known for any given \( \theta^* \) without requiring that \( \theta^* = \theta_{sat} \). Thus, Eq. (B6) can be rewritten as

\[ t_{FC} = \frac{L(\theta^* - \theta_r)\varepsilon}{K^*(\varepsilon - 1)} \left\{ \frac{1}{(\theta_{FC} - \theta_r)\varepsilon^{-1}} - \frac{1}{(\theta_0 - \theta_r)\varepsilon^{-1}} \right\} \]  

(B7)

The average seepage rate \( \bar{Q} \) is given by the integral

\[ \bar{Q} = \frac{A}{t_{FC}} \int_{0}^{t_{FC}} q(t) dt \]  

(B7)

where \( A \) is the surface area of the base of the tailings stack. Substituting the expression for \( q \) in Eq. (B2) yields

\[ \bar{Q} = -\frac{AL}{t_{FC}} \int_{0}^{t_{FC}} \frac{d\theta}{dt} dt = -AL \int_{\theta_0}^{\theta_{FC}} \frac{d\theta}{t_{FC}} \]  

(B8)

resulting in

\[ \bar{Q} = \frac{AL(\theta_0 - \theta_{FC})}{t_{FC}} \]  

(B9)