NEVADA DIVISION OF
**ENVIRONMENTAL PROTECTION**

**STATE OF NEVADA**
Department of Conservation & Natural Resources
Steve Sisolak, *Governor*
James R. Lawrence, *Acting Director*
Greg Lovato, *Administrator*

November 16, 2022

Jay A. Steinberg
Nevada Environmental Response Trust
35 East Wacker Drive, Suite 690
Chicago, IL 60601

Re: **Tronox LLC (TRX) Facility**
**Nevada Environmental Response Trust (Trust) Property**
**NDEP Facility ID #H-000539**
Nevada Division of Environmental Protection (NDEP) Response to: *Hydrogen-Based Gas Permeable Membrane Pilot Test Results Report*

Dated: July 29, 2022

Dear Mr. Steinberg,

The NDEP has received and reviewed the Trust's above-identified Deliverable and provides comments in Attachment A. A revised Deliverable should be submitted by **01/16/2023** based on the comments. The Trust should additionally provide an annotated response-to-comments letter as part of the revised Deliverable.

Please contact the undersigned with any questions at wdong@ndep.nv.gov or 702-668-3929.

Sincerely,

Dong Weiquan

Weiquan Dong, P.E.
Bureau of Industrial Site Cleanup
NDEP-Las Vegas City Office

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**Attachment A**

## General Comments

### General Comment 1

Biological reduction of oxidized pollutants using (potentially renewable) hydrogen offers a sustainable solution to not only the remove, but to destroy these pollutants. A biofilm-based process would be well suited for using a gaseous substrate. Biofilm thickness control is the key challenge with these process units. In this study it appears that biofilm thickness increased until the pressure required in the hydrogen supply increased to above 25 psig, which was considered excessive or unsustainable, despite efforts to use sparging to control film thickness. The undesired sulfate reduction that was observed during the initial phase may also be related to excessive biofilm thickness. In response, it is proposed to clean the membrane every 12 weeks. This introduces several issues, including operating cost, interruption of service and extended startup after resumption of service. Table 10 shows that the cleaning solution and its disposal after use represents more than 27 percent of the operating cost. This does not include the cost of regular interruption to operations. In addition, after cleaning a new biofilm must develop and some of the figures, specifically Figure 7 and 10 or 11, suggest that after cleaning, startup takes up around 50% of the total run time. Regular cleaning would also increase wear on the membranes so that more frequent membrane replacement would be required. The mention in Section 6.4.3 of a new module configuration with improved sparging is of interest and would be key to making the technology viable by allowing continuous operation. This option should be explored further.

### General Comment 2

Producing hydrogen on site requires resources, and that very much includes renewable hydrogen. For example, using current technology approximately 60 liters of high-quality water is required per kg of hydrogen produced or about 7 gallons per pound of hydrogen, as mentioned in the comments below. Different methods of hydrogen generation and the economic implications of each method should be considered.

### General Comment 3

With regards to the costs developed for the hypothetical design, based on operational cost savings of $529700-$185300 = $344,400 (there may be other savings not listed in this report), a 7 percent discount factor, development costs in year 0 and delivery in years 1 and 2 (with operational savings commencing in year 3). It would take 165 years to "pay off" the $48M HBGPM facility. However, this does not consider any process augmentations that may be required for the existing FBR system and a complete NPV analysis of these two systems should be undertaken to understand feasibility.

## Essential Corrections

### Essential Correction 1: Section Number 2.1 Technology Description Page 2

The chemical reaction equations are not balanced for both FBR and MBfR. Please address and revise as necessary.

### Essential Correction 2: Section Number 2.1 Technology Description Page 2

Revisit theoretical quantity of ethanol after nitrate equations have been balanced to ensure that quantities are still accurate. Quantities will likely not change as it appears that revising the number of moles of the byproducts produced will balance the equation, however this should be verified.

### Essential Correction 3: Section Number 2.1 Technology Description Page 3

Results presented later for both $H_2$ consumption and biomass production, suggest that the chemical reactions may be underestimating the hydrogen requirement. Please discuss how this can be mitigated.

### Essential Correction 4: Section Number 2.1 Technology Description Page 3

"Another potential advantage of using hydrogen as the electron donor versus carbon-based electron donor is that the amount of excess biomass generated is theoretically less than that generated when an organic compound (such as ethanol) is used as the electron donor. A system using hydrogen as the electron donor would theoretically generate less waste biomass than a system using ethanol."

Please quantify theoretical solids production for review after rebalancing the chemical reaction equations so that comparisons between to the two donors may be evaluated.

### Essential Correction 5: Section Number 2.1 Technology Description Page 3

There are still hurdles to be overcome for hydrogen generation, assuming the hydrogen is generated via electrolysis some challenges include:

1) Water availability/proximity to a water source, feed water quality, brine stream management, and adiabatic cooling requirements which can be a challenge for hot inland areas due to local humidity and ambient temperature conditions.
2) Hydrogen can also be obtained from natural gas reforming, sewage biogas reforming, coal gasification, biomass gasification, etc.

Please discuss the means of obtaining the hydrogen at the site and relative economic implications to assess feasibility.

### Essential Correction 6: Section Number 2.1 Technology Description Page 3

Hydrogen can be generated in real time and fed directly to the bioreactor only if there is a ready source of fuel i.e., suitable quality water and/or methane/steam. The feasibility assessment in this report assumes supply of hydrogen gas. Please discuss how realistic this is.

**Essential Correction 7: Section Number 2.3 General Operations Page 5**

Is it possible to have an online continuous feedback loop as opposed to relying on updating control manually based on system data/perchlorate lab analysis? If the system changes when no monitoring is occurring (i.e., weekend/holiday) what are the risks associated with under/overdosing hydrogen and how should they be controlled? For a full-scale system, the hydrogen generation should be automated so it matches hydrogen consumption in real time.

**Essential Correction 8: Section Number 2.3 General Operations Page 5**

If the process is up-scaled to full-scale installation it is important to also monitor alkalinity which is a buffer to pH. In some biological systems once the pH shifts the biomass is already impacted.

**Essential Correction 9: Section Number 4.2.1 Inspection and Maintenance Page 10**

After cleaning is the membrane free of biofilm? Is time needed for re-seeding/acclimatization of biomass following cleaning?

**Essential Correction 10: Section Number 4.2.1 Inspection and Maintenance Page 10**

Is the whole system offline for several days? If so, the full-scale facility needs to consider redundancy considering these maintenance requirements.

**Essential Correction 11: Section Number 5.1.1.1 Test Scenario #1A Page 15**

The system appears not to be stable with flow variations, how would a full-scale facility respond to shutdowns?

**Essential Correction 12: Section Number 5.1.1.1 Test Scenario #1A Page 16**

Some discussion is required surrounding the need for thermal insulation in certain applications depending on the site climate and ambient temperature fluctuations. Does thermal insulation need to be included for the NERT facility in the cost feasibility analysis?

**Essential Correction 13: Section Number 5.1.1.1 Test Scenario #1A Page 16**

The oxygen may inhibit the nitrate/chlorate/perchlorate reactions and increase hydrogen demand. One strategy could be to use air to maintain the ORP at a point where nitrate/chlorate/perchlorate reduction is achieved but before $H_2S$ forms. Please discuss whether this strategy could be implemented or whether there is an alternate strategy under consideration.

**Essential Correction 14: Section Number 5.1.1.1 Test Scenario #1A Page 16**

The PFD does not show the ability to change reactor sequence. This is an important consideration for the full-scale facility. This facility would also allow cleaning one of the reactors while the others remain in service.

**Essential Correction 15: Section Number 5.1.1.2 Test Scenario #1B Page 16**

For full-scale installations is pre-treatment recommended before the membranes? If so, this is currently not shown on the full-scale PFD.

**Essential Correction 16: Section Number 5.1.1.2 Test Scenario #1B Page 17**

The variable ORP may indicate sub optimal control of the hydrogen dose. Further investigation into the use of ORP as an online measure is recommended as it could have potential benefits for system control.

**Essential Correction 17: Section Number 5.2.1 Mass Loading Capacity Page 21**

Adding the pollutant concentrations is not appropriate, as they would each have different hydrogen demands (i.e., perchlorate is the most difficult to remove) the hydrogen demands for each individual COPC should be added.

**Essential Correction 18: Section Number 5.2.2 Treatment System Flux Page 22**

Similar to comment in 5.2.1, hydrogen gas transfer kg $H_2/d/m^2$ membrane should be considered. Total mass of COPC is not a valid comparison for scaling up.

**Essential Correction 19: Section Number 5.3 Hydrogen Consumption. Table 4. Page 23**

Recommend estimating how much hydrogen is theoretically lost by dissolving in the water. What would be the impact of impurities in the hydrogen feed gas?

**Essential Correction 20: Section Number 5.3 Hydrogen Consumption Page 23**

Some discussion is required on the possible reasons for the difference between the theoretical/actual dosages and whether this will gap will increase during scaling up. Also per earlier comments the chemical reaction equations were not balanced properly.

**Essential Correction 21: Section Number 5.6.1 Biomass Generation Page 26**

It's not clear what the units of measurement are (i.e., concentration or mass). Sm needs to be corrected for duration of scenario when solids could accumulate (i.e., in between clean outs)

**Essential Correction 22: Section Number 5.6.1 Biomass Generation Page 26, Table 5**

The theoretical biomass should be revised once the chemical reaction equations from Section 2.1 are balanced

**Essential Correction 23: Section Number 5.6.1 Biomass Generation Page 26, Table 5**

The pilot system appears to be generating more solids than the theoretical amount. This could explain why the pilot was using more hydrogen than theoretically calculated. Perhaps the theoretical equations don't apply and future scaling up should be based on the measured solids production. Please discuss the approach that will be taken.

**Essential Correction 24: Section Number 6.1 Design Basis for a Hypothetical Full-Scale HBGPM System Page 29**

As discussed in comment on Section 5.2.1, adding the pollutant concentrations is not appropriate, as they would each have different hydrogen demands (i.e., perchlorate is the most difficult to remove) the hydrogen demands for each individual COPC should be added.

**Essential Correction 25: Section Number 6.2 Reaction Rates for Reduction of Contaminants Page 29**

As discussed in comment on Section 5.2.2, hydrogen gas transfer kg $H_2/d/m^2$ membrane should be considered. Total mass of COPC is not a valid comparison for scaling up.

**Essential Correction 26: Section Number 6.3.1 Influent Feed Equalization Tank and Nutrient Delivery System Page 30**

The choice of the 25-hour holding time should be explained e.g., is that to hold water during membrane cleaning?

**Essential Correction 27: Section Number 6.3.4 Carbon Dioxide Delivery System Page 31**

This section states that the hypothetical system would require 11,010 cubic feet of $CO_2$ per day to buffer elevated pH conditions that would develop during nitrate reduction. $CO_2$ requirement would be a function of the contaminant removal. Depending on the influent alkalinity, the $CO_2$

requirement may be met by the influent. Please comment on the possibility of a reduced need for $CO_2$ by the system depending on alkalinity of the influent.

**Essential Correction 28: Section Number 6.3.7 Maintenance of the Membrane Modules Page 32**

More discussion surrounding system sequencing/bypassing/redundancy during membrane cleans is required. Will the flow be held upstream during cleaning? Will the reactors be cleaned one by one, and flows bypassed around the reactor being cleaned?

**Essential Correction 29: Section Number 6.4.1 Capital Costs Page 33**

A contingency of 25 percent was added to the total cost to account for project unknowns during the preliminary stages of the project development; however, this contingency may not fully capture cost escalation associated with the current inflationary environment, supply chain restrictions and other factor associated with the current global economic conditions. It would be beneficial to investigate to identify supply chain issues in more depth in relation to the capital cost of the full-scale facility

**Essential Correction 30: Section Number 6.4.1 Capital Costs Page 33, Table 8**

Please include either a hydrogen generator/supply infrastructure or if assuming the gas is delivered then cost a hydrogen storage system.

**Essential Correction 31: Section Number 6.4.2 Operating Cost Estimate Page 35**

Most of this report has discussed generating hydrogen on-site. Some discussion surrounding the source/availability of the hydrogen gas would be beneficial. Is the intent for the full-scale facility to have green hydrogen? If so approximately 2,400 gallons of suitable quality water would be required per day based on 60L/kg $H_2$ (Naylor, Dagg, Potts, Brannock, Coertzen 2022)

**Essential Correction 32: Section Number 6.4.2 Operating Cost Estimate Page 35**

Does the carbon dioxide cost include supply to the site? Please provide the quote.

**Essential Correction 33: Section Number 6.4.2 Operating Cost Estimate Page 36**

Annual maintenance based on mechanical and electrical capital costs would be more realistic (as these are the items requiring ongoing maintenance)

**Essential Correction 34: Section Number 6.4.2 Operating Cost Estimate Page 36, Table 10**

This cost assumes 24-hour operation of the centrifuge 365 days per year. Earlier in the report it was stated the centrifuges will operate 4 hours per day. Same comment applies for all other electrical units, are these operating 24 hours per day or intermittently?

**Essential Correction 35: Section Number 6.4.2 Operating Cost Estimate Page 36, Table 10**

The module replacement cost seems high, what is the anticipated life of the membrane modules? Future optimization efforts should focus on membrane replacement/cleaning (highest cost)

**Essential Correction 36: Section Number 6.4.2 Operating Cost Estimate Page 36, Table 10**

The maintenance cost is a fairly significant cost. It might be more accurate to assume a percentage of the mechanical and electrical items which will require maintenance rather than a percentage of the entire capital cost.

**Essential Correction 37: Section Number 6.4.2 Operating Cost Estimate Page 36**

Is the solids disposal cost just the gate fee or does it also include the cost of tanks for the liquid waste to the Republic Services Facility?

**Essential Correction 38: Section Number 6.5 Cost Comparison for Hydrogen vs Ethanol Page 38**

Please append the AirGas quote to the report considering it is what is being relied upon for the cost comparison

**Essential Correction 39: Section Number 6.5 Cost Comparison for Hydrogen vs Ethanol Page 38, Table 11**

A NPV analysis is required to understand if the operational cost savings claimed from $H_2$/HBGPM over ethanol/FBR warrant capital investment.

**Essential Correction 40: Section Number 7.0 Summary of Key Findings Page 39**

Perchlorate concentrations were not reduced to below the 18 µg/L treatment goal in all scenarios. Scenario 1A did not achieve the target concentration per discussion in 5.1.1.1. The statement that perchlorate concentrations were reduced to below treatment goals in all scenarios should be revised.

**Essential Correction 41: Figure Number 12**

Supporting infrastructure required to generate hydrogen e.g., methane/steam reforming or water electrolysis should be considered and show in this Figure.

**Essential Correction 42: Figure Number 12**

Consider the addition of a cartridge filter upstream of the equalization tank to protect the downstream membranes

**Essential Correction 43: Figure Number 12**

Please show valving/controls to change sequencing of reactors as was necessary during the pilot test.

**Essential Correction 44: Figure Number 12**

This bypass would have high COPC concentrations. If the system has the valving to change the lead/mid/lag reactor sequence, The bypass seems unnecessary. Please explain this.

**Minor Corrections**

**Minor Correction 1: Section Number 2.1 Technology Description Page 3**

Change $H^+$ to $H_2$ as $H_2$ is the reducing agent. Repeat throughout paragraph.

**Minor Correction 2: Section Number 2.1 Technology Description Page 3**

It would be easy for the reader if the predicted capacity of the NERT trial and full-scale facility was stated as well as effluent requirements upfront for comparison.

**Essential Correction 3: Section Number 5.1.1.2 Test Scenario #1B Page 16**

Typo – Achievement is misspelled.