Memorandum

February 18, 2020

To: Dan Heilig, Wyoming Outdoor Council, Lander, WY; and
Jill Morrison, Powder River Basin Resource Council, Sheridan, WY

From: Harold Bergman, PhD, Professor Emeritus, University of Wyoming, Laramie, WY; and
Joseph Meyer, PhD, Chief Scientist, Applied Limnology Professionals LLC, Golden, CO

Regarding: Analysis of, and comments on, proposed WDEQ Wastewater Discharge Permit for Aethon Energy Operating, LLC – WY0002062-RENEWAL-12-17-19 (Draft 2)

We have reviewed a series of documents including WDEQ-WQD's proposed WYPDES discharge permit WY0002062-RENEWAL-12-17-19 (Draft 2) for Aethon Energy Operating, LLC, Moneta Divide Gas Field; Aethon's original application for this permit renewal dated August 8, 2016; portions of Environmental Resources Management's (ERM's) Water Quality Compliance Analysis report to Aethon Energy dated April 23, 2018; ERM's Blackwater – Alkali Creek: Sediment and Surface Water Sampling Results report to Aethon Energy dated October 23, 2019; WDEQ's Response to Public Comments from the original draft permit; ERM Whole Effluent Toxicity Test Result reports dated 12 July 2017 and 13 March 2019; WDEQ's Letter of Violation for WYPDES permit WY0002060 dated December 17, 2019; and Aethon's Response to Letter of Violation dated January 16, 2020. We also have reviewed and used information from a several peer-reviewed publications on the chemistry of produced waters from oil and gas operations and the toxicity of these waters to aquatic biota, and we have cited these references, as appropriate, in the text below.

We commend the WDEQ-WQD for this improved draft WYPDES renewal permit, which is a substantial improvement compared to DEQ's earlier draft renewal permit, in that the current draft includes better analysis of the conditions related to Aethon's discharge and its effects on downstream water quality, and it imposes more stringent requirements of the discharger, particularly a reduction in allowed discharge from 8.274 MGD to 2 MGD and the eventual effluent limit of 230 mg Chloride/L. However, we have several concerns about other parts of the draft renewal permit.

In the text that follows, we present our analyses, conclusions and positions related to water chemistry and aquatic toxicity of Aethon's produced water and WDEQ's proposed issuance of a discharge permit renewal for Aethon's discharge.

Compliance schedule for Chloride final effluent limits (Pages 2 and 3):

The compliance schedule of 4 years until July 1, 2024 to meet the 230 mg Cl/L effluent limit is much too long and should be shortened, especially since WDEQ has provided no justification for a 4-year compliance schedule or provided interim effluent limits at, say, annual

intervals up to the 4-year deadline to meet the 230 mg Cl/L limit. A shorter compliance schedule or, at least, annually staged improvements in effluent limits for Chloride would be reasonable, given that the technology for water treatment to reduce Chloride is straightforward, and given that Aethon already has a reverse osmosis plant in place (Neptune Plant). This plant is apparently inoperable at this time but could be repaired/improved in time to meet a shorter compliance schedule.

We acknowledge, however, that the draft permit specifies that the 230 mg Cl/L effluent limit is being required for all Aethon outfalls (001-016), and this is what will be required to begin the recovery of what can clearly be characterized as severely impaired conditions in both Alkali and Badwater creeks. With this Chloride limit placed on all 16 discharge outfalls, it is likely that Aethon will need to consolidate its outfalls to one reverse osmosis treatment plant to reduce the current untreated discharge of around 2,200 mg Cl/L. Aethon's current Neptune Plant is located at outfall 001, yet Aethon is actively considering consolidating all its surface discharges to outfall 016 (Aethon's January 16, 2020, Response to WDEQ Letter of Violation), to improve their ability to treat wastewater for reduction of sulfide and temperature.

Thus, given the requirement to meet the 230 mg Cl/L discharge limit for all outfalls (including unnamed tributaries to Alkali Creek and Alkali Creek), Aethon may need to consolidate its discharges to outfall 001 where the current Neptune Plant is located, or build a new reverse osmosis plant at a consolidation location at outfall 016. Under these circumstances, Aethon and WDEQ will likely need to negotiate an appropriate time frame for consolidating all the current outfalls (presumably using pipelines to avoid in-stream violations in Alkali Creek and Alkali Creek tributaries) and treatment upgrades at this new outfall location to achieve compliance with the 230 mg Cl/L discharge limit as well as the need to comply with limits for sulfide and temperature. Under no circumstances, though, should the discharge be allowed to exceed the 230 mg Cl/L at any discharge location, including on Alkali Creek or tributaries to Alkali Creek.

Instream Monitoring (Pages 3 and 4):

In WDEQ's new draft 2 Aethon discharge permit, the only monitoring station WDEQ will require on Badwater Creek is BWC1 "below its confluence with Alkali Creek." The BWC1 station will likely totally miss the elevated pH that we predicted in our earlier comments (dated June 27, 2019 on the first proposed renewal permit) will occur as the over-saturated CO_2 gas in the effluent degasses from Alkali and Badwater Creeks enroute to Badwater Bay in Boysen Reservoir. We strongly recommend that, in addition to BWC1, at least one other monitoring station on Badwater Creek should be required immediately upstream of Badwater Bay (where the highest pH values in Badwater Creek might be expected).

We extensively explained and reviewed this likely problem of over-saturated CO_2 partial pressure in Aethon's produced water causing elevated instream pH values above 9 in our earlier comments (dated June 27, 2019) to WDEQ's draft 1 proposed permit. In summary, we estimated that the partial pressure of CO_2 (pCO_2) in Aethon's discharge could be approximately 372-fold over-saturated in CO_2 at Aethon's discharge. This means that the over-saturated CO_2 will de-gas from the discharge water as it flows downstream in Alkali and Badwater Creeks until the CO_2

reaches equilibrium with the atmosphere. As the CO_2 degasses, the H^+ concentration will decrease and, thus, the pH of the water will increase. In our earlier analysis of this issue, we used the WHAM geochemical-speciation software (Lofts, 2012) and calculated that the in-stream water might reach a pH as high as 9.6 after the discharged produced water's over-saturated pCO_2 level fully equilibrated with the atmosphere, thus exceeding WDEQ's instream standard of pH 6.5 to 9. The realized pH will also depend on the extent to which concomitant precipitation of calcite ($CaCO_3$) remains oversaturated in the creek water.

Based on this analysis, as noted above, we strongly recommend an additional Badwater Creek monitoring station immediately upstream of its discharge into Badwater Bay. In addition, we also strongly recommend that Aethon be required to report temperature and alkalinity (from which, along with pH, pCO_2 can be calculated) of the discharge and at all monitoring sites so that this potential instream pH violation can be evaluated.

Water Quality Based Effluent Limits (Pages 4-7):

Chloride:

In the Compliance Schedule section of the draft permit, WDEQ concludes that there is a reasonable potential for this facility to exceed the in-stream chloride standard of 230 mg Cl/L for Badwater Creek (Class 2AB), because Badwater Creek is intermittent, resulting in no dilution flow during parts of the year. Thus, in the draft permit WDEQ appropriately sets the discharge limit for all of Aethon's outfalls the same as the in-stream standard of 230 mg Cl/L in Badwater Creek.

We note that this 230 mg Cl/L effluent limit technically applies to all of the unnamed tributaries to Alkali Creek and to Alkali Creek as well as Badwater Creek, particularly because outfalls 001 to 015 all discharge to unnamed tributaries of Alkali Creek and outfall 016 discharges to Alkali Creek (Table 1 and Attachment 1 in Aethon's original application for this permit renewal dated August 8, 2016).

Even though WDEQ's justification for the 230 mg Cl/L effluent limit is based on a reasonable potential analysis of in-stream requirements in Badwater Creek, WDEQ should explicitly also apply that same logic and same reasonable potential analysis for in-stream requirements and effluent limits for Alkali Creek and its tributaries (Class 3B – aquatic life other than fish). Because Alkali Creek and its tributaries are also intermittent, no dilution flow can be expected for much of the year; and because a Class 3B water should protect aquatic life other than fish, the same 230 mg Cl/L instream requirement should also apply. Given a recent analyzed Chloride concentration of 1,540 mg/L in Alkali Creek on August 20, 2019 (Table 2 in ERM's Blackwater – Alkali Creek: Sediment and Surface Water Sampling Results report), the aquatic community in Alkali Creek needs more regulatory protection than the draft renewal permit will provide.

The current USEPA freshwater aquatic life chronic criterion for chloride of 230 mg Cl/L was derived numerically (i.e., based on lab toxicity tests, not based on field observations) and first appeared in the USEPA water quality criteria document for chloride in 1988 (EPA 440/5-

88-001) (https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table#table). The chloride criterion is "driven" by invertebrates (see Table 3 in that document). Of the 12 genera of aquatic organisms used in the 1988 derivation, the 6 most-sensitive genera were invertebrates [including cladocerans (two *Daphnia* species), a snail, an isopod, midges, and a caddisfly -- meaning a wide variety of types of aquatic invertebrates]; and 5 of the 6 least-sensitive genera were fish [i.e., only 1 of the 6 least-sensitive genera was an invertebrate (a mosquito)]. Thus, based on that toxicity dataset, it would be appropriate to conclude that chloride concentrations exceeding 230 mg Cl/L would not be safe for many invertebrates. [Note: The USEPA water quality criteria are intended to protect 95% of species. Thus, "on average", one might expect approximately 5% of the species to be adversely affected even at only 230 mg Cl/L.]

Thus, in our professional opinion, the existing USEPA criteria document provides sufficient evidence to support an argument that 230 mg Cl/L should be a maximum instream chloride concentration for protection of aquatic invertebrates in Alkali Creek, and a reasonable potential analysis would support an effluent limit of 230 mg Cl/L for all permitted effluent outfalls into Alkali Creek or its tributaries.

Total Dissolved Solids (TDS):

Though water quality for protection of aquatic life in Alkali and Badwater Creeks would be improved by reducing Chloride concentrations in the Aethon effluent to 230 mg/L, there is still a major problem with WDEQ's allowed in-stream Total Dissolved Solids (TDS) concentrations. High concentrations of TDS, exceeding 5,000 mg/L, in the effluent have clearly harmed aquatic life in Alkali Creek. The proposed waiver of the Appendix H effluent concentration limit for TDS will continue to cause harm to aquatic life in Alkali Creek and downstream in Badwater Creek, threatening aquatic life use designation for these surface waters. Table 2 in Aethon's original application for permit renewal at Frenchie Draw (dated August 8, 2016) shows a TDS concentration of 5,940 mg/L in the effluent at outfall 6. A more recent analysis of inorganic constituents from an in-stream water sample from Alkali Creek taken immediately upstream of the confluence with Badwater Creek on August 20, 2019, added up to a TDS concentration of 6,303 mg/L (Table 2 in ERM's Sediment and Surface Water Sampling Results report to Aethon Energy).

To estimate the effect of this high a measure of TDS on aquatic biota, we ran the Mount et al. (1997) major-ion-toxicity model with the water chemistry data in Table 2 of the 2019 ERM report. The model-predicted survivals of *Ceriodaphnia dubia* (48 hours), *Daphnia magna* (48 hours), and fathead minnows (96 hours) are less than or equal to 0.2%. An approximately 5-fold dilution of that high TDS water with distilled water (or with really pure reverse-osmosis water) would be needed for the model-predicted survivals to exceed 90%. And that's only for acute toxicity, which is all the model is designed to predict. By simple logic, even more dilution would be needed to avoid chronic toxicity. These model-predicted acute toxicity results demonstrate that Alkali Creek is impaired downstream of the Aethon effluent discharges.

In our professional opinion, even the WDEQ's traditionally allowed TDS limit of 5,000 mg/L is way too high for protection of aquatic life. WDEQ should complete a reasonable potential analysis to re-evaluate the 5,000 mg/L TDS limit.

Total Sulfide:

In our professional opinion, the WDEQ effluent limit of 20 micrograms/L (µg/L) for Total Sulfide in this proposed discharge permit will not be stringent enough to meet the 2 µg/L instream standard for Hydrogen Sulfide. WDEQ is requiring a Total Sulfides analysis rather than a direct Hydrogen Sulfide measurement, which would be acceptable if the permit limit for Total Sulfide were set low enough to not allow high concentrations of Hydrogen Sulfide at all times. However, they used an indirect approach for estimating Hydrogen Sulfide concentrations that would allow the Hydrogen Sulfide concentration to exceed the 2 µg/L standard 50% of the time. Specifically, WDEQ looked at the historical pH data for the effluent (data not provided) and stated that the median pH was 7.9. At that pH, only approximately 10% of the total sulfide ($H_2S + HS^- + S^{2-}$) is H_2S. Thus, WDEQ reasoned that if "the instream standard for Hydrogen Sulfide is 2 µg/L, a Total Sulfide level of 20 µg/L or less at the outfalls would be required to achieve an output level 2 µg/L or less for Hydrogen Sulfide." But hidden in that reasoning is the fact that 50% of the historical pH values were, by definition of the word "median", less than pH 7.9 -- meaning that the H_2S concentration exceeded 10% of the total sulfide concentration more than 50% of the time. Therefore, WDEQ should have chosen a lower pH percentile than the median (which is the 50^{th} percentile), perhaps something like the 10^{th} percentile (meaning one would not expect to err more than 10% of the time). We don't know what the 10^{th} percentile of those historical pH values is, because WDEQ did not provide the pH data. However, just to give an idea of how important this could be, H_2S is approximately 50% of the total sulfide concentration at pH 7.0 (see the speciation diagram at the top of page 6 in the proposed permit). Thus, at a pH of 7.0, the total sulfides concentration should not exceed 4 µg/L (instead of the 20 µg/L at pH 7.9) in order to not exceed an H_2S concentration of 2 µg/L. Therefore, it is important to know the entire distribution of historical pH values, not only the median pH.

Actually, the simplest and best thing for WDEQ to do would be to specify that the water quality based effluent limit is 2 µg H_2S/L and require that the permit holder calculate and report the H_2S concentration based on the measured and reported pH and the measured and reported total sulfide concentration in each effluent, using the well-known pK_a (acid dissociation constant) of H_2S (Broderius and Smith 1976) -- thus avoiding any intermediate assumptions and thereby directly knowing the concentration of actual interest rather than a measurement of Total Sulfide.

Reasonable Potential (Page 7):

WDEQ should provide the historical data, that they presumably have, for concluding that there is no reasonable potential for exceedances of the standards (or limits) for F, Mn, U, and *E. coli*.

Screening for Well Additives and Hydraulic Fracturing Fluids (Pages 9-10):

We agree that these kinds of well additives and fracturing chemicals should be monitored in the Aethon discharge to demonstrate that Aethon is not violating its permit by comingling these chemicals with production water and including them in their discharge. But we recommend that, in addition to listing of the suspect chemicals and their CAS#, WDEQ also should require reporting of analytical methods used and the detection limit for each analysis. In our professional experience, under these circumstances, a "non-detectable" analyte determination may not be trustworthy or may not be at a low enough detection limit to be toxicologically interpretable. By requiring the permittee to report the analytical method and detection limit, this potential problem can be avoided.

Whole Effluent Testing (Pages 10-11):

The newly revised draft permit only requires annual acute lethality Whole Effluent Toxicity (WET) tests with *Daphnia magna* and Fathead Minnows (*Pimephales promelas*). It is problematic that, in this new Aethon draft renewal discharge permit (12/17/2019), WDEQ eliminated chronic WET testing that had been included in the earlier draft permit dated 5/4/2017. Alkali Creek is Class 3B, and "Uses protected for Class 3B streams such as this include aquatic life, …" (page 8). We do not understand how WDEQ can support an argument that passing only acute lethality toxicity tests with *Daphnia magna* and Fathead Minnows (*Pimephales promelas*) will ensure protection of aquatic life, especially sensitive invertebrates.

As we stated in our earlier comments (dated June 27, 2019) related to the earlier draft permit, to test whether Aethon's produced water discharges might adversely affect fish and/or other aquatic organisms in Alkali Creek, Badwater Creek and Badwater Bay, stricter toxicity testing requirements will be needed in a final discharge permit. Whole Effluent Toxicity (WET) tests should be required quarterly (rather than annually), include each outfall, include acute 48-hour lethality tests with *Daphnia magna* and acute 96-hour lethality tests with Fathead Minnows, and include chronic toxicity tests for 7-day larval Fathead Minnow growth and 7-day *Ceriodaphnia magna* reproduction. In addition, to facilitate interpretation of all WET test results, WDEQ should require Aethon to analyze and report concentrations of a full suite of inorganic constituents (including Ca, Mg, Na, K, Cl, and SO_4), alkalinity, pH, BETX constituents, and Total Organic Carbon in the water sample collected for each WET test.

In fact, from several sets of information available to us now from reports on in-stream sample chemistry and toxicity, we already know that the Aethon discharge will be toxic most or all the time. For instance, WET test results on in-stream samples from monitoring site DMP1 in Alkali Creek above its confluence with Badwater Creek from June 2017 and February 2019 were recently released by WDEQ (ERM Whole Effluent Toxicity Test Result reports dated 12 July 2017 and 13 March 2019). The two WET test files present two different views of Alkali Creek. In June 2017, the acute toxicity for *Daphnia magna* and Fathead Minnows at all sites in Alkali and Badwater Creeks was almost nil, even at the Alkali Creek DMP1 site many miles downstream from Aethon's discharge and above Alkali Creek's confluence with Badwater Creek. However, in February 2019, the acute toxicity for *Daphnia magna* and Fathead Minnows

at the same DMP1 site was substantial, resulting in test failure. And, as might be expected, the chronic toxicity for Fathead Minnows in the February, 2019 sample from DMP1 was even greater than the acute toxicity, with significant lethality and growth reduction. We can only speculate about the difference in the June 2017 and February 2019 WET test results, but it may be that there was significant dilution flow in Alkali Creek in June 2017, when no toxicity was observed, and little or no dilution flow in Alkali Creek in February 2019, when significant toxicity was observed. Or perhaps treatment-plant operating conditions differed considerably between the two time periods. Since stream discharge in Alkali Creek and descriptions of operating conditions were not included in these reports, we can only speculate about the observed difference in toxicity.

Given what we know about Aethon's discharge, at least until Aethon completes its effluent treatment upgrades under the WDEQ's proposed Compliance Schedule, we can be sure that Aethon's effluent will consistently fail any WET tests. We base this conclusion on mortality predictions for *Ceriodaphnia dubia*, *Daphnia magna*, and Fathead Minnows using Mount et al. (1997) models for major-ion toxicity, with major-ion concentrations that were reported in Table 2 in the first version of the draft renewal permit and in Table 2 in ERM's Blackwater – Alkali Creek: Sediment and Surface Water Sampling Results report. Additionally, the untreated effluent is highly contaminated with roughly 2,200 mg Cl/L plus very high concentrations of organic carbon (68 mg/L on August 20, 2019, as reported in Table 2 in ERM's Blackwater – Alkali Creek: Sediment and Surface Water Sampling Results report), Hydrogen Sulfide and other contaminants; and the Neptune reverse osmosis plant at outfall 001 is inoperable at this time. With regulatory oversight from WDEQ, Aethon should use regular WET tests along with Toxicity Identification procedures to identify other specific contaminants in addition to Chloride, Hydrogen Sulfide and temperature that will need to be controlled during the period of time allowed under WDEQ's proposed Compliance Schedule.

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Curriculum Vitae for Bergman and Meyer

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EDUCATION
Eastern Michigan University Biology B.A., 1968
Eastern Michigan University Biology M.S., 1971
Michigan State University Fisheries Biology Ph.D., 1973

PROFESSIONAL POSITIONS
2011-2013 Department Head, Department of Zoology and Physiology, University of Wyoming
1995-2016 J.E. Warren Distinguished Professor of Energy and Environment, University of Wyoming
1998-2008 Director, William D. Ruckelshaus Institute and Helga Otto Haub School of Environment and Natural Resources, University of Wyoming
1988 Visiting Scientist, U.S. Environmental Protection Agency, Duluth, Minnesota
1986-1987 Acting Director, Wyoming Water Research Center, University of Wyoming
1984-2016 Professor, Department of Zoology and Physiology, University of Wyoming (Retired 2016)
1984-1999 Director, Red Buttes Environmental Biology Laboratory, University of Wyoming
1975-1984 Asst. & Assoc. Professor, Dept. of Zoology and Physiology, University of Wyoming

PROFESSIONAL AWARDS AND DISTINCTIONS (Selected)
Founder's Award, Society of Environmental Toxicology and Chemistry, 2018
Distinguished Faculty Graduate Mentor Award, University of Wyoming, 2014
Extraordinary Merit in Advising, Arts & Sciences College, University of Wyoming, 2014
Elected Fellow, American Association for the Advancement of Science, 1995
George Duke Humphrey Distinguished Faculty Award, University of Wyoming, 1995
Conservation Educator of the Year, Wyoming Wildlife Federation, 1986
President of the Society of Environmental Toxicology and Chemistry, 1984-85
President of the Water Quality Section, American Fisheries Society, 1982-83
Editorial Board, Environmental Toxicology and Chemistry, 1981-84
EPA Doctoral Traineeship, Michigan State University, 1971-73

STATE, NATIONAL AND INTERNATIONAL ADVISORY & REVIEW PANELS (Selected)
Wyoming Environmental Quality Council, 1983-95; Chairman, 1985-87
National Research Council - National Academy of Sciences Committees/Board
- Ecological Risk Assessment, 1986-87
- Animals as Monitors of Environmental Hazards, 1987-91
- NRC Board of Agriculture and Natural Resources, 2009-2016

Environmental Protection Agency, ORD, Peer Review Panels/Review Committees
- Exploratory Grants Program, Environmental Biology Panel, 1986-96
- National Acid Precipitation Assessment Program, Aquatic Effects Program, Panel Chair, 1987
- Graduate Fellowship Review Panel, 1995-98, 2009-12
- Environmental Protection Agency, Science Advisory Panel for Pesticides (FIFRA), 1984-87
- Science and Technology Achievement Awards, 1986-87
- Water Quality Standards Research Review, 1986
- Ecological Risk Assessment Research Review, 1986
- Environmental Protection Agency, Board of Scientific Councilors, 1996-97

The Royal Society (London), Surface Water Acidification Program Review Panel, 1990
Private Sector Board and Advisory Positions
- PacifiCorp, Inc., Environmental Forum, Portland, OR, 2000-04
- Wyoming Outdoor Council Board, Lander, WY, 2009-2015; 2017-present

SELECTED RELEVANT PUBLICATIONS (Selected from over 100 publications)

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EDUCATION
Lehigh University, Chemical Engineering B.S., 1973
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PROFESSIONAL POSITIONS

2016-Present	Chief Scientist, Applied Limnology Professionals LLC, Golden, CO
2012-Present	Affiliated Faculty Member, Department of Chemistry and Geochemistry, Colorado School of Mines, Golden, CO
2007-2016	Technical Expert and Principal Scientist, Arcadis, Lakewood, Colorado
2005-2007	Professor, Department of Zoology and Physiology, University of Wyoming
1999-2005	Associate Professor, Department of Zoology and Physiology, University of Wyoming
1999 2004	Director, Red Buttes Environmental Biology Laboratory, University of Wyoming
1994-1999	Assistant Professor, Department of Zoology and Physiology, University of Wyoming
1991-1993	Coordinator, Wastewater Utilization Graduate Program, Humboldt State University, Arcata, CA
1990-1993	Lecturer, Department of Fisheries, Humboldt State University, Arcata, CA
1989-1990	Postdoctoral Researcher, University of Wyoming-National Park Service Research Center, University of Wyoming
1988-1989	Postdoctoral Researcher, Lake Research Laboratory, Swiss Federal Institute for Water Resources and Water Pollution Control (EAWAG/ETH), Kastanienbaum, Switzerland
1987-1988	NATO Postdoctoral Research Fellow, Lake Research Laboratory, Swiss Federal Institute for Water Resources and Water Pollution Control (EAWAG/ETH), Kastanienbaum, Switzerland
1987	Research Scientist, Department of Zoology and Physiology, University of Wyoming
1986	Graduate Research and Teaching Assistant, Department of Zoology and Physiology, University of Wyoming
1980-1983	Associate Scientist, Western Aquatics, Inc., Laramie, WY [part-time]
1976-1985	Research Scientist, Department of Zoology and Physiology, University of Wyoming
1972	Student Participant, NASA Summer Institute for Biomedical Engineering, Howard University and Goddard Space Flight Center, Greenbelt, MD

PROFESSIONAL AWARDS AND DISTINCTIONS (Selected)
Fellow of Society of Environmental Toxicology and Chemistry, 2018-Present
President of Rocky Mountain Chapter of Society of Environmental Toxicology and Chemistry, 2004-2005
Member of Editorial Board, *Environmental Toxicology and Chemistry*, 1997-2000
Member of Board of Directors of Rocky Mountain Association of Environmental Professionals, 1983-1984

STATE, NATIONAL AND INTERNATIONAL ADVISORY & REVIEW PANELS (Selected)
U.S. Environmental Protection Agency: Member, Aquatic Life Criteria Consultative Panel of the Science Advisory Board of the U.S. Environmental Protection Agency. 2005.
U.S. Environmental Protection Agency: Member, Health and Ecological Effects Subcommittee of the Advisory Council on Clean Air Compliance Analysis of the Science Advisory Board (SAB) of the U.S. Environmental Protection Agency. 1998-2002.
Environment Canada: Member, Environmental Resource Group for the Assessment of Chloramine under the Canadian Environmental Protection Act. 1996-1999.
U.S. Environmental Protection Agency: Member, Advisory Council on Clean Air Compliance Analysis Physical Effects Review Subcommittee of the Science Advisory Board of the U.S. Environmental Protection Agency. 1994-1997.
U.S. Department of Energy: Review of documents addressing damages and benefits of various fuel cycles. 1992-1993.

SELECTED RELEVANT PUBLICATIONS (Selected from 100 publications)

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