GRADIENT

August 28, 2017

Mr. Jeffrey A. Cummins
Director, Division of Enforcement
Kentucky Energy and Environment Cabinet
Department for Environmental Protection

Re: Response to Blue Ridge Landfill Corrective Action Plan – Cabinet Comments dated July 21, 2017

Dear Mr. Cummins:

On behalf of Advanced Disposal Services Blue Ridge Landfill, Inc. and in accordance with the Agreed Order Case No. DWM – 160048, Gradient, in collaboration with Risk Assessment Corporation (RAC), is submitting this response to the Cabinet's July 21, 2017, comments on the Blue Ridge Landfill Corrective Action Plan (CAP) dated May 3, 2017. The CAP and its attachments have been revised accordingly and are submitted herein.

Energy and Environment Cabinet (EEC) Comment #1:
In the Executive Summary of the Corrective Action Plan (CAP), it is stated that "...Kentucky allows TENORM with "radiation levels" up to 2,000 pCi/g, generated within the State, to be disposed of in solid waste landfills, and therefore has implicitly determined that solid waste landfills can safely contain TENORM below this radioactivity level." Further **Sec. 2.5.1 State of Kentucky Landfill Requirements**, states "Since Kentucky allows TENORM up to 2,000 pCi/g generated within the state to be disposed of in solid waste landfills, the State has already determined that these landfills can safely contain whatever risk these materials may pose". These are misstatements of the Commonwealth's requirements for TENORM provided under the Central Midwest Interstate Low-Level Radioactive Waste Commission, which states that "TENORM with concentrations greater than 2,000 pCi/g shall be disposed of at the regional low-level radioactive waste disposal facility and TENORM waste with concentrations less than 2,000 pCi/g shall be disposed of in accordance with the method approved by the appropriate state regulatory agency." The Commonwealth has not concluded that municipal solid waste landfills can safely contain TENORM below 2,000 pCi/g. As page 14 of the CAP notes, regulations for TENORM waste are currently pending by the Cabinet for Health and Family Services (CHFS) and the Energy and Environment Cabinet (EEC). The regulations will include specific requirements for the operation and closure for contained landfills and other disposal facilities which accept TENORM waste in order to be protective of public health and the environment.

Response #1:
The Executive Summary of the CAP has been revised accordingly. Conforming changes have also been made to Section 2.5.1 (State of Kentucky Landfill Requirements) of the CAP.

EEC Comment #2:
The Executive Summary of the CAP states that "sampling investigations indicate that radionuclide concentrations in areas of the landfill containing the BES Waste are below those of samples from naturally occurring radioactive material (NORM) inside and outside of the permitted solid waste boundary." This does not seem to be possible, considering the average radium concentrations in the wastes as described in the RAC reports. Please clarify this statement.

Response #2:
To clarify, the BES Waste was mixed with municipal solid waste (MSW) when it was disposed of at the Blue Ridge Landfill; therefore, radionuclide concentrations of the *in situ* BES Waste mixed with MSW were compared to background levels. The Executive Summary of the CAP has been revised accordingly.

EEC Comment #3:
In accordance with the landfill operating permit, groundwater, storm water, surface water, and leachate are routinely monitored for a "suite of constituents" (Table 2.4 and Remediation Alternative 1, page 25 of the Plan). The constituents currently monitored in these media do not include radionuclides. Due to the presence of TENORM wastes, the groundwater monitoring plan and surface water monitoring plan required pursuant to 401 KAR 48:300 and 48:090 for the solid waste contained landfill permit must be amended to include radionuclides (particularly radium-226, radium-228, gross alpha, and gross beta) as parameters for monitoring groundwater and surface water in addition to other parameters that are currently analyzed. For storm water and surface water discharges from the facility, the KPDES permit will also need to be amended to add these parameters. Leachate analysis should also include radionuclide parameters and appropriate heavy metals prior to discharge to the wastewater treatment plant (WWTP). The WWTP must be capable of treating and testing for the relevant parameters.

Response #3:
Advanced Disposal Services (ADS) will work with the Cabinet to develop a Radionuclide Sampling Plan. Given the elevated background NORM in the region, establishing statistically significant background concentrations will be an important component of the monitoring plan. The Radionuclide Sampling Plan will also factor in the regulations for TENORM waste that are currently being prepared by CHFS and the EEC, to the extent that they apply. The Radionuclide Sampling Plan will be submitted under separate cover for Cabinet review and approval.

In the interim, ADS will perform quarterly groundwater sampling at all monitoring well locations (see Figure 2.3 of the CAP) for radium-226 [Ra-226], radium-228 [Ra-228], gross alpha, and gross beta in order to establish Site-specific background concentrations of naturally occurring radionuclides (which are known to be present regionally). Subsequently, ADS will sample monitoring wells downgradient (MW-13, MW-15R) of the BES Waste on a semi-annual basis to determine if radionuclides have impacted groundwater. The semi-annual sampling will include analyses for the aforementioned radionuclides.

EEC Comment #4:
Remediation Alternative 2, as described in the Executive Summary, is to "excavate and transport the BES Waste from the BRL to another disposal facility, where it would be redisposed, subject to similar environmental controls." The re-disposal site considered in the evaluation is the Mostoller Landfill, in Somerset, PA - a facility approved by the state of Pennsylvania to receive TENORM wastes. Are the environmental controls for the two landfills "similar" or are there more stringent design and operating requirements at the Mostoller landfill, based on its approval to receive TENORM waste?

Response #4:
The engineering design and environmental controls for the Blue Ridge Landfill and the Mostoller Landfill are similar. Based on our evaluation, Pennsylvania imposes no additional controls from a design or operational standpoint upon a landfill that accepts TENORM as opposed to one that does not, except to limit, on a monthly basis, the total amount of TENORM accepted.

Attached to this letter is a figure providing a comparison between base liners and final cross sections of the Blue Ridge and Mostoller Landfills. Based on this comparison, we believe the environmental controls are essentially the same, except with regard to the final cover design, because we believe the Blue Ridge Landfill liner offers more environmental protection.

All permitted Pennsylvania solid waste landfills, whether they accept TENORM or not, must contain a double composite liner system. Even though the Blue Ridge Landfill contains a single composite liner, the high-density polyethylene liners are both 60 mil thick, and the Blue Ridge Landfill liner is underlain by 3 ft of low-permeability soil along its floor. Importantly, however, the Blue Ridge Landfill bottom grades are constructed with a 10% slope, as compared to a 4% slope at the Mostoller Landfill. Therefore, leachate at the bottom of the Blue Ridge Landfill flows quicker to the leachate collection sump, where it is lifted out of the landfill to the publically owned treatment works (POTW).

Also, the Blue Ridge Landfill's permitted final cover is more protective than the Mostoller Landfill's final cover. The Mostoller Landfill's final cover has a geomembrane that is 30 mil thick *versus* 40 mil thick for the Blue Ridge Landfill's final cover. Also, the Blue Ridge Landfill's vegetative cover is 12 in thicker.

Pennsylvania imposes no additional radioactive testing (*i.e.*, Ra-226, Ra-228, gross alpha, gross beta) for groundwater, stormwater, or leachate for ADS Pennsylvania landfills that accept TENORM wastes. Nor is the Mostoller Landfill subject to different closure requirements or a longer post-closure period.

EEC Comment #5:
The BRL and immediate surrounding area are described in Section 2 of the CAP. Some information that would be important to consider in the risk assessment which is not included in the Risk Assessment Corporation (RAC) documents is the estimated population, land use and groundwater usage in the vicinity of the landfill currently and projected into the future. Also, please provide information on the potentially 'exposed populations and estimated or modelled effects of radiation doses, if any, on these groups.

Response #5:
Information about the population and land and groundwater use in the area surrounding the Blue Ridge Landfill has been added to the risk assessment (Attachment A2 of the CAP) to provide context to the dose estimates presented in the report. In addition, further groundwater use information will be provided in the well survey update (see Response #10). The exposure scenarios and parameters used in the radiological risk assessment were selected to provide bounding estimates of the potential radiation doses to members of the public or workers. To address releases to the atmosphere, potential public receptors located closest to the disposal area were identified, characterized, and the doses calculated. Any member of the public at more distant locations would receive lower doses or no dose at all. Similarly, the evaluation of the groundwater exposure pathway was designed to be bounding. A hypothetical well was assumed to be located directly downgradient from the source and the water extracted for human consumption directly. Any potential impacts to groundwater wells located at greater distances or in geological formations that supply drinking water would result in lower doses. RAC's risk assessment (Attachment A2 of the CAP) was updated to clarify these points.

EEC Comment #6:
The landfill is estimated to operate approximately 40 more years, after which the approved closure plan will be implemented. Closure will include: capping of the landfill pursuant to the requirements of 401 KAR 48:080 and the landfill permit, recording of an environmental covenant which prevents disturbance of the cap and prevents residential and groundwater use, 30 year post-closure maintenance and groundwater monitoring, and a plan for long-term maintenance and monitoring. The lifetime of the landfill cap, used for the RAC evaluation, is 200 years. How do these expectations and closure practices compare with those of a landfill authorized to receive TENORM wastes, such as the Mostoller facility?

Response #6:
We provide a comparison of the Blue Ridge and Mostoller Landfills' physical characteristics and closure requirements in Response #4.

We also note that Section 4.2.1 of the CAP has been revised to reflect that an enhanced cap will be placed over the BES Waste area, and the landfill gas collection system will be modified to relocate landfill gas extraction wells out of the BES Waste area (see Response #8).

EEC Comment #7:
Original quarterly landfill waste reports submitted by the facility indicated that the TENORM waste was used as alternate daily cover. ADS later submitted revised reports to indicate that the material was not used as daily cover but was mixed with municipal solid waste (MSW) and covered in place with soil and additional MSW. Due to uncertainty as to the disposition of the TENORM waste, it is recommended that the risk calculations for "maximum reasonable exposure" be revised by RAC to address possible use of the material as alternate daily cover. Figure 2.10 below indicates the highest levels measured in the Gamma Scan Survey are shown outside of the permitted solid waste boundary. A brine filtration sock was found in the material and ADS has stated the material originated from an oil and gas well located in eastern Kentucky that had been disposed of years earlier and resurfaced as part of constructing a new landfill cell. Please provide information as to how potential exposure resulting from incidental resurfacing of previously buried TENORM waste will be addressed.

Response #7:
ADS is certain the BES Waste was not used as daily cover and does not believe that evaluating this hypothetical scenario would yield meaningful or realistic data. Immediately after learning about the possible TENORM disposal, ADS reviewed the disposal records and discovered that the material was wrongly coded as "alternative daily cover," a designation used for soil, not for sludges. ADS management interviewed the former Site manager, who confirmed that the material was not used as daily cover. Last, if the material was used as daily cover, the extensive gamma ray scans conducted in the spring and summer of 2016 would have shown increased activity at the surface, but the scans did not. ADS is certain that the BES Waste was mixed with MSW and disposed of in the sections of the landfill shown in Figure 2.5 of the CAP.

Further, ADS has buried the BES Waste under additional MSW and a protective 6-in cover, and final Site plans include burial of the BES Waste with a minimum of 30 ft of additional MSW and the final cover system. These measures will prevent resurfacing and further reduce exposure potential.

Regarding the brine filter sock, this material appears to have been present at the ground surface from direct placement, not resurfacing. No additional filter socks were found in or around the adjacent waste pile. The sock was removed for analytical testing, and the adjacent waste pile was excavated and disposed of at a different facility (the Mostoller Landfill in Somerset, PA).

EEC Comment #8: Potential Additional Source
One other issue that should be considered is the likelihood of radon in the collected landfill gas that is extracted, transported, treated, and then used to generate electricity at the onsite 1600-kilowatt electrical generation plant. The method of "treatment" is not specified and radon from this potential source does not appear to have been modeled or measured. From Section 2.1.3 of the CAP: The vertical gas extraction wells collect methane gas and transport it to an on-site treatment facility. A header system collects condensate as the landfill gas is cooled. This condensate is removed and disposed of, along with the landfill leachate. The remaining treated gas is used for electricity generation at the landfill.

Response #8:
The percentage of total methane gas production in the BES Waste area is a small fraction of the total gas production. As such, it is unlikely to be a significant source of exposure. Nonetheless, to further reduce methane generation from the area of the landfill where BES Waste was disposed of, ADS intends to relocate

the existing landfill gas extraction wells from the BES Waste area to other areas of the landfill and prohibit drilling landfill gas extraction wells in the BES Waste area (see Figure 4.1 of the CAP).

EEC Comment #9: 2.5.2 State of Kentucky Remediation Requirements
This section states that identification of final remediation goals for the proposed remedy can be based on USEPA Region IX Preliminary Remediation Goals (PRGs) pending review by the cabinet of site-specific conditions." Pursuant to KRS 224.1-530, the cabinet uses the Regional Screening Levels (RSL) Table published by USEPA Region 3 as screening levels in conformance with the Risk-Based Concentration Table Users Guide.

Response #9:
Section 2.5.2 of the CAP has been updated to reflect that KRS 224.1-530 specifies use of US EPA Region 3 Regional Screening Levels.

EEC Comment #10: Table 3-1 Site-Specific Factors for Remedial Action Objective Determination
For groundwater use, it is stated that there is not potable water use at the site and that a 1992 well search identified 16 wells within one mile of the downgradient (northwest) site boundary. Updated information must be provided related to water use in the vicinity of the site.

Response #10:
An updated well search is underway. As part of that well search, the Kentucky Geological Survey database[1] for water supply wells and springs was queried for wells and springs within 1 mile of the Site boundary. The results of the database query are provided in Section 2.1 and Figure 2.2b (2017 Water Well Survey Results) of the revised CAP. In addition, a well survey within 1 mile of the downgradient (northwest) Site boundary is currently being implemented. Details of this well survey methodology are provided in Attachment G of the CAP, and its results will be submitted to the Cabinet in a separate report upon completion.

EEC Comment #11:
Figure 2-9 noted on page 23 could not be located in the CAP.

Response #11:
Figure 2.9 is included on page 10 of the original CAP (embedded in the report text). The CAP List of Figures was updated to clarify that Figure 2.9 is embedded in Section 2.3 of the report.

EEC Comment #12: 4.2.1 Remediation Alternative 1: Closure-in-Place and Monitoring
It is stated that "sampling will be conducted for the closure period of 2 years and the post-closure care period of at least 30 years." Page 25 notes that long-term monitoring of surface water and groundwater beyond the "containment zone" will be conducted to ensure protectiveness. Clarify what area is included in the containment zone.

Measures must be taken to ensure long-term protectiveness for Remediation Alternative 1: Closure in Place and Monitoring, due to the nature of long-term decay of the TENORM constituents. This section states that "prior to construction of the final cover system, a minimum of 30 feet of MSW will be placed on top of the BES waste", with the final cap to be constructed in phases upon closure of the landfill. It should be noted that the closure and final cap requirements for facilities disposing of TENORM wastes may be amended by the pending regulations. Following closure of the site under the solid waste contained landfill permit requirements, 401 KAR 48:080 and 48:090, and the pending amended regulations for TENORM disposal, the site should be subject to regular inspections, a long-term monitoring program, and an

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[1] The Kentucky Geological Survey Data Repository can be accessed at: http://www.uky.edu/KGS/water/research/gwreposit.htm.

operations and maintenance (O&M) Plan to ensure overall stability and performance of the cap and an environmental covenant pursuant to KRS 224.80 should be filed to restrict future use of the property. A Five Year Review and annual certification is also required under 401 KAR 100:030 Section 8 (3)(b).

Response #12:
The Blue Ridge Landfill will comply with the final regulations regarding TENORM that would apply to the Blue Ridge Landfill's receipt of BES Waste in late 2015 to early 2016. Section 4.2.1 of the CAP was revised to indicate that ADS will comply with these pending regulations, and to clarify that the containment zone consists of waste that is located within the landfill containment systems, consisting of the landfill liner system, leachate collection system, landfill gas management system, and stormwater controls (as described in Section 2.1 of the CAP).

In addition, as described in Response #3, ADS will work with the Cabinet to develop a Radionuclide Sampling Plan. Given the elevated background NORM in the region, establishing statistically significant background concentrations will be an important component of the monitoring plan. The Radionuclide Sampling Plan will also factor in the regulations for TENORM waste that are currently being prepared by CHFS and EEC, to the extent that they are relevant.

EEC Comment #13: 4.2.2 Remediation Alternative 2, Excavate and Redispose BES Waste
Please describe measures that would be employed to control storm water run-on and runoff while the TENORM material is excavated during the estimated 90-day construction period. Explain the procedures for handling and disposal of water in the excavation.

Response #13:
ADS agrees that stormwater controls would be necessary to control stormwater run-on and run-off during a potential excavation of the BES Waste. However, details regarding these controls are typically provided during remedial design, and thus would be premature to include within the scope of this CAP (prior to remedy selection). Such stormwater controls, however, would increase the engineering design and construction effort required, thereby increasing the overall cost and further reducing the implementability of Remediation Alternative 2.

The CAP has been revised (Section 4.2.2) to indicate that stormwater controls would be required to implement Remediation Alternative 2.

EEC Comment #14: 4.2.2 Remediation Alternative 2, Excavate and Redispose BES Waste
A typo is noted in "...amount of soil and overlying MSW to be excavated is approximately 16,300 cubic yards (45,575 cubic yards) assuming a "fluff factor" of 15%. It should be 18,745 cubic yards assuming a 15% fluff factor.

Response #14:
We agree that the correct amount of potentially excavated soil and MSW overlying the BES Waste should be 18,745 yd^3 (assuming a fluff factor of 15%). Section 4.2.2 of the CAP was revised accordingly.

EEC Comment #15: 6.5.1 Short-Term Radiological Risks
It is unclear as to whether the RAC report includes the potential risk incurred by the receiving landfill facility workers including the Landfill Laborer, Supervisor and Other Landfill Customers. Please clarify.

Response #15:
The radiological risks to landfill facility workers at a landfill to which the excavated waste is shipped for redisposal were not evaluated explicitly because the specific details of the receiving landfill are unknown.

However, it was assumed that the risks would be comparable to those experienced during the original disposals at the Blue Ridge Landfill.

EEC Comment #16: Table 6-3 Cancer Morbidity Risk Estimates for the Remediation Alternatives During Excavation.
The excess cancer risk for the Landfill Laborer (1.8 X 10-5) and Supervisor (2.2 X 10-6) is within the USEPA risk range of 1 X 10-4 to 1 X 10-6 but it exceeds Kentucky's target risk level of I X 10-6.

Response #16:
Table 6.3 of the CAP has been updated to explain that for Remediation Alternative 2 (Excavate and Redispose BES Waste), the risk estimates for the future Landfill Laborer and Supervisor exceed Kentucky's target cancer risk of 1×10^{-6} (401 KAR 100:030). Based on a comparative analysis of the remediation alternatives, including consideration of the Kentucky target risk level, Remediation Alternative 1 would provide a higher level of overall protectiveness than Remediation Alternative 2.

Attachment A2 of the CAP has also been updated to reflect that the Kentucky's target risk level of 1×10^{-6} was exceeded for the Remediation Alternative 2. We now also reference Kentucky risk levels alongside those of US EPA throughout Attachment A2 of the CAP.

EEC Comment #17: 6.5.3 Green and Sustainable Remediation (GSR)
For Remediation Alternative 2, hauling the TENORM and associated wastes from the landfill over county and state roads to another disposal location could damage the roadways which would need to be repaired. This would increase the cost for labor, materials and fuel, and would also increase air emissions from heavy equipment for road repair.

Response #17:
We agree that hauling TENORM from the Blue Ridge Landfill to another facility could cause road damage. Repairing road damage would increase the costs and air emissions for Remediation Alternative 2. Section 6.5.3 of the CAP has been revised accordingly.

EEC Comment #18: 6.6 Implementability
Decontamination of the trucks after each shipment will generate additional waste which would have to be properly disposed.

Response #18:
We agree that decontamination of trucks and excavation equipment would generate additional waste that would have to be properly managed and disposed. This would further impact the implementability and cost of Remediation Alternative 2. Section 6.6 of the CAP has been revised accordingly.

EEC Comment #19: 6.7 Cost
Additional costs will be incurred for laboratory analytical analyses to add radionuclides to the surface water, groundwater and leachate samples. There could also be additional costs for leachate disposal if the levels are elevated above levels accepted by the Irvine Municipal Utility Wastewater Treatment Plant. Additional radiation safety procedures may be necessary when collecting and handling these media during sampling.

Response #19:
As described in Response #3, ADS will work with the Cabinet to develop a Radionuclide Sampling Plan. For the purposes of the CAP, we prepared a cost estimate of sampling for these additional analytes. The table below provides a summary of these costs and assumptions used in the calculations. ADS will adhere to appropriate health and safety procedures for its workers and contractors performing the sampling.

Summary of Additional Costs for Radionuclide Sampling

Sampling Frequency	Total Number of Samples	Total Cost	Total Present Value Cost at 7%[a]
Quarterly (2 years)[b,c]	40	$5,800	$5,200
Semi-annual (28 years)[b,c]	112	$16,800	$7,300
Totals	**152**	**$22,800**	**$12,500**

Notes:

(a) Total present value was estimated based on the method presented by US Army Corps of Engineers and US EPA (2000) ("A Guide to Developing and Documenting Cost Estimates During the Feasibility Study"), using a 7% discount rate.

(b) Sampling includes groundwater from all monitoring wells for the first 2 years and downgradient wells (MW-13, MW-15R) only for up to 28 years (locations shown in Figure 2.3). Analytical analyses include gross alpha, gross beta, and gamma spectroscopy. An additional 10% was added for field and trip blanks.

(c) No additional labor costs were included for sampling.

In addition, an enhanced cap will be placed over the BES Waste area as part of the final cover system, and the landfill gas collection system will be modified to relocate landfill gas extraction wells from the BES Waste area (see Response #8). Costs for these landfill modifications have been added to Remediation Alternative 1.

Section 6.7 and Attachment E of the CAP have been revised accordingly. These costs do not alter the conclusion that Remediation Alternative 1 is more cost-effective than Remediation Alternative 2.

EEC Comment #20: Table 6.6 Summary of Incremental Remediation Alternative Costs
There would be some increased costs for monitoring long-term for radionuclides at the landfill which would be in addition to the other constituents that are monitored.

Response #20:
We agree that long-term monitoring for radionuclides would increase costs. Please refer to Response #19, above.

In addition, an enhanced cap will be placed over the BES Waste area, and the landfill gas collection system will be modified to relocate landfill gas extraction wells from the BES Waste area (see Response #8). Costs for these landfill modifications have been included in Remediation Alternative 1.

Section 6.7 of the CAP and Attachment E have been revised accordingly. These costs do not alter the conclusion that Remediation Alternative 1 is more cost-effective than Remediation Alternative 2.

EEC Comment #21:
Although some of the exposure factors used by RAC will need to be recalculated as noted in further comments on the risk assessment reports, it is evident that radiation doses received by individual workers and members of the public, during the placement of the wastes in the landfill are low and within regulatory limits. The modeling of potential groundwater exposure and dose into the future does appear to be reasonably conservative. Estimated future radiation doses to a worker and maximally exposed member of the public from wastes left in the landfill will also be quite low. The adverse impacts of excavating and relocating the wastes will likely be greater than those of leaving them in place, due in large part to the potential for accidents during the physical actions to excavate, transport, and redispose of the wastes.

Therefore it seems clear that "Remediation Alternative 2: Excavate and Redispose the BES Waste" would present a higher potential risk than "Remediation Alternative 1: Closure-in-place and Monitoring." However, for the purposes of ensuring safety of the landfill workers, it is recommended that ADS develop a landfill worker training and safety program to meet the requirements of 902 KAR 100:019 including the use of personnel radiation badges (dosimeters) to measure potential doses in real time.

Response #21:
We agree that Remediation Alternative 2 (Excavate and Redispose the BES Waste) poses higher potential risk than Remediation Alternative 1 (Closure-in-Place and Monitoring).

ADS understands and agrees that the safety of our landfill workers is vitally important. The dose assessment conducted by RAC has shown that landfill workers received limited doses during the BES Waste disposals, and that potential future doses are at very low levels given the depth of the BES Waste if left in place. Given the conditions at the Blue Ridge Landfill, under Federal law, environmental conditions would not require the landfill workers to wear dosimeters (10 CFR 20.1502). Thus, ADS does not believe that it is necessary to equip their workers with personnel radiation badges (dosimeters).

ADS has developed a Radiation Screening and Monitoring Plan for the Blue Ridge Landfill that describes waste material profiling and testing prior to landfill acceptance. ADS has also installed radiation monitors to prevent future NORM/TENORM disposals. Because the Blue Ridge Landfill will not receive additional TENORM waste, dosimeters, per the proposed TENORM regulations, would not be required.

ADS landfill workers will be trained on the Radiation Screening and Monitoring Plan for the Blue Ridge Landfill.

RAC 2016 Dose and Risk Assessment (Attachment A1) and RAC 2017 Radiological Risk Assessment (Attachment A2)

EEC Comment #22:
The original 2016 Risk Assessment was reviewed by the KY Department of Public Health, whose comments were used to revise the RA in 2017. If we assume that these parameters are representative of reasonable maximum exposure (RME), the result of the revised risk assessment is that the dose calculated for the most exposed receptor (landfill worker) results in a potential risk of 2.0E-05, which is within the USEPA risk range, but above our *de minimis* value of 1.0E-06. As with all risk assessments, there were many assumptions made, some of which seem to err on the side of conservatism, with some notable exceptions, shown below.

The risk assessment parameters that were used for the most exposed receptor include:

- **Soil ingestion rate - 330 mg/day over an 8 hour workday.** This is less conservative than the KDEP recommended rate of 480 mg/day, but it is in line with USEPA and is a reasonable value for an outdoor worker
- **Exposure Time - 20 minutes per disposal for the most exposed receptor)**. (The landfill worker). This leads to a soil ingestion rate per disposal of only 13.75 mg. This is particularly important for extremal exposure, which drives the risk for these workers.
- **Inhalation rate - 1.8 m^3/hour.** This is less conservative than the KDEP recommended rate of 2.5 m^3/hour, but is probably reasonable for the level of activity for a landfill worker.

Additional issues and assumptions were made in the risk assessment that may need to be considered and re-evaluated including:

- The fact that **TENORM waste from in-state** was also disposed of at the site, but the areas of the site that received these wastes are **not included** in the risk assessment.
- The assumption that the heavy-equipment operator is inside an air-conditioned cab exposed only to filtered air.
- The assumption that the TENORM waste in question was covered within an hour of receipt, since there is uncertainty as whether the TENORM may have been used as alternate daily cover or placed in disposal cells. Due to the uncertainty of the disposition of the TENORM, it is recommended that the risk calculations for the most exposed receptor be recalculated to account for the increased time of exposure as the worker would grade the cover material over the entire working face at the end of the day and would also remove it at the beginning of the next work day.

Response #22:
The radiological dose and risk calculations performed for the CAP represent bounding scenarios whereby the results are expected to overestimate actual doses and risks significantly. Although the exposure parameters are, in many respects, representative of a reasonable maximum exposure (RME), there are some instances in which a slightly larger value might be considered, as suggested by the reviewer. However, it is important to note that the underlying transport calculations used to determine the media concentrations, such as concentrations in air and groundwater, were not designed to provide realistic estimates of dose or risk; they were deliberately high-sided, resulting in higher estimates of risk than would actually occur.

We believe that part of the confusion is because we use the terms "landfill laborer" and "landfill worker" interchangeably, and we revised the exposure times between the 2016 Dose and Risk Assessment and the 2017 Radiological Risk Assessment. The exposure times were increased slightly based on comments received from KYDPH.

In the 2016 Dose and Risk Assessment, the landfill laborer/worker receptors are broken into two groups: laborers/workers and heavy-equipment operators. The laborer/worker is assumed to spend 15 minutes, or 0.25 hours, per disposal 1 m from the truck containing TENORM waste, plus 5 minutes at 1 m from a truckload of unshielded TENORM waste. The heavy-equipment operator is assumed to spend 20 minutes, or 0.33 hours, per disposal sitting in the cab of the equipment.

In the 2017 Radiological Risk Assessment, we only calculated doses and risks for the landfill laborer/worker, because the heavy-equipment operator will receive a lower dose. Here, the landfill laborer/worker is assumed to spend 20 minutes, or 0.33 hours, per disposal 1 m from the truck containing TENORM waste, plus 5 minutes at 1 m from a truckload of unshielded TENORM waste.

In the appendix to the 2017 Radiological Risk Assessment, we revised the 2016 dose calculations based on the comment we received from KYDPH on January 20, 2017. In those calculations, we also assume 20 minutes, or 0.33 hours, per disposal 1 m from the truck containing TENORM waste.

These assumptions will tend to overestimate actual exposures because the same individual is assumed to be present at every disposal of the TENORM waste, and the wind is assumed to be always blowing towards that individual from the waste. Additionally, landfill workers are not typically at the working face of the landfill.

All heavy-equipment operators at the Blue Ridge Landfill work from inside air-conditioned cabs that filter the incoming air. These assumptions will tend to overestimate actual exposures from external radiation, because this assumes the same individual was present at every disposal of the TENORM waste.

Although the heavy-equipment operator is located at the active face and on the landfill for longer than each disposal, the waste is continuously being covered by fresh loads of municipal waste.

EEC Comment #23: Comparison to North Dakota TENORM Risk Assessment

The volume of BES waste was compared with proposed allowable TENORM disposal regulations in other states. As an example, Argonne National Laboratory produced a document for the North Dakota Department of Health, in which they propose allowing TENORM wastes containing an average concentration of less than or equal to 50 *pCi/g* of total radium (independent of background radium levels) to be disposed of in either Industrial Landfills or Special Wastes Landfills, provided the following conditions are met:

- No more than 25,000 tons of TENORM wastes are disposed of in a single year
- The average thorium activity concentration in the waste does not exceed 24 pCi/g (assuming a thorium to radium ratio of 49% at 50 pCi/g total radium)
- TENORM wastes must be covered by at least 2 m (6 ft) of a combination of the landfill cover materials and clean wastes that do not contain radionuclides

If we calculate the inventory in Ci for a year's worth of TENORM that would be allowed based on this assessment, the annual result is approximately 0.59 Ci from Radium and 0.55 Ci from Thorium, for a total of 1.14 Ci.

Comparing that to BES waste at BRLF (which is neither an Industrial Landfill nor a Special Waste Landfill), approximately 1157 tons of out-of-state TENORM wastes were disposed of at BRLF, with an average concentration of total radium of approximately 700 pCi/g. If we assume the same thorium to radium ratio of 49%, the result is 673 pCi/g for thorium (NOTE: The thorium to radium activity ratios in the RA/CAP, which were derived from the filter sock found at the landfill, would result in even higher thorium levels). If we calculate the inventory in Ci for the 92 loads of out-of-state TENORM, the result is approximately 0.73 Ci from Radium and 0.66 Ci from Thorium, for a total of 1.4 Ci. This not only exceeds what would be allowed in a ND industrial or special waste landfill, but only accounts for out-of-state TENORM. In addition, the average concentration of each load is 14 times that allowed in ND (with at least one load above 2000 pCi/g*)*.

Argonne National Laboratory. 2014. "Radiological Dose and Risk Assessment of Landfill Disposal of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) in North Dakota." Environmental Science Division. November. Available at https://www.ndhealth.gov/EHS/TENORM/ArgonneStudy/ANL-NDDH%20TENORM%20Landfill%20Study%20(ANL%20EVS-14_13)%20Final%20Report.pdf.

Response #23:

The reviewer is correct; those conditions are being proposed for North Dakota Industrial Landfills or Special Wastes Landfills as possible criteria for accepting TENORM wastes. They are established assuming continuous annual TENORM disposals of 25,000 tons per year at the stated concentrations. The BES Waste disposal at the Blue Ridge Landfill was a single event in which the BES Waste was disposed of and will not continue in the future. The North Dakota TENORM study also evaluated the radiological doses and risks associated with both landfill worker and future resident scenarios. The authors determined that the total activity that can be brought into the landfill while remaining in compliance with the 100 mrem/year public dose limit is as follows (reported here only for the most limiting case of the waste placement landfill worker, see Table 6.10, p. 73/140 and Table 6.15, p. 79/140 of the North Dakota report for others): 1.2 Ci Th-232, 5.0 Ci Ra-228, 2.6 Ci Ra-226, and 110 Ci Pb-210 (from Table 6.15, p. 79/140 of the North Dakota report). Additionally, the depth to the TENORM waste used to derive allowable concentrations in the North Dakota report was only 2 m, or ~6 ft. In the case of the Blue Ridge Landfill, the depth to the TENORM waste will be at least 30 ft, which will reduce potential doses substantially.

EEC Comment #24: Attachment A1 Waste Handling Procedure, Page 5
It is mentioned that ADS added sawdust to absorb the excess liquid to seven of the 92 loads. Based on information received, L. R. Daniels also solidified some of the waste. Eleven (11) unsealed truckloads of waste mixed with absorbent were trucked from the Ashland area to the Blue Ridge Landfill. Some of the waste from Fairmont Brine Processing appears to have been hauled in an uncovered trailer instead of being sealed. Given the nature of the waste and its small particle size, fugitive dust emissions from the trucks must be considered.

Response #24:
The particle size distribution of the various wastes that were hauled to the Blue Ridge Landfill is not known and is not something that is reported in the literature. It can be assumed that the addition of sawdust and other materials to solidify the wastes reduced the magnitude of any fugitive dust emissions from this source significantly. For RAC's analysis, it was assumed that the waste material could be characterized like soil that is susceptible to suspension, so that particulate emissions would not be underestimated and in all likelihood would be overestimated. Fugitive dust emissions during transportation to the Site were not evaluated explicitly. This pathway was eliminated from further consideration based on the exposure concentration and exposure duration for a member of the public to a passing truck hauling the waste. Attachment A2 of the CAP has been revised to clarify this aspect.

EEC Comment #25: Attachment A1 Fracking Waste and Treatment, Page 11
The waste from Fairmont Brine was described as "Exploration and production soil and debris". However the physical nature of the Fairmont Brine waste is not that of a soil; rather it is a chemical precipitate resulting from Fairmont's operations which extract radionuclides, recycle salts and water and concentrate the radionuclides through a chemical precipitation process. The resulting Fairmont Brine material is different from the soils and debris generated directly from the exploration and production facilities, as it is made up of much smaller particulates which should be considered for fugitive emissions.

Response #25:
A chemical precipitate is likely to be more uniform in nature than soil, with regard to particle size. RAC assumed the characteristics of soil and debris with a variety of particle sizes in the respirable range, so that potential exposures were not underestimated. Attachment A2 of the CAP has been revised to clarify this aspect.

EEC Comment #26: Attachment A1 Particulate Emissions and Inhalation and Ingestion Doses During Disposal, Page 34
It is stated that "Radionuclide emissions during disposal are based on EPA emission model for aggregate handling and storage piles during drop loading operations as described in AP-42 Compilation of Air Pollutant Emission Factors (EPA 1995). Aggregate material is typically much drier and particulate aggregate is more easily dispersed in air than the solidified brines that comprise most of the TENORM material disposed in the Blue Ridge Landfill." Therefore the AP-42 emission factor for aggregate may not be the most appropriate factor.

Response #26:
We agree with the reviewer's comments. However, in the absence of specific data on a more realistic emission factor for this material, the AP-42 emission factor for aggregate material was considered to be a cautious assumption that ensured emissions, and thus, doses, would not be underestimated. Attachment A2 of the CAP has been revised to clarify this aspect.

EEC Comment #27: Attachment A1 Equation 2, Page 35
What was the value of "k" used in the calculations for the "particle size multiplier"?

Response #27:
The value used for k was 0.48, and is from AP-42 Section 13.2.4 – Aggregate Handling and Storage Piles. This assumes that particles less than 15 μm in size are respirable. This parameter is defined in Table 4 of the revised Attachment A2 of the CAP.

EEC Comment #28: Attachment A1, Page 36
Please describe if the wind speed used in the air emission model was representative. The standard meteorological for wind speed measurements is 10 meters. Often the actual wind speed in the vicinity of the emission source is significantly different due to the surface of the local terrain and boundary layer effects.

Response #28:
The wind speed used in the emission calculations was based on the mean measured wind speed at Lexington, Kentucky, as provided in the referenced website (http://www.climate-zone.com/climate/united-states/kentucky/lexington). Lexington is located about 50 km from the Blue Ridge Landfill. When site-specific data are lacking, US EPA allows for the use of meteorological data from nearby airports when performing an air quality analysis using the AERMOD code. Because there were not Site-specific data, the nearest location with meteorological data available was used. In flat-plane environments, wind speed and direction will tend to be constant. Meteorological measurements are typically taken at the 10-m level and away from structures and trees, to avoid perturbations caused by these features. Thus, the wind speed measured at Lexington would be representative of the regional airflow. Local topography and features can influence both wind speed and direction. In general, these features will tend to decrease wind speed in valleys and near the ground surface, and increase wind speed at ridge tops. The disposal of BES Waste did not occur on a ridge top or at 10 m, and thus, the average wind speed at ground level would be lower than the mean value of 9.1 mph that was used in the calculation. Therefore, releases were overestimated and provided an upper-bound estimate of radionuclide releases. Using a mean wind speed accounts for times of higher and lower wind speeds during the disposal. If the wind speed was higher during the disposals, releases would be higher (based on the suspension model), but relative air concentrations would also decrease due to increased dilution. If, for example, the wind speed during all the disposals was doubled, to 18.2 mph instead of 9.1 mph, the total dose to an individual who was present for all disposals would increase by only a factor of 1.07.

EEC Comment #29: Attachment A1, Page 38
The inhalation dose to off-site receptors was calculated using the "classic Gaussian plume model" as described in the second edition of *Workbook of Atmospheric Diffusion Estimates (Tumer* 1994 and is shown as Equation 10. The basic Gaussian equation model and dispersion coefficients were first published by Turner in the 1968-1969 time period (the report dated their reference to 1995). The model/equation is somewhat dated and has a high margin of error, and there are better approaches to modeling downwind transport today in the peer reviewed published literature. Also the model does not consider particulate deposition and re-suspension and treats the behavior of any particles entrained in the emission plume as following the ~streamlines of air flow (modeled as behaving as gas molecules where the momentum and inertia and mass differences between the gas molecules and entrained particles are not accounted for.) Also

the model equation is a point source model and a more accurate approach would have been to use an area source model to accurately capture the receptor concentrations close to the source. The dispersion coefficients developed by Turner were based on very different terrain than is present at Blue Ridge Landfill. Also the model assumes a statistical Gaussian plume (concentration profile) and works better for elevated point sources instead of ground-level area sources.

Response #29:
The Gaussian Plume model has certainly been around for many years, and is still relied on by the Nuclear Regulatory Commission (NRC) (as implemented in Reg. Guide 1.111) and US EPA (as implemented in the CAP88 code) to demonstrate compliance with radiation doses to off-site persons from airborne releases. Until recently, US EPA has also relied on the Gaussian plume model (as implemented in the ISC2 code) for demonstrating compliance with non-radiological Prevention of Significant Deterioration (PSD) requirements. Advances in atmospheric dispersion modeling have led to the development of the AERMOD code as a replacement for ISC2. However, a study performed by Arthur Rood and published in the peer-reviewed literature (Rood, 2014) compared the results from AERMOD and ISC2. He concluded that: "Based on the overall performance of ISC2, assessment models that rely on the Gaussian plume model are not necessarily inferior to the current state-of-the-art models in terms of meeting regulatory performance objectives" (Rood, 2014). The fact that US EPA and NRC still use the Gaussian Plume model is a testament to its reliability for demonstrating compliance with regulations.

It is important to understand that the purpose of this assessment was not to accurately estimate the dose to any individual, hypothetical or real. Rather, it was to provide an upper-bound estimate of dose to a hypothetical person that can be compared with regulatory limits that are intended to be protective of human health. This type of bounding assessment is endorsed by NRC, US DOE, and US EPA as a means of evaluating sources using a simple analysis to determine if there is a potential for impacts. For example, US EPA allows the use of AERSCREEN (a simplified version of AERMOD) to be run first, and if compliance can be demonstrated using AERSCREEN, then a detailed analysis using AERMOD is not necessary. This approach of using simplified models and assumptions that result in upper-bound dose estimates is what was used in this assessment.

Consideration of processes such as deposition and area sources will only decrease the estimated dose. Deposition depletes the plume of particles, resulting in lower air concentrations and, consequently, lower inhalation doses. An area source provides initial dilution of the plume, and thereby lower air concentrations and inhalation dose. All dispersion models rely on empirically determined dispersion coefficient formulations that were determined in different environments than those where they are used. The Gaussian Plume formulation for an elevated plume works equally as well for a ground-level release, because reflection of the plume from the ground surface is accounted for in the equation.

Reference (provided as an attachment to this letter):

Rood, AS. 2014. "Performance evaluation of AERMOD, CALPUFF, and legacy air dispersion models using the Winter Validation Tracer Study dataset." *Atmos. Environ.* 89:707-720.

EEC Comment #30: Attachment A1, Table 11. Parameters for Emission Model during Disposal and Transport in Air, Page 39
The emission factor indicates that 2.01 grams of particulate matter is being released to the atmosphere per load. This emission factor was developed for soil placement at a construction site and is not representative of the particle size distribution for Blue Ridge which affects its transport and inhalation properties. Also the waste from Ohio and West Virginia should have emission factors representative of their respective waste characteristics.

Response #30:
As stated earlier, there are no airborne emission factors that we are aware of that pertain to the unloading of solidified brine. Moreover, we have not received or identified any particle size information that would pertain to airborne particulates or particles in the brine. Based on photographs of the material we reviewed (Attachment A1 of the CAP; Figure 6), the solidified brine appears very wet, and the description provided by the generator states that sawdust was added to the mixture to absorb the water and solidify it. Based on this description, we would not expect any fugitive releases from the material, because by its very nature (*i.e.*, brine is a liquid), the material is too wet to support fugitive emissions. As stated earlier, the purpose of the assessment was to provide an upper-bound estimate of doses. By assuming that the material is similar to a dry aggregate soil, an upper-bound estimate of releases to the air is provided. An assessment of TENORM doses to landfill workers in North Dakota (Argonne National Laboratory, 2014) also had the same difficulty in addressing suspended particulates during disposal. That study used the RESRAD methodology, which employs a mass loading factor approach. This approach assumes that all the dust in the air is from the TENORM disposal (an extreme upper-bound assumption) and used a mass-loading factor of 1 mg/m^3, which the authors state is appropriate for landfills. Thus, the Argonne National Laboratory assessment also assumed a fugitive emission rate from TENORM that was based on general landfill operations and not specific to actual TENORM waste characteristics.

Reference:

Argonne National Laboratory. 2014. "Radiological Dose and Risk Assessment of Landfill Disposal of Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) in North Dakota." ANL/EVS-14/13. Environmental Science Division. November.

EEC Comment #31: Attachment A1 Uncertainty in Dose Estimates, Source Term, Pages 50-51
It is stated that "the bulk of TENORM activity received was from Fairmont Brine. Based on mean exposure readings taken on the shipments and the conversion factor developed by PADEP, the Ra-226/228 concentrations were estimated. Concentrations of the remaining radionuclides were estimated based on activity rations from a single sock sample that maximized thorium isotope concentrations." Please clarify this statement as no brine filtration socks were disposed of by Fairmont Brine. Filter socks are typically generated on-site at oil and gas exploration/production facilities.

Response #31:
First, we wish to correct the statement that RAC used the conversion factor developed by PADEP. In our original report (Attachment A1 of the CAP), we used this factor, but based on earlier comments provided by the EEC, we modified this approach and instead used the actual measurements to develop a Site-specific conversion factor of 0.377 µR hour^{-1} per pCi g^{-1} total radium (Attachment A2 of the CAP).

For some loads, complete data for all relevant radionuclides were not available. To fill the gaps in a scientifically rigorous manner, radionuclide ratios from the filter sock found near the location where the TENORM waste was disposed of were used as follows:

U-238 for all loads was based on the activity ratio of U-238 to Ra-226 of 0.0818; Th-230 for all loads except Fairmont Brine loads 5-40 (see Attachment A1 of the CAP for details) was determined using the activity ratio of Th-230 to Ra-226 of 1.0370.

EEC Comment #32: Dose Estimates Page 53
The exposure times for the landfill workers should be recalculated to address their day to- day work activities. The dose estimates were calculated "assuming a laborer spends 0.25 hours per disposal at a distance of 1.0 m from the TENORM container, and 0.083 hours 1 meter from the waste pile." A landfill equipment operator spends much of the work day at the working face, spreading incoming waste and is still

in the vicinity of the TENORM waste and can be exposed to additional inhalation hazards as the operator works around the disposal area with incoming waste loads.

Response #32:
Landfill worker job duties and exposure times were based on conversations with David Rettell, who directly observed operations at the Blue Ridge Landfill to ensure the exposure parameters were reliable. Additionally, heavy-equipment operators at the Blue Ridge Landfill work from inside air-conditioned cabs that use filtered air, and although the heavy-equipment operator is located at the active face and on the landfill for longer than each disposal, the waste is continuously being covered by fresh loads of municipal waste. See also Response #22 for details on the exposure times.

EEC Comment #33:
The risk assessment does not consider air scouring at the atmosphere/soil-waste interface and the generation of airborne inhalable particulate matter being generated from the equipment activity during placement of waste and its use and management as ADC.

Response #33:
Air scouring is a function of wind speed, the geometry of the soil surface relative to wind direction, the amount of loose unconsolidated soil, and the moisture content of the soil. Mechanistic models for these types of processes are research-grade and not suitable for this type of assessment. The AP-42 emission factors for wind erosion are empirically based and would implicitly include these types of processes. Air scouring and wind erosion would only be applicable to waste that is exposed at the surface. Thus, once buried, wind erosion releases are not possible. Because the waste spends little time exposed on the surface, release during the disposal (*i.e.*, releases from material suspended when the material is disposed) is the dominant release process, and thus the only process that was considered.

Further, as described in Response #7, ADS is certain that the BES Waste was not used as daily cover.

EEC Comment #34:
The risk assessment should include calculations for incidental residential exposure as it was reported that local citizens were allowed to drive up to the working face to dump their loads in their personal vehicles during the time span for receipt of the TENORM waste.

Response #34:
This assessment does not directly address the possibility of residential exposure. However, exposure to any resident that may have been at the landfill during the BES Waste disposal would be bounded by that of the landfill laborer, who spent more time in closer proximity to the waste than a resident. Thus, residential doses would be quite small. Attachment A2 of the CAP has been revised to reflect this.

Cornerstone Environmental 2017 BES Waste Depth Memo (Attachment B)

EEC Comment #35:
As a point of clarification the CAP prepared by Gradient notes that 92 separate loads of TENORM waste (1,157 tons) were disposed at the landfill, which the cabinet has confirmed. However, the Cornerstone memorandum in Attachment B and the Agreed Order indicates 47 sealed boxes of TENORM waste were disposed at the landfill.

The RAC reports indicate that the TENORM wastes of concern have been covered with a minimum of 30 feet of municipal waste, while the Cornerstone memorandum indicates that there may be as little as 0 feet of cover in 8 of the 17 affected landfill grids. Please clarify these statements.

Response #35:
We agree with the Cabinet that the CAP correctly states that 92 separate loads of BES Waste (1,157 tons) were disposed of at the landfill (see also RAC, 2016, Dose and Risk Assessment, Attachment A1 of the CAP). The Cornerstone Memorandum (Attachment B of the CAP) has been revised accordingly. Further, final Site plans include burial of the BES Waste with a minimum of 30 ft of additional MSW.

Weaver 2017 Radioactive Material Screening Plan (Attachment C)

EEC Comment #36:
Page 45. Procedures to detect radioactive materials should include: <u>Profiling in-state generated waste and drilling mud waste.</u>

EEC Comment #37:
The Ludlum Model 375P-1000 with dual plastic scintillation detectors as described in the Screening Plan is an instrument typically used by landfills to screen incoming waste for radioactive material content. Paragraph 19 c of the agreed order requires ADS to submit "A plan for detecting and preventing the disposal of unpermitted TENORM wastes at the Facility that shall be incorporated into the Permit as a condition." For purposes of this agreement "unpermitted TENORM waste" means out-of-state generated TENORM waste material with combined concentrations of Radium 226 and 228 greater than 5 p/Ci per dry weight gram of waste material over background." At 10 μR/h the acceptable background variation of +/- 20 % would be equivalent to 2 μR/h. Based on the average radiation level on the BES Wastes of 0.377 μR/h per pCi/g of total Ra-226 and Ra-228 determined by RAC, the screening process would therefore not be able to determine TENORM concentrations less than approximately 5 to 6 pCi/g of TENORM. Section 3.1.2 of the Screening Plan recommends setting the instrument to alarm at 5 times background. If the background is 10 uR/H, the alarm would be at 50 μR/h. This would be a net of 40 μR/h above background, which, based on 0.377 μR/h per pCi/g of total Ra-226 and Ra-228, would be equivalent to alarming at a TENORM concentration of slightly over 100 pCi/g. Therefore, ADS should consider setting the instrument to trigger an alarm at a lower total radium concentration threshold of 5 to 10 pCi/g in order to provide a "go/no go" signal with possible further evaluation by other instrumentation to quantify the levels. It is recommended that ADS consult with the Cabinet for Health and Family Services (CHFS) to determine overall acceptability of the radiation portal monitor.

EEC Comment #38:
The Screening Plan for the Ludlum monitor does not include a detailed description of the installation and operation of such an instrument. For example, the distance between the detectors, the distance from the centerline of the waste container to the detectors, the speed at which the container would pass through the sensitive detection region (or length of counting time, if a static measurement), and, finally, the minimum detection sensitivity (e.g., exposure rate [μR/h] and activity concentration [pCi/g] of the system for a typical container of waste) should be estimated for TENORM and other potential radioactive contents when operating the system in a screening mode. Note that the instruments may be set to display in exposure rate, count rate, or integrated counts over a preset monitoring period. Please provide the additional information for the monitor.

EEC Comment #39:
10 μR/h is a typical background exposure rate to be expected. The background recorded by the screening instrument may be lower, depending on the effect of shielding around the detectors. It should not be necessary to collect 100 individual background measurements to determine an accurate and reproducible average; 20 individual determinations are usually adequate to determine the average. The average background and source response level should be determined, along with the acceptable variability *(+/-* 20% or +/- 3σ*)* should be recorded and the instrument performance compared with those values by completing a "control chart" for each day of use (more often if the background is found to be highly variable).

EEC Comment #40:
Ideally, after triggering an alarm setting, additional evaluations could be used to identify the radioactive source, estimate the activity or concentration in the waste, and determine whether contamination and radiation levels are compliant with Department of Transportation regulations. These actions typically require a level of technical training and experience associated with professional radiation protection personnel. The level of sophistication described in the Screening Plan is beyond what needs to be readily available "in-house" at the landfill. Without extensive training and experience, use of gamma spectrometers and radiation contamination survey instruments and procedures, interpretation of the results, and actions based on the findings, relative to Federal and State regulations may easily cause greater "harm" than they prevent. If an alarm is triggered and a recheck confirms that level, the vehicle should be rejected and impounded, and notification made to CHFS Dept. for Public Health, Radiation Health Branch. Actions beyond Step 2 of Section 5 of the Screening Plan, raise the necessary knowledge, training, and experience to a completely different level. It is recommended that ADS consider contracting with radiation safety professionals for any activities related to the assessment and detailed screening for suspect waste shipments. At a minimum, such a firm could assist in developing a worker safety program, a comprehensive Screening Plan and providing appropriate training and oversight in its implementation.

EEC Comment #41:
A radiation level greater than 50 mR/h in the vehicle cab (screening step 5.C.3) could be indicative of a major problem. Please clarify.

EEC Comment #42:
Page 4 typo. Should be Scree**n**ing

EEC Comment #43:
It is unclear as to the training requirements for the Supervisor who has been given responsibility for implementing the screening plan. It is recommended that a radiation safety professional handle portable hand-held screening of suspected TENORM materials.

EEC Comment #44: Section 6.2 Action Level 2, Paragraph A
It states that workers should stop leakage of material leaking from the vehicle and "try to catch material leaking from the vehicle" in a container or absorbent material. Only specially equipped, trained radiation professionals should attempt to address leaks, contain or handle potentially radioactive materials utilizing appropriate personnel protective equipment.

EEC Comment #45: Section 7 Characterization, Page 15
It states that it may be necessary to unload waste from a vehicle to remove a radiation source if it is determined to be a medical radionuclide, consumer product, NORM, TENORM or potassium-40 to obtain a sample for characterization. This work should only be done by trained radiation safety professionals.

Response to Comments #36-45:
The Radioactive Material Screening Plan (Attachment C of the CAP) has been revised per Comments #36-45 and based on subsequent discussions with the Cabinet.

EEC Comment #46: Comments from the Community
The cabinet received comments from members of the community that obtained the CAP through an Open Records request. The comments requested information on potential future safeguards that could be implemented to make the landfill more protective should the waste be left in place as proposed under the preferred remedial alternative including whether the landfill or the portion of the landfill which received the TENORM waste be closed under the requirements for a hazardous waste landfill including a RCRA

Subtitle C cap and whether additional bonding should be required due to the presence of the TENORM waste? Other comments on the Weaver 2017 Radioactive Material Screening Plan (Attachment C) noted that the Emergency Contact List does not include any local contacts (i.e., the Solid Waste Coordinator and the County Health Department) and also noted that the document contains grammatical errors and should be written in layman's language.

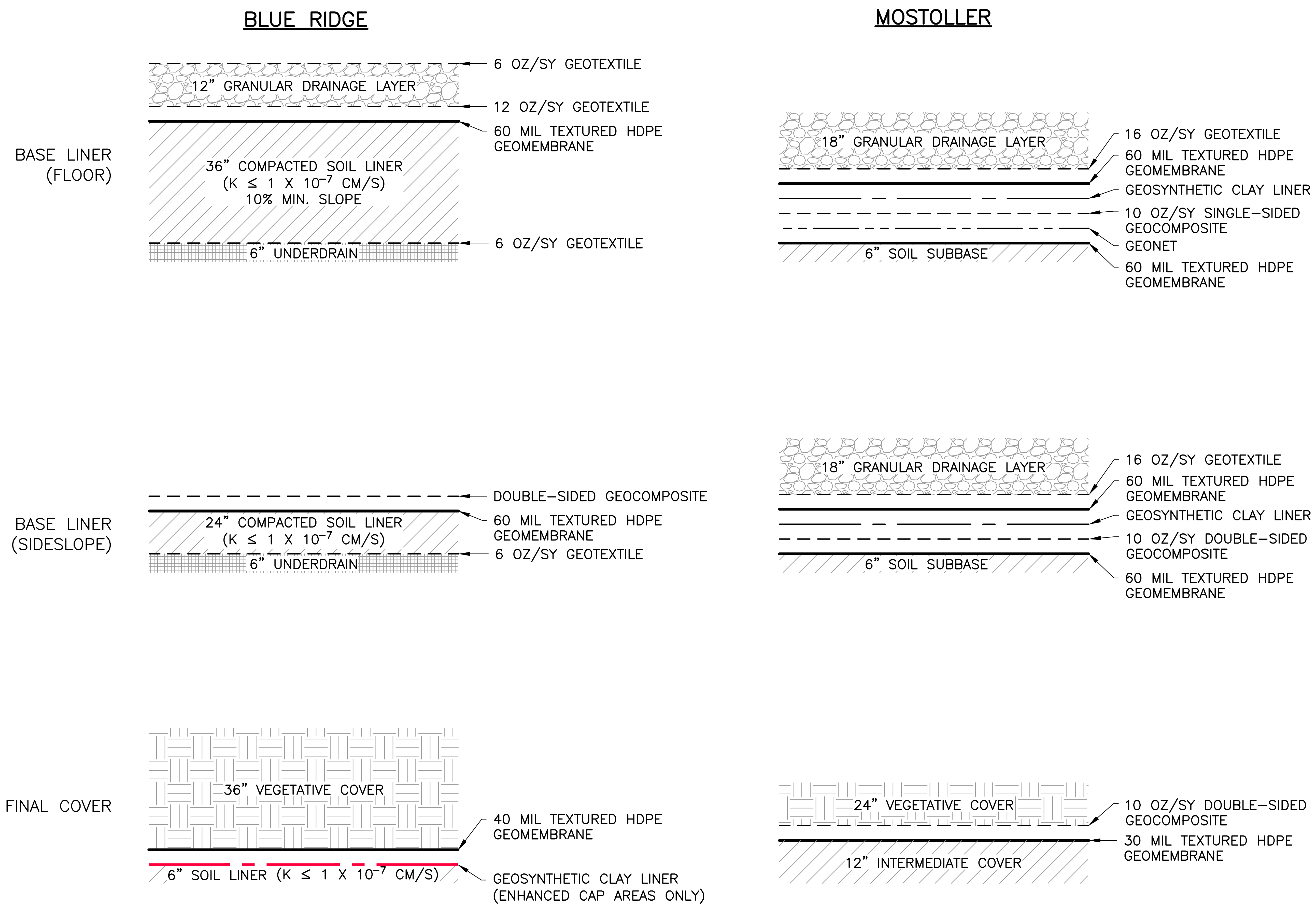
Response #46:
We acknowledge the community's comments and will work collaboratively with the Cabinet in response to these comments.

Sincerely,

GRADIENT

Kurt Herman, M.Eng., P.G.
Principal

Attachments: Weaver Consultants (2017), "Liner System Comparison Blue Ridge *vs*. Mostoller"
Rood (2014), "Performance evaluation of AERMOD, CALPUFF, and legacy air dispersion models using the Winter Validation Tracer Study dataset"



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BLUE RIDGE VS. MOSTOLLER

ADVANCED DISPOSAL SERVICES BLUE RIDGE LANDFILL, INC.
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Performance evaluation of AERMOD, CALPUFF, and legacy air dispersion models using the Winter Validation Tracer Study dataset

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HIGHLIGHTS

- Steady-state and Lagrangian puff models compared.
- SF_6 tracer data at 140 samplers in concentric rings 8- and 16-km from release point.
- Paired and unpaired 1- and 9-h average concentrations performance objectives.
- Puff models showed the lower bias and variance and higher correlation.
- Steady-state models were less likely to underpredict concentrations.

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ABSTRACT

The performance of the steady-state air dispersion models AERMOD and Industrial Source Complex 2 (ISC2), and Lagrangian puff models CALPUFF and RATCHET were evaluated using the Winter Validation Tracer Study dataset. The Winter Validation Tracer Study was performed in February 1991 at the former Rocky Flats Environmental Technology Site near Denver, Colorado. Twelve, 11-h tests were conducted where a conservative tracer was released and measured hourly at 140 samplers in concentric rings 8 km and 16 km from the release point. Performance objectives were unpaired maximum one- and nine-hour average concentration, location of plume maximum, plume impact area, arc-integrated concentration, unpaired nine-hour average concentration, and paired ensemble means. Performance objectives were aimed at addressing regulatory compliance, and dose reconstruction assessment questions. The objective of regulatory compliance is not to underestimate maximum concentrations whereas for dose reconstruction, the objective is an unbiased estimate of concentration in space and time. Performance measures included the fractional bias, normalized mean square error, geometric mean, geometric mean variance, correlation coefficient, and fraction of observations within a factor of two. The Lagrangian puff models tended to exhibit the smallest variance, highest correlation, and highest number of predictions within a factor of two compared to the steady-state models at both the 8-km and 16-km distance. Maximum one- and nine-hour average concentrations were less likely to be under-predicted by the steady-state models compared to the Lagrangian puff models. The characteristic of the steady-state models not to under-predict maximum concentrations make them well suited for regulatory compliance demonstration, whereas the Lagrangian puff models are better suited for dose reconstruction and long range transport.

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1. Introduction

The steady-state model AERMOD and Lagrangian puff model CALPUFF are the U.S. Environmental Protection Agency (EPA) preferred models for demonstrating regulatory compliance in the near field (<50 km) and far field (>50 km), respectively. The CALPUFF model has also been used in non-regulatory retrospective studies of radiation dose in the near field (Rood et al., 2008) and far field environments (Grogan et al., 2007). Demonstration of regulatory compliance and accident consequence analysis are generally prospective assessments, whereas dose reconstruction and epidemiological studies are generally retrospective in nature. The assessment questions for the prospective and retrospective analyses are fundamentally different and require different model performance objectives.

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For the prospective analysis, the assessment question is whether air emissions will exceed ambient air quality standards, or result in impacts that are unacceptable. This assessment question can initially be addressed using conservative assumptions and simple models. It may not be critical to accurately estimate temporal and spatial variations in concentration, as long as the estimated impacts do not exceed the standards within a safety margin of error. More detailed model applications may be required if simple models cannot demonstrate that regulatory standards are achieved.

For a retrospective assessment, the assessment question is an unbiased estimate of the temporal and spatial distribution of concentration and deposition. Examples of a retrospective analysis include the dose reconstructions performed at U.S. Department of Energy Facilities (Farris et al., 1994; Till et al., 2000, 2002; Rood et al., 2002) and other special studies (Rood et al., 2008; Grogan et al., 2007). Simple models may be used in initial scoping calculations. However, ultimately an unbiased estimate of the temporal and spatial distribution of air concentration and deposition with estimated uncertainty is desired.

The purpose of this paper is to examine the performance of AERMOD, CALPUFF, and two legacy models using the Winter Validation Tracer Study (WVTS) dataset conducted in February 1991 at the former Rocky Flats Environmental Technology Site (RFETS). Performance objectives were tailored toward addressing the assessment questions posed by the prospective and retrospective analysis. Two legacy models, Industrial Source Complex Short Term Version 2 (ISC2) (EPA, 1992) and Regional Atmospheric Transport Code for Hanford Emission Tracking (RATCHET) (Ramsdell et al., 1994), were included in the evaluation because the formulations of these models are currently used in radiological assessment codes (EPA, 2007; Chanin et al., 1998; Ramsdell et al., 2010). Model simulations and performance evaluation of ISC2 using the WVTS was originally reported in Haugen and Fontino (1993). Performance evaluation of RATCHET using the WVTS dataset was originally reported in Rood (1999) and Rood et al. (1999). Model-predicted concentrations for ISC2 and RATCHET were taken from Haugen and Fontino (1993) and Rood (1999), respectively, and were used without modification.

A description of the tracer measurements and meteorological data is provided first, followed by modeling protocol, performance objectives, and performance measures. Finally, the model performance results, in terms of addressing the prospective and retrospective assessment questions, are discussed.

2. Methods

Model performance was evaluated in terms of fundamental plume properties, paired ensemble mean concentrations, and concentrations unpaired in space. The WVTS dataset and meteorological data are presented first, followed by modeling protocol, performance objectives, and performance measures.

2.1. Winter Validation Tracer Study

The WVTS was conducted in February 1991 near the former RFETS located on the Front Range of the Colorado Rocky Mountains about 25 km northwest of Denver (Brown, 1991). The study consisted of 12 separate tests (Table 1). For each test, an inert tracer (sulfur hexafluoride [SF_6]) was emitted continuously for 11 h from a 10-m high stack located on the east side of the main plant complex (Fig. 1). The main plant complex was located about 2.5 km east of the foothills on an alluvial plain ranging in elevation from 1750 m to 1850 m above sea level. The primary purpose of the study was to gather data for validation of emergency response atmospheric transport models. Samplers were arranged in concentric circles 8-km and 16-km from the release point so as to capture any possible transport trajectories. One-hour average air concentrations were then measured for the last nine hours of the release at each of the 140 samplers. Six tests were performed under nighttime conditions, four under daytime conditions, one under day–night transition, and one under night–day transition. A total of 108 h of data were recorded. Seventy-two samplers were distributed at the 8-km distance and 68 samplers at the 16-km distance. Sampler elevations ranged from about 1600 m to 2600 m above sea level. The study domain is considered near field because the maximum distance to the samplers is $<$50 km.

Previous investigators (Haugen and Fontino, 1993) used this data set in a performance evaluation of the TRAC (Hodgin, 1991) and ISC2 models. The electronic copy of this data set was obtained from Haugen and Fontino (1993) for use in the model performance evaluation for the Historical Public Exposures Studies at Rocky Flats (Rood, 1999). These data included the observed hourly-average concentrations for all 12 tests, the sampler ID numbers and locations, and the TRAC and ISC2 predicted concentrations. The ISC2 results provided by Haugen were used in this paper without modification.

2.2. Meteorological data

Meteorological data were recorded for every tracer test at the 10-m and 61-m level from the RFETS 61-m tower located 790 m west and 87 m south of the release point. Only data from the 10-m level were used in the model simulations. Data were provided as 15-min averages of wind speed and direction, temperature, heat flux, and standard deviations of these parameters. Hourly averages of these data were calculated using EPA protocol (EPA, 2000).

Table 1
Winter Validation Tracer Study start and end times and source strength.

Test	Start date	Start time (MST)[a]	End date	End time (MST)[a]	MFC[b] (kg h^{-1})	CWL[c] (kg h^{-1})	Average (kg h^{-1})
1	02/03/91	20:00:00	02/04/91	07:00:00	13.71	13.24	13.48
2	02/04/91	20:00:00	02/05/91	07:00:00	13.05	12.16	12.61
3	02/06/91	20:00:00	02/07/91	07:00:00	13.71	13.33	13.52
4	02/07/91	20:00:00	02/08/91	07:00:00	16.53	16.84	16.69
5	02/09/91	13:00:00	02/09/91	00:00:00	23.61	22.63	23.12
6	02/11/91	07:00:00	02/11/91	18:00:00	23.61	22.94	23.28
7	02/12/91	07:00:00	02/12/91	18:00:00	23.61	23.99	23.80
8	02/14/91	01:00:00	02/14/91	12:00:00	23.61	23.44	23.53
9	02/15/91	07:00:00	02/15/91	18:00:00	23.61	23.29	23.45
10	02/16/91	20:00:00	02/17/91	07:00:00	23.61	23.47	23.54
11	02/17/91	20:00:00	02/18/91	07:00:00	23.61	23.04	23.33
12	02/19/91	07:00:00	02/19/91	18:00:00	23.21	22.97	23.09

[a] Mountain standard time.
[b] Release rate calculated from mass flow controllers (MFCs) that were calibrated at 760 mm Hg, 21.11 °C.
[c] Release rate determined from cylinder weight loss (CWL).

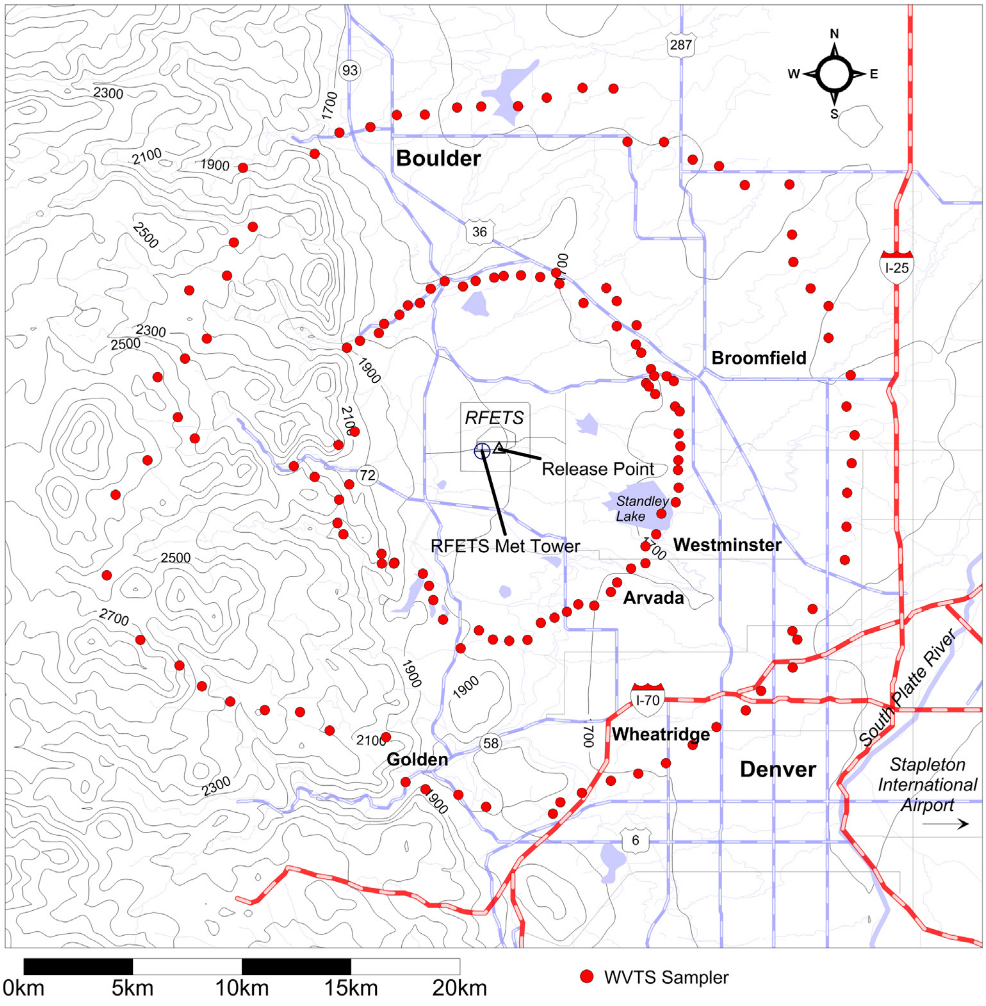

Fig. 1. CALPUFF model domain showing location of the WVTS samplers and terrain features of the Colorado Front Range.

Mixing depth estimates for the ISC2 simulations were derived from linear interpolation for each 15-min period from the rawinsonde data taken every 12 h at Denver Stapleton airport. No precipitation was measured during any of the 12 tests, and there was no snow cover during February 1991.

Additional surface and upper air meteorological data were obtained from Denver Stapleton airport located about 25 km southeast of the RFETS. Surface data included wind speed and direction, cloud cover, and ceiling height and were used with the RFETS data to calculate stability class. The RATCHET and CALPUFF models utilized the wind speed and direction measurements in their wind field interpolation.

Surface observations from Denver Stapleton are strongly influenced by air movement within the Platte River Valley, which flows to the northeast from the city center. By contrast, Rocky Flats is more strongly influenced by its proximity to the foothills. Both locations are influenced by the diurnal pattern of upslope-downslope conditions that characterize the general air movement on the Colorado Front Range environs. Downslope conditions typically occur during the evening hours and are characterized by drainage flow of cooler surface air from the foothills and upper reaches of the Platte River Valley northeastward to the plains. Airflow at Rocky Flats is typically from the west-northwest, and converges with the flow from the south within the Platte River Valley in a broad zone 20 km–30 km east–northeast of the RFETS (Lange, 1992). During daylight hours and after surface heating has eliminated the cooler surface layer, the downslope conditions cease. This is followed by a brief period of relatively calm winds, which in turn is followed by return of air up the valley or upslope conditions. Upslope conditions were weak to non-existent during the WVTS.

2.3. Atmospheric transport models and protocol

A brief description of each of the models included in this study is presented along with the modeling protocol. Because the SF_6 tracer is an inert gas, all model simulations did not include deposition and plume depletion.

2.3.1. AERMOD

The American Meteorological Society and EPA developed the AERMOD modeling system (Cimorelli et al. 2004). Model development began in 1991 with the objective to incorporate current planetary boundary layer concepts into regulatory compliance models. Treatment of both surface and elevated point sources, area sources, and volume sources in a simple or complex terrain model domain are addressed in the model. It was intended as a replacement of the Industrial Source Complex Version 3 (ISC3) model. Currently, AERMOD is the EPA's preferred model for regulatory compliance demonstration for criteria pollutants in the near field (<50 km).

2.3.1.1. AERMOD modeling protocol. The modeling domain consisted of a 46.2-km × 49.8-km region centered on the RFETS. Meteorological data were the same used in the CALPUFF simulation and included surface and upper-air data from Denver Stapleton airport and onsite data from RFETS.

AERMOD and AERMET version 12345 were used in the model simulations. Special processing of AERMOD output was required because minimum model-simulation times are one-day, and nine-hour averaging times are not an option. Nine-hour average concentrations were calculated by inputting the tracer release rate for the last nine hours of the 11-h tracer test and setting the release rate to zero for the remaining hours in the simulation. The maximum one-hour, and 12-h average concentration at each of the samplers for a simulation period that encompassed each test was output. The nine-hour average concentration was calculated by multiplying the 12-h average concentration by the ratio of 12/9.

2.3.2. CALPUFF

The CALPUFF modeling system (Scire et al., 2002) is a non-steady-state Lagrangian puff model that simulates pollutant transport, transformation, and deposition in a three-dimensional spatially and temporally variable wind field. CALPUFF can be applied on local and regional scales. The modeling system is composed of three primary modules: CALMET, CALPUFF, and CALPOST and collectively these are referred to as the CALPUFF modeling system.

The CALMET module is a meteorological model that generates a three-dimensional hourly wind field within a three-dimensional gridded modeling domain. The CALPUFF module uses the CALMET-generated wind field and micrometeorological parameters to advect and disperse “puffs”. The CALPOST module reads the CALPUFF concentration and deposition flux files and produces time-averaged concentration and deposition output along with visibility impacts.

CALPUFF is currently the EPA preferred long-range (>50 km) dispersion model for demonstration of compliance with Prevention of Significant Deterioration increment levels and National Ambient Air Quality Standards in Class I areas.

2.3.2.1. CALPUFF modeling protocol. A 45.2-km × 43.6-km model domain having a grid spacing of 400 m (113 × 109 grid cells) was established (Fig. 1). It was centered approximately on the WVTS release point and included the Platte River Valley in the southeast corner. Vertical discretization consisted of eight layers 20 m, 40 m, 60 m, 100 m, 200 m, 400 m, 800 m, 1200 m, and 1800 m above land surface.

For the CALMET simulations, EPA-Federal-Land-Manager-recommended parameter values (Fox, 2009) or CALMET default values were generally used where applicable. The model parameters BIAS, RMAX1, RMAX2, TERRAD, R1, and R2 were chosen on a site-specific basis. The BIAS parameter assigns weights to the surface and upper-air stations data for each vertical layer. Surface data were given 100% of the weight (BIAS = 1) in the first layer with zero weight in the last two vertical layers (BIAS = 1). Equal weight was assigned to the fourth layer (BIAS = 0) with a gradation of weights between the lower and upper for the remaining layers.

The RMAX1 and RMAX2 parameters define the maximum radius of influence for surface and upper data, respectively, over land surfaces. To incorporate the influence of flow in the Platte River Valley as represented by the surface data at Denver Stapleton airport, a value of 32 km for RMAX1 was used. The RMAX2 value serves the same purpose as RMAX1 but is used for upper-air data. A value of 100 km was selected for the RMAX2 parameter.

The TERRAD parameter defines the radius of influence of terrain features. A TERRAD value of 7 km was used so that the terrain influence of the foothills encompassed RFETS. The parameters R1 and R2 are the distance from an observation where the observation and the initial guess field are equally weighted for surface and layers aloft, respectively. A value of 17 km and 56 km were chosen for R1 and R2, respectively.

The CALPUFF runs were performed using dispersion coefficients calculated from micrometeorological variables (MDISP = 2), and the simple CALPUFF-type terrain adjustment algorithm (MCTADJ = 2). The remaining parameters were CALPUFF defaults. CALPUFF Version 5.8, Level 070623, and CALMET Version 5.8, Level 060811, were used in the model simulations.

2.3.3. Industrial Source Complex Short Term Version 2 (ISC2)

The ISC2 model is an augmented steady-state Gaussian plume model primarily used to demonstrate regulatory compliance with criteria pollutants emitted by industrial facilities. It was replaced by ISC Version 3 and was the EPA preferred model until the promulgation of AERMOD in December of 2005. The model was included in the evaluation because straight-line Gaussian plume models form the basis of the CAP88 (EPA, 2007) model for demonstration of compliance with the Clean Air Act, and of the MACCS2 code (Chanin et al., 1998) for reactor accident consequence analysis.

2.3.3.1. ISC2 modeling protocol. The ISC2 simulations were performed by Haugen and Fontino (1993) using 15-min meteorological data from the 10-m level taken at the RFETS and mixing depth estimated from the rawinsonde data at Denver Stapleton airport. Four ISC2 runs were performed for each hour of simulation using the four, 15-min average data from the Rocky Flats meteorological station. The results from the four simulations were averaged to provide hourly-average concentrations at each of the sampler locations. These hourly concentrations were then averaged across each test by Rood (1999) to provide nine-hour average concentrations at each sampler.

The performance evaluation of this model was originally reported in Rood (1999) and Rood et al. (1999). The results presented here are based on the original data using slightly different performance measures.

2.3.4. RATCHET

The Regional Atmospheric Transport Code for Hanford Emission Tracking (RATCHET) (Ramsdell et al., 1994) is a Lagrangian puff model developed by Pacific Northwest Laboratories for the Hanford Dose Reconstruction Project (Farris et al., 1994). Its primary purpose was to estimate transport and deposition of ^{131}I released from the Hanford facility across a 194,250 km^2 model domain located in eastern Washington State. The model includes a surface wind field interpolator that allows incorporation of multiple surface meteorological stations into a model simulation. Upper-air data were not considered in the model. Terrain complexities were not explicitly treated, but are implicitly represented by using multiple meteorological surface stations that reflect major topographical features. Surface roughness features are spatially variable across the model domain. Diffusion coefficients are estimated from statistics of atmospheric turbulence that are inferred from estimates of atmospheric stability, surface roughness length, and the Monin–Obukhov length. The current radiological assessment models, RASCAL (Ramsdell et al., 2010) and GENII (Napier, 2009), employ the RATCHET air dispersion model.

2.3.4.1. RATCHET modeling protocol. Model simulations with RATCHET were performed by the author (Rood et al., 1999) as part of Phase II of the Historical Public Exposures at Rocky Flats (Till et al., 2002). Hourly-average meteorological data at the 10-m level from the Rocky Flats plant and Denver Stapleton airport were used in the model simulations. A 37-km × 37-km model domain centered on the RFETS with 500-m grid spacing was established. RATCHET does not allow discrete receptors, and therefore, calculated concentrations were extracted from the grid node nearest the sampler. Surface roughness lengths (z_0) ranged from 2-m in the foothills to 0.05-m in the farmland east of the RFETS.

2.4. Performance objectives

Performance objectives consisted of four fundamental plume properties and a paired and unpaired comparison of individual samplers. The four fundamental plume properties were maximum concentration, location of the plume maximum, plume width, and arc-integrated concentration. An additional objective of the maximum one-hour average concentration unpaired in space and time was also included to provide insight into model performance for short-term maximum concentrations. Descriptions of each modeling objective follows.

2.4.1. Maximum hourly and nine-hour average concentration and plume maximum location

This modeling objective compared the predicted and observed maximum one-hour and nine-hour average concentration measured at a sampler during the nine-hour test period at either the 8-km or 16-km distance from the release point. The predicted maximum concentration was not paired in space, and also unpaired in time for the maximum-hourly average concentration. The nine-hour average concentration was determined by a simple arithmetic average of the nine, one-hour average concentrations. Sampler data that were missing were not included when computing the predicted or observed average concentration.

The plume maximum location was only computed for the nine-hour average concentration and was quantified in terms of the absolute value of angular difference between the predicted and observed location of the plume maximum.

2.4.2. Plume width

The plume width objective evaluated the predicted impact area of the plume. Each sampler was assigned an arc length equal to the arc length between the midpoints of the sampler and each of its adjacent samplers. The plume width was sum of the arc lengths of samplers that had a concentration greater than zero, or in the case of the observed values, a concentration greater than the minimum detectable concentration.

2.4.3. Arc-integrated concentration

The arc-integrated concentration evaluated the plume mass at the 8-km and 16-km distance. The arc-integrated concentration is the sum of the product of the sampler arc lengths as defined in Section 2.4.2 and the nine-hour average predicted or observed concentration.

2.4.4. Unpaired time-averaged concentration

This modeling objective compared the ranked predicted and observed time-averaged (nine-hour) concentrations. Only predicted and observed concentrations that met the selection criteria stated in Section 2.6 were included. Samples were blocked into those performed at night (Tests 1, 2, 3, 4, 10, and 11), those performed during the day (Tests 6, 7, 9, and 12), and those performed during transition periods (Tests 5 and 8). Sample blocking is used in bootstrap resampling to avoid block-to-block variance (Chang and Hanna, 2005).

2.4.5. Paired ensemble means (ASTM procedure)

The American Society for Testing and Materials (ASTM) proposed a procedure for evaluation of models, recognizing that model predictions are ensemble-mean predictions, while observations correspond to realizations of ensembles (ASTM, 2000). An ensemble is defined as a set of experiments having fixed external conditions, such as meteorological conditions and downwind distance. In the WVTS, fixed external conditions were the distance to the sampling arc and meteorological conditions. In general, repeatable diurnal flow and stability regimes are established during nighttime, daytime, and day–night transitional periods along the Colorado Front Range. Thus, averages across the tests representing these similar conditions would approximate ensemble means to compare with model predictions for the same period.

Predictions and observations were grouped into three blocks consisting of nighttime (six tests), daytime (four tests), and transition period (two tests). Average concentrations were calculated across all tests in the block for each sampler, and performance statistics were calculated separately for each block.

2.5. Performance measures

Several simplified measures were used to evaluate model performance (Cox and Tikvart, 1990; Weil et al., 1992). These measures were the fractional bias (*FB*) and normalized mean square error (*NMSE*). Fractional bias is given by

$$FB = \frac{2\left(\overline{C}_o - \overline{C}_p\right)}{\overline{C}_o + \overline{C}_p} \tag{1}$$

where C_p and C_o are the predicted and observed concentrations, respectively. Overbars indicate averages over the sample. The *NMSE* given by

$$NMSE = \frac{\overline{(C_o - C_p)^2}}{\overline{C}_o\overline{C}_p} \tag{2}$$

The *FB* is a measure of mean bias. A *FB* of 0.6 is equivalent to model under-prediction by about a factor of two. A negative value indicates model over-prediction. The *NMSE* is a measure of variance, and a value of 1.0 indicates that a typical difference between predictions and observations is approximately equal to the mean. The *NMSE* and *FB* are appropriate when the typical difference between the predictions and observations are approximately a factor of two (Hanna et al., 1991) and the range of predictions and observations in the dataset is small (i.e., less than a factor of two). This was not the case in this study where ratios of model predictions to observations often ranged from 0.01 to 100, and within a data set, the predicted and observed concentrations ranged from the zero to ~10,000 ng m^{-3}. In these cases a log-transformed measure of model bias and variance is more appropriate because it provides a more balanced approach (Hanna et al., 1991). The log-transformed measures described in Hanna et al. (1991) are the geometric mean bias (*MG*) and the geometric mean variance (*VG*) and are defined by

$$MG = \exp\left(\overline{\ln C_o} - \overline{\ln C_p}\right) = \exp\left(\overline{\ln \frac{C_o}{C_p}}\right) \tag{3}$$

$$VG = \exp\left[\overline{(\ln C_o - \ln C_p)^2}\right] \tag{4}$$

Geometric mean bias values of 0.5 and 2.0 indicate a factor of two over-prediction and under-prediction, respectively. A *VG* value of 1.6 indicates about a factor of two difference between predicted and observed data pairs.

A more easily understood log-transformed quantity that is related to the *MG* and *VG* is the geometric mean (*GM*) and geometric standard deviation (*GSD*) of the predicted-to-observed ratio (C_p/C_o). The *GM* and *GSD* are given by

$$GM = \exp\left(\overline{\ln\frac{C_p}{C_o}}\right) \tag{5}$$

$$GSD = \exp\left[\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\ln\frac{C_{p_i}}{C_{oi}} - \overline{\ln\frac{C_p}{C_o}}\right)^2}\right] \tag{6}$$

where n = the sample size. Because the *MG* is simply the inverse of the *GM*, only the *GM* is reported. A perfect model would have *FB* and *NMSE* values of 0, and *GM, GSD,* and *VG* values of 1.0. With the exception of the plume width and location of plume maximum performance objectives, the log-transformed performance measures are considered more appropriate than the *FB* and *NMSE*, and thus only the log-transformed measures are reported. The location of plume maximum does not lend itself to the above performance measures, mainly because the objective considered the absolute angular difference between the predicted and observed location of maximum. For this performance objective, the mean difference, standard deviation of the mean (i.e., standard error), and the minimum and maximum differences are reported. Because differences between predicted and observed values and the range of predictions and observations were less than about a factor of two, the *FB* and *NMSE* were considered more appropriate for the plume width objective.

In addition to the above measures, the correlation coefficient (r) between predicted and observed values and the number of predictions within a factor of two of the observations were also reported. The correlation coefficient was determined using least-squares linear regression and log-transformed data except for the plume width performance objective. Scatter plots were also included as visual measures of performance for the paired ensemble means and unpaired time-averaged concentration modeling objectives.

Confidence intervals were estimated for each of the performance measures using the bootstrap methodology described in BOOT software (Hanna et al., 1991; Chang and Hanna, 2005). Confidence intervals were used to determine if the estimated performance measure was significantly different than its optimum value and whether a statistically significant difference existed between the performance measures for each model. Confidence interval estimates were based on the cumulative density function generated from 1000 bootstrap samples.

2.6. Selection criteria

The observed data set only reported nonzero hourly average concentrations greater than the minimum detectable sampler concentration (*mdc*) of 33 ng m^{-3}. Measured concentrations below this value were reported as zero. A sampler that had only one hour of data (in the nine-hour measurement period) greater than the *mdc* would have a nine-hour average concentration of 3.7 ng m^{-3} (33 ng m^{-3}/9). This value represents the nine-hour time-averaged *mdc* for a sampler.

For the paired ensemble means performance objective, the dataset was based on the union of the predicted and observed concentrations. The *mdc* was substituted for predicted concentrations that were less than the *mdc* if the paired observed concentration was greater than zero. Likewise, the *mdc* was substituted for observed concentrations less than the *mdc* if the paired predicted concentration was greater than zero. Predicted and observed pairs that were both zero were omitted from the analysis.

For the unpaired analysis only predicted *and* observed concentration pairs greater than the *mdc* were considered. Samplers missing all nine hours of data were eliminated from the data set.

3. Results

The paired ensemble means and unpaired scatter plots are perhaps the most illustrative in terms of summarizing model performance qualitatively (Figs. 2–5). In general, the highest predicted and observed concentrations were during nighttime and transition period tests and the lowest during daytime tests.

The paired ensemble mean scatter plot at the 8-km distance (Fig. 2) showed the transition period tests as having the highest observed concentrations, some exceeding 8000 ng m^{-3}. Nighttime tests had maximum observed concentrations between 3000 and 4000 ng m^{-3}. As expected, daytime tests had the lowest observed maximum concentrations, the maximum being slightly less than 600 ng m^{-3}. All models performed poorly for the transition period tests, underestimating observed concentrations that were >1000 ng m^{-3}. In general, the puff models exhibited better correlation to the observations for daytime and nighttime tests and concentrations that were >100 ng m^{-3} compared to the steady-state models.

At the 16-km distance (Fig. 3) the nighttime period tests had the highest observed concentrations (~3500 ng m^{-3}), followed by transition period tests (~1800 ng m^{-3}). Daytime tests had maximum observed concentrations that were ~70 ng m^{-3}. The puff models exhibited better correlation, less variability, and a greater number of points within a factor of two of the observations compared to the steady state models for nighttime tests and concentrations >100 ng m^{-3}.

Scatter plots of the unpaired data at the 8-km distance (Fig. 4) showed that all models underestimated transition period observed concentrations that were greater than 1000 ng m^{-3}. Predicted concentrations from RATCHET were within a factor of two of the observations for almost all the daytime tests and most of the nighttime tests for the entire concentration range. Most of the ISC2 concentrations for daytime and nighttime tests were within a factor of two of the observations for concentrations that were >100 ng m^{-3}.

At the 16-km distance (Fig. 5), scatter plots of the unpaired data were similar to those at the 8-km distance, although CALPUFF underestimated almost all the concentrations for transition period tests by more than a factor of two. The three highest observed concentrations were within a factor of two of the corresponding AERMOD predicted concentrations. A similar result was found for ISC2, except the highest observed nighttime concentration was underestimated by more than a factor of two. Observed nighttime concentrations that were <100 ng m^{-3} were overestimated by more than a factor of two by RATCHET.

3.1. Maximum one-hour and nine-hour average concentration

Performance measure results for the maximum one-hour average concentration modeling objective (Table 2) indicate a strong positive bias for the steady-state models, especially AERMOD, and nearly no bias for puff models RATCHET and CALPUFF (GM confidence interval included 1.0). The positive bias for the steady-state models was greater at the 16-km distance. Ninety-two percent of the ISC2-estimated maximum one-hour average

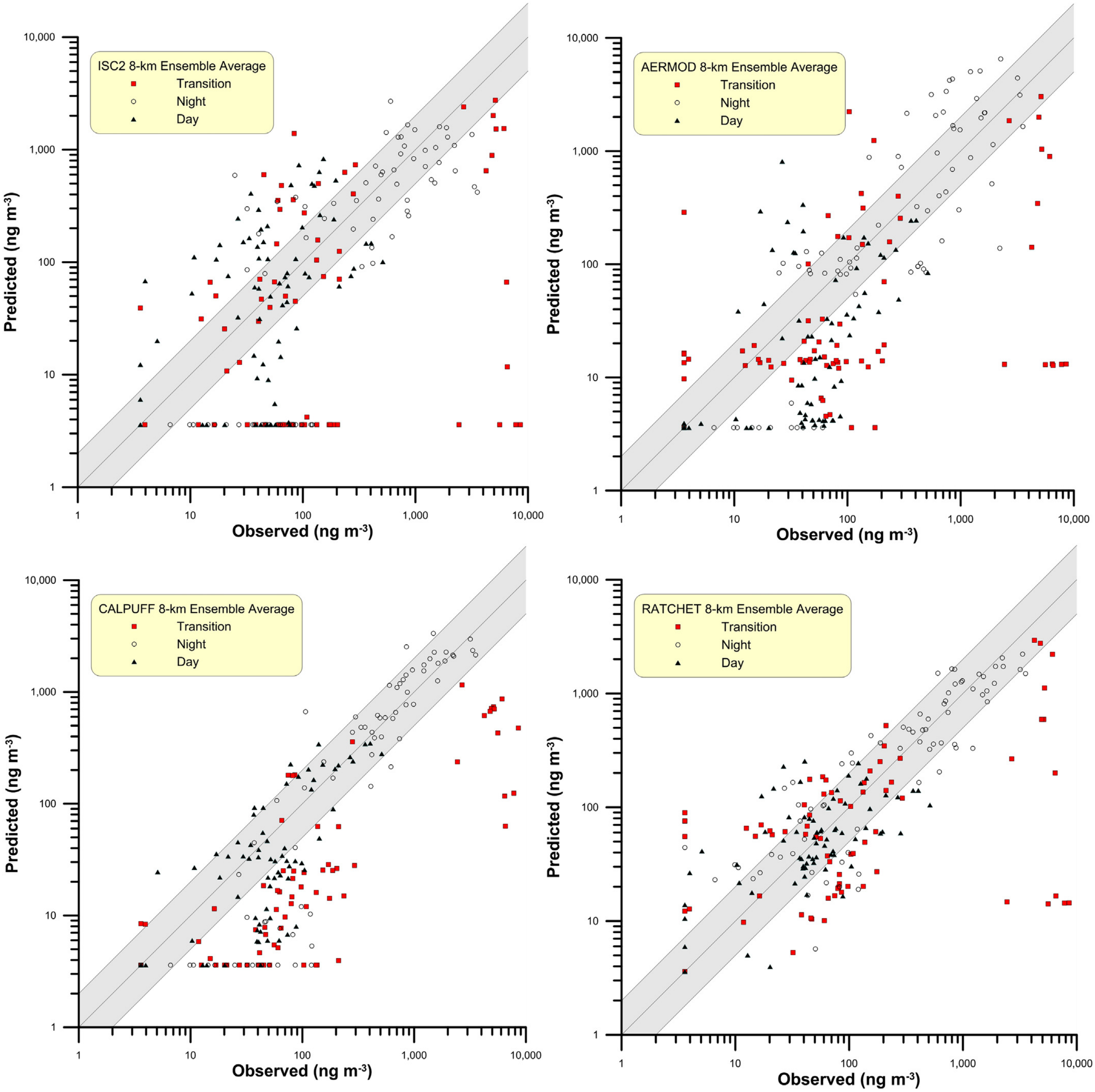

Fig. 2. Scatter plots of paired nine-hour average ensemble mean concentrations at the 8-km distance. Points that lie within the shaded region are within a factor of 2 of the observations.

concentrations and 83% of the AERMOD values had predicted-to-observed ratios of 0.95 or higher. In contrast, only 50% of the CALPUFF- and RATCHET-estimated maximum one-hour average concentrations had a predicted-to-observed ratio greater than 0.95.

Predicted maximum nine-hour average concentrations (Table 3) showed a similar trend to those of the maximum hourly-average concentrations. That is, the steady-state models exhibited positive bias, while the Lagrangian puff models exhibited negative bias. However, the GM confidence interval included 1.0 for all models. Measures of variance were generally lower for the puff models and correlation coefficients were higher compared to the steady state models.

Measures of bias among the steady state models were significantly different from those of the puff models (Table 4). None of the model performance measures for CALPUFF and RATCHET were significantly different from one another.

3.2. Plume maximum location, plume width, and arc-integrated concentration

Plume maximum location at the 8-km distance (Table 5) showed that the mean deviation was smallest for AERMOD and RATCHET (14°) and greatest for CALPUFF and ISC2 (26 and 24° respectively). Based on a *t*-test difference of the means, the

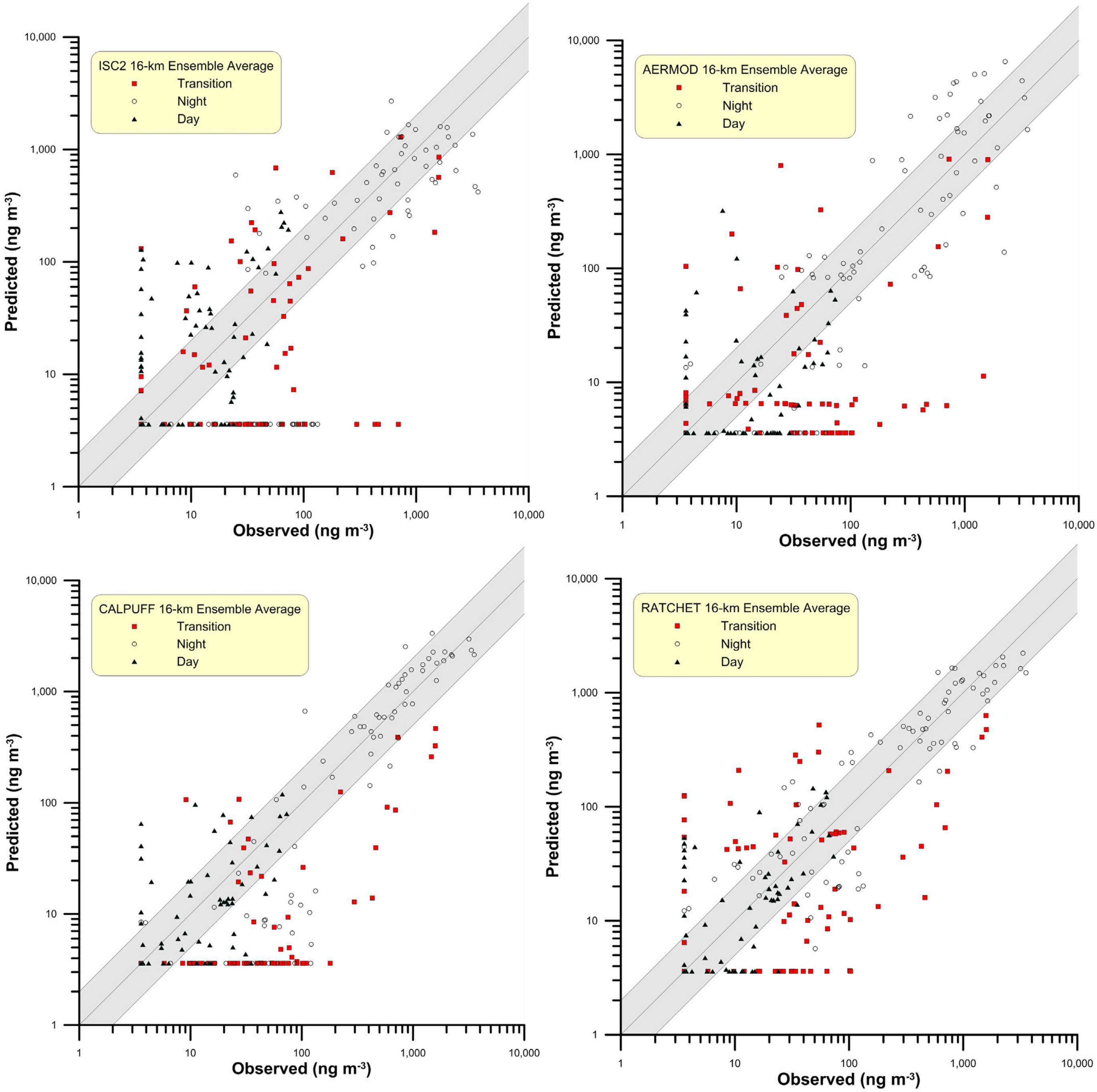

Fig. 3. Scatter plots of paired nine-hour average ensemble mean concentrations at the 16-km distance. Points that lie within the shaded region are within a factor of 2 of the observations.

mean deviation for CALPUFF and ISC2 was significantly different from the mean deviation for AERMOD and RATCHET ($P > 0.005$).

Plume width performance measures at the 8-km distance (Table 5) showed that ISC2 and CALPUFF underestimated plume width while RATCHET and AERMOD overestimated plume width. Although the FB confidence interval for CALPUFF included the optimum value of zero and CALPUFF had the smallest NMSE value.

Arc-integrated concentration at the 8-km distance showed little bias for the steady state models (GM confidence interval included 1.0) and a negative bias for the puff models. However, only 50% of the predictions were within a factor of two for the steady-state models while over 90% of the predictions were within a factor of two for the puff models.

Plume maximum location at the 16-km distance (Table 6) showed that the mean deviation was smallest for CALPUFF and RATCHET (26 and 24 degrees respectively) and greatest for ISC2 and AERMOD (34 and 36 degrees respectively). Based on a *t*-test difference of the means, the differences between the steady state and puff models were significant at the 99% level ($0.01 < P < 0.005$).

Plume width performance measures at the 16-km distance (Table 6) showed that ISC2 underestimated plume width while

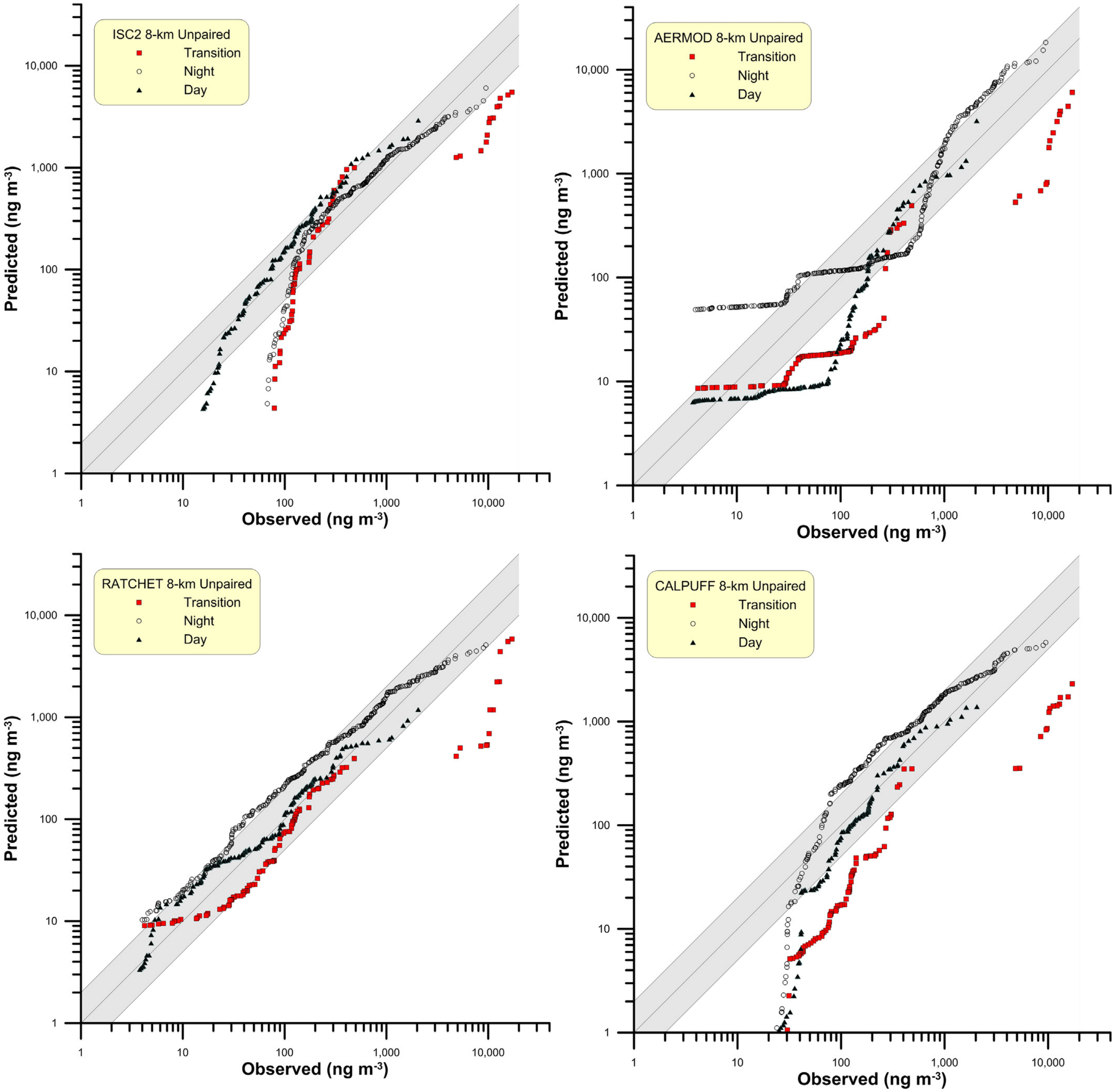

Fig. 4. Scatter plots of unpaired nine-hour average concentrations at the 8-km distance. Points that lie within the shaded region are within a factor of 2 of the observations.

RATCHET and AERMOD overestimated plume width. The CALPUFF *FB* was not significantly different from zero.

Arc-integrated concentration at the 16-km distance showed positive bias for ISC2. The GM confidence interval for the other models included the optimum value of 1.0. Puff models showed a greater percentage of predictions within a factor of two of the observations.

Significant differences among models (Table 7) were noted for the bias performance measures and the correlation coefficients.

3.3. *Unpaired nine-hour average concentration*

The performance measure results at the 8-km distance for the unpaired nine-hour average concentration (Table 8) indicated a negative bias in predicted concentrations for AERMOD and CALPUFF, slight negative bias for ISC2, and positive bias for RATCHET. ISC2 and RATCHET also had the smallest variance, highest correlation coefficient, and highest percentage of predictions within a factor of two of the observations.

At the 16-km distance, ISC2 and RATCHET exhibited positive bias, AERMOD exhibited negative bias, and CALPUFF nearly no bias. RATCHET and ISC2 had the highest correlation coefficients and CALPUFF and RATCHET had the highest percentage of predictions within a factor of two of the observations.

Except for AERMOD and CALPUFF at the 8-km distance, and ISC2 and RATCHET at the 16-km distance, all bias performance measures among the models were significantly different from one another (Table 9).

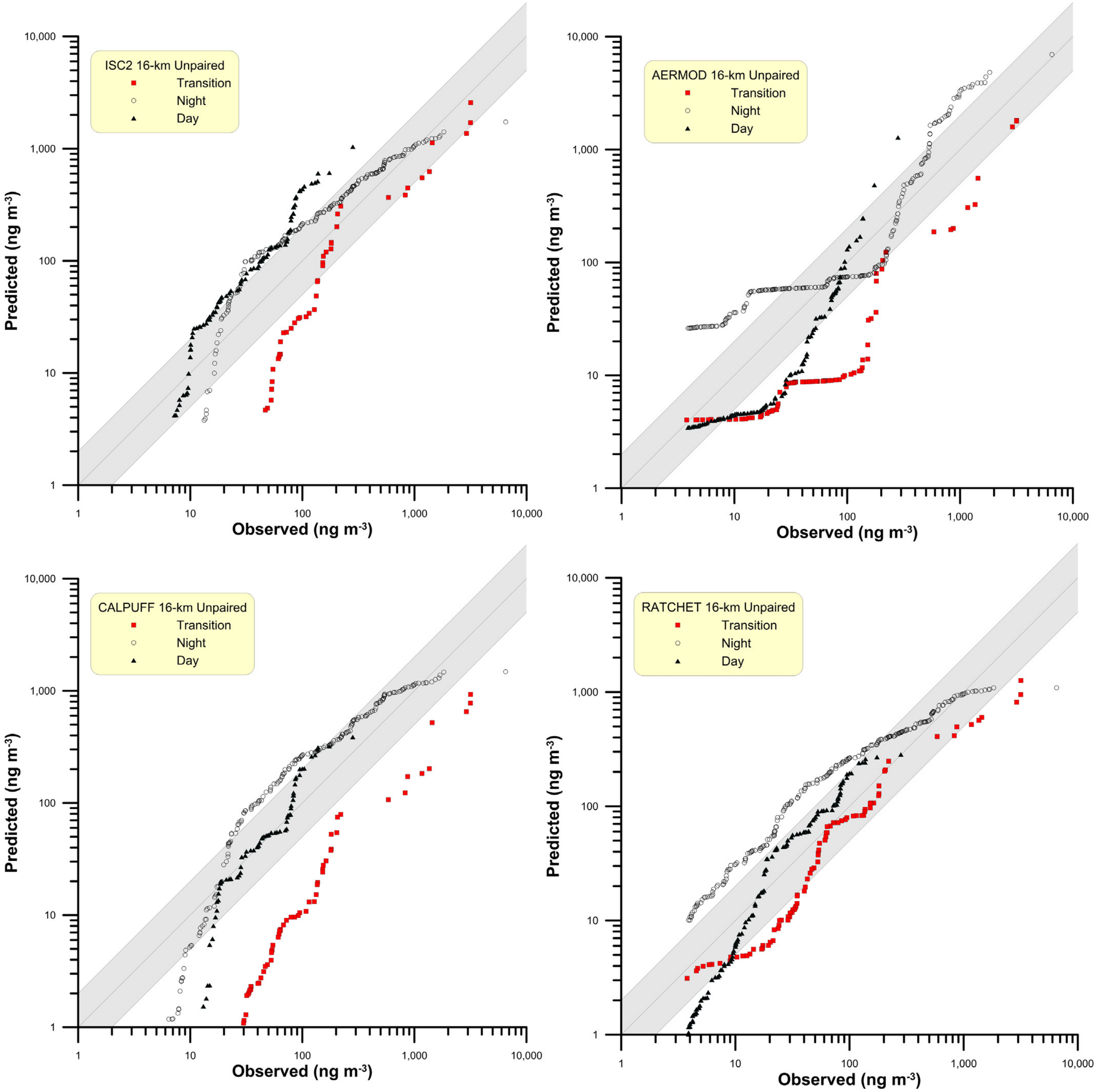

Fig. 5. Scatter plots of unpaired nine-hour average concentrations at the 16-km distance. Points that lie within the shaded region are within a factor of 2 of the observations.

3.4. Paired ensemble means

No one model showed overall better performance across all ensemble groups and all models performed poorly for the transition period ensemble means (Tables 10 and 11). However, excluding the transition ensemble means, RATCHET and CALPUFF had the highest percentage of predictions within a factor of two of the observations, the highest correlation coefficients, and generally the lowest variance compared to the steady-state models. For daytime and nighttime ensemble means, the GM confidence interval for RATCHET encompassed 1.0 at both the 8- and 16-km distances. AERMOD was biased low for daytime tests and showed little bias for nighttime tests (GM confidence interval encompassed 1.0). ISC2 exhibited no bias for daytime tests (GM = 1.0) at the 8-km distance but was biased high at the 16 km distance (GM confidence interval excluded 1.0). For nighttime tests, ISC2 was biased low at the 8-km distance but exhibited nearly zero bias at the 16 km distance. CALPUFF was biased low for daytime and nighttime tests at the 8-km distance (GM confidence interval excluded 1.0), but the GM confidence interval encompassed 1.0 at the 16-km distance.

All models were biased low for the transition period ensemble means at both the 8 and 16-km distances, and exhibited large variances, although the variance measures for CALPUFF and RATCHET were considerable smaller than those for ISC2 and AERMOD. Puff model *VG* and *r* values were significantly different than steady-state models for nighttime tests at the 16-km distance (Table 12).

Table 2
Performance measures for the maximum one-hour average concentration unpaired in time and space modeling objective.

	ISC2	AERMOD	CALPUFF	RATCHET
8-km results				
GM C_p/C_o	1.9	3.4	0.99	0.92
GM confidence interval	1.24–2.87	2.15–5.94	0.65–1.56	0.55–1.65
GSD C_p/C_o	2.2	3.4	2.2	2.8
VG	2.7	17.4	1.8	2.6
log (VG) confidence interval	0.40–1.59	1.78–4.15	0.26–0.92	0.48–1.35
r	0.748	0.742	0.76	0.612
r confidence interval	0.55–0.92	0.46–0.90	0.58–0.96	0.27–0.89
% within a factor of 2	33.3%	25.0%	58.3%	58.3%
16-km results				
GM C_p/C_o	2.7	4.9	0.98	0.93
GM confidence interval	1.71–3.94	2.40–9.34	0.59–1.62	0.57–1.47
GSD C_p/C_o	2.2	3.5	2.8	2.5
VG	4.7	54.8	2.7	2.2
log (VG) confidence interval	0.57–2.42	2.25–5.85	0.41–1.47	0.55–1.07
r	0.885	0.727	0.742	0.828
r confidence interval	0.78–0.97	0.55–0.92	0.58–0.93	0.69–0.95
% within a factor of 2	50.0%	16.7%	50.0%	58.3%

Table 4
Significant differences in model performance measures for the maximum one-hour and nine-hour-average concentration unpaired in space and time modeling objective. An "X" indicates a significant difference.

Model	8-km data			16-km data		
	GM	VG	*r*	GM	VG	*r*
Maximum one-hour						
ISC2-AERMOD	X	X		X	X	X
ISC2-CALPUFF	X			X		
ISC2-RATCHET	X			X		
AERMOD-CALPUFF	X	X		X	X	
AERMOD-RATCHET	X	X		X	X	
CALPUFF-RATCHET						
Maximum nine-hour						
ISC2-AERMOD						
ISC2-CALPUFF	X			X		
ISC2-RATCHET	X	X	X	X		
AERMOD-CALPUFF	X			X		
AERMOD-RATCHET	X	X	X	X		
CALPUFF-RATCHET						

4. Discussion

Model performance is judged in terms of the assessment question that the model is intended to address. As stated in the introduction, the assessment questions are different for a prospective regulatory compliance calculation compared to a retrospective dose reconstruction.

In terms of the prospective assessment where it is important that regulatory limits are not exceeded (i.e., highest concentrations are not underestimated), the steady-state models were less likely to underestimate maximum one- and nine-hour average concentrations compared to the Lagrangian puff models. However, this result is not only due to differences in model formulation, but also the model parameters such as diffusion coefficients. The unpaired scatter plots (Figs. 4 and 5) showed that the *maximum* observed concentration across all tests was not underestimated by AERMOD at both the 8 and 16-km distance, although the time and place of the observed maximum was not the same as the predicted maximum.

In terms of the retrospective assessment where the objective is an unbiased estimate of the concentration in space and time, the Lagrangian puffs models showed overall better performance, especially at the 16-km distance. In most cases, the Lagrangian puff models for the paired ensemble means exhibited lower variance higher correlation to observed values and a higher percentage of observations within a factor of two of the observations compared to steady-state models.

In terms of the four fundamental plume properties, the steady-state models tended to overestimate maximum concentrations but provide unbiased estimates of the plume mass at the 8-km distance and the 16-km distance for ISC2. Puff models tended to slightly underestimate plume maximums, but were better at locating the

Table 3
Performance measures for the maximum nine-hour average concentration unpaired in time and space modeling objective.

	ISC2	AERMOD	CALPUFF	RATCHET
8-km results				
GM C_p/C_o	1.2	1.5	0.79	0.75
GM confidence interval	0.70–2.02	0.94–2.52	0.59–1.03	0.55–1.00
GSD C_p/C_o	2.9	3.0	1.9	1.8
VG	2.9	3.6	1.6	1.5
log (VG) confidence interval	0.78–1.39	0.69–1.88	0.08–0.82	0.13–0.68
r	0.56	0.73	0.86	0.90
r confidence interval	0.35–0.88	0.49–0.89	0.67–0.98	0.78–0.98
% within a factor of 2	33.3%	16.7%	91.7%	75.0%
16-km results				
GM C_p/C_o	1.4	1.8	0.90	0.85
GM confidence interval	0.96–1.99	0.94–3.14	0.59–1.30	0.56–1.23
GSD C_p/C_o	2.7	3.1	2.4	2.6
VG	2.9	4.4	2.0	2.4
log (VG) confidence interval	0.41–1.76	0.86–2.17	0.27–1.31	0.40–1.44
r	0.80	0.76	0.87	0.84
r confidence interval	0.66–0.96	0.63–0.90	0.81–0.94	0.68–0.97
% within a factor of 2	58.3%	16.7%	66.7%	41.7%

Table 5
Performance measures for plume maximum location, plume width, and the arc integrated concentration at the 8-km distance.

	ISC2	AERMOD	CALPUFF	RATCHET
Plume maximum location				
Mean deviation (degrees)	26	14	24	14
Standard error (degrees)	11	3.0	10	3.2
Minimum (degrees)	4.2	0.0	3.3	0.0
Maximum (degrees)	133	31	129	29
Plume width				
FB	0.42	−0.43	0.14	−0.34
FB confidence interval	0.31–0.54	−0.52 to −0.35	−0.06 to 0.37	−0.51 to −0.15
NMSE	0.25	0.22	0.15	0.25
NMSE confidence interval	0.13–0.38	0.15–0.32	0.07–0.31	0.15–0.36
r	0.57	0.19	0.71	−0.22
r confidence interval	0.00–0.88	−0.24 to 0.50	0.44–0.88	−0.79 to 1.00
% within a factor of 2	83.3%	91.7%	75.0%	91.7%
Arc-integrated concentration				
GM C_p/C_o	1.1	0.94	0.76	0.79
GM confidence interval	0.71–1.66	0.68–1.29	0.61–0.94	0.60–1.03
GSD C_p/C_o	2.4	2.3	2.0	1.8
VG	2.1	1.9	1.7	1.5
log (VG) confidence interval	0.52–0.93	0.29–0.94	0.07–0.98	0.05–0.70
r	0.81	0.86	0.86	0.89
r confidence interval	0.64–0.96	0.67–0.96	0.60–1.00	0.75–0.98
% within a factor of 2	50.0%	50.0%	91.7%	91.7%

Table 6
Performance measures for plume maximum location, plume width, and the arc integrated concentration at the 16-km distance.

	ISC2	AERMOD	CALPUFF	RATCHET
Plume maximum location				
Mean deviation (degrees)	34	36	26	23
Standard error (degrees)	9.4	9.0	8.0	7.2
Minimum (degrees)	0.0	0.0	3.8	0.0
Maximum (degrees)	95	98	86	74
Plume width				
FB	0.30	−0.57	0.081	−0.47
FB confidence interval	0.10–0.49	−0.71 to −0.44	−0.18 to 0.37	−0.66 to −0.27
NMSE	0.26	0.44	0.26	0.39
NMSE confidence interval	0.09–0.42	0.28–0.63	0.11–0.48	0.20–0.60
r	0.074	−0.022	0.49	0.065
r confidence interval	−0.36 to 0.51	−0.63 to 0.36	0.20–0.79	−0.57 to 0.54
% within a factor of 2	83.3%	50.0%	66.7%	58.3%
Arc-integrated concentration				
GM C_p/C_o	1.4	1.2	0.88	1.1
GM confidence interval	1.11–1.87	0.77–1.70	0.66–1.16	0.77–1.60
GSD C_p/C_o	2.0	2.4	1.9	2.1
VG	1.8	2.1	1.5	1.6
log (VG) confidence interval	0.28–0.85	0.36–1.15	0.13–0.71	0.40–0.58
r	0.92	0.85	0.87	0.82
r confidence interval	0.88–0.97	0.75–0.96	0.70–0.98	0.76–0.89
% within a factor of 2	66.7%	50.0%	75.0%	83.3%

plume maximum at the 16-km distance. CALPUFF appeared to more accurately estimate the plume impact region, whereas AERMOD and RATCHET tended to overestimate it and ISC2 underestimated it.

The WVTS consists of only 108 h of measurements taken during February 1991 and are not representative of annual average concentrations. However, the high sampler density resulted in the likelihood that the maximum concentration was detected at either the 8-km or 16-km sampling distance. Moreover, the tests were conducted during the wintertime when stable dispersion conditions would likely result in the maximum one- or eight-hour average concentration over the course of a year. Achieving compliance with National Ambient Air Quality Standards typically is limited by the short-term average concentration limits. Therefore, these results have relevance in terms of model performance for short-term averages over the period of a year.

Table 7
Significant differences in model performance measures for the plume width and arc integrated concentration modeling objective. An “X” indicates a significant difference.

Model	8-km data			16-km data		
	FB	NMSE	r	FB	NMSE	r
Plume width						
ISC2-AERMOD	X			X		
ISC2-CALPUFF						
ISC2-RATCHET	X			X		
AERMOD-CALPUFF	X		X	X		
AERMOD-RATCHET						
CALPUFF-RATCHET	X		X	X		
Model	8-km data			16-km data		
	GM	VG	r	GM	VG	r
Arc-integrated concentration						
ISC2-AERMOD						
ISC2-CALPUFF				X		
ISC2-RATCHET	X					X
AERMOD-CALPUFF						
AERMOD-RATCHET						
CALPUFF-RATCHET						

Table 8
Performance measures for the unpaired nine-hour averaged concentration modeling objective.

	ISC2	AERMOD	CALPUFF	RATCHET
8-km results				
GM C_p/C_o	0.93	0.82	0.89	1.3
GM confidence interval	0.90–1.00	0.77–0.87	0.84–0.92	1.22–1.31
GSD C_p/C_o	1.9	2.8	2.7	1.8
GSD confidence interval	1.77–1.96	2.62–2.88	2.56–2.76	1.66–1.90
n	392	564	430	560
VG	1.5	2.9	2.5	1.5
log (VG) confidence interval	0.33–0.46	0.97–1.16	0.89–1.04	0.32–0.46
r	0.92	0.87	0.87	0.95
r confidence interval	0.91–0.94	0.85–0.89	0.85–0.89	0.94–0.96
% within a factor of 2	85%	56%	58%	81%
16-km results				
GM C_p/C_o	1.4	0.86	1.1	1.4
GM confidence interval	1.35–1.50	0.81–0.92	1.08–1.19	1.32–1.45
GSD C_p/C_o	2.1	2.9	2.5	2.0
GSD confidence interval	1.93–2.17	2.75–3.04	2.43–2.62	1.94–2.08
n	316	410	299	399
VG	1.9	3.2	2.4	1.8
log (VG) confidence interval	0.57–0.71	1.04–1.25	0.80–0.94	0.54–0.63
r	0.88	0.82	0.82	0.90
r confidence interval	0.86–0.90	0.79–0.85	0.80–0.85	0.89–0.91
% within a factor of 2	51%	49%	62%	62%

5. Conclusions

No one single model consistently out-performed the others in all performance objectives or measures and the state-of the art models (CALPUFF and AERMOD) did not exhibit superior performance in all performance objectives to the legacy models (ISC2 and RATCHET). Lagrangian puff models generally exhibited smaller variances, higher correlation, and higher percentage of predictions within a factor of two compared to the steady-state models at these distances. The conceptual framework of a Lagrangian puff model is better suited for long range transport where winds vary spatially across the model domain. Hence, Lagrangian puff models may be preferable for dose reconstruction where model domains can be large and where the assessment question is an unbiased estimate of concentration in time and space. However, model choice depends on site-specific considerations and the assessment questions to be addressed, and therefore no categorical statement can be made

Table 9
Significant differences in model performance measures for the unpaired nine-hour average concentration modeling objective. An “X” indicates a significant difference.

Model	8-km data			16-km data		
	GM	VG	r	GM	VG	r
ISC2-AERMOD	X	X	X	X	X	X
ISC2-CALPUFF	X	X	X	X	X	X
ISC2-RATCHET	X		X			
AERMOD-CALPUFF		X		X	X	
AERMOD-RATCHET	X	X	X	X	X	X
CALPUFF-RATCHET	X	X	X	X	X	X

Table 10
Performance measures for the daytime, transition, and nighttime period ensemble means modeling objective at the 8-km distance.

	ISC2	AERMOD	CALPUFF	RATCHET
Daytime tests				
GM C_p/C_o	1.0	0.43	0.61	1.05
GM confidence interval	0.71–1.46	0.31–0.59	0.49–0.76	0.87–1.30
GSD C_p/C_o	4.7	4.3	2.6	2.5
GSD confidence interval	3.87–5.60	3.25–5.36	2.29–2.92	2.16–2.87
VG	11	16	3.2	2.3
log (VG) confidence interval	1.83–2.97	2.12–3.45	0.81–1.52	0.59–1.11
r	0.45	0.46	0.74	0.63
r confidence interval	0.26–0.58	0.28–0.62	0.62–0.82	0.46–0.76
% within a factor of 2	32%	38%	61%	69%
Transition period tests				
GM C_p/C_o	0.3	0.31	0.19	0.56
GM confidence interval	0.15–0.48	0.19–0.51	0.15–0.25	0.36–0.90
GSD C_p/C_o	12.1	8.3	3.4	7.4
GSD confidence interval	8.06–19.6	5.30–12.5	2.70–4.07	4.44–11.0
VG	2024	326	68.2	71.2
log (VG) confidence interval	5.19–11.50	3.49–8.31	3.32–5.17	2.31–6.56
r	0.36	0.41	0.82	0.43
r confidence interval	0.01–0.51	0.17–0.61	0.73–0.88	0.18–0.66
% within a factor of 2	35%	38%	18%	40%
Nighttime period tests				
GM C_p/C_o	0.5	0.84	0.56	1.0
GM confidence interval	0.36–0.71	0.64–1.10	0.43–0.75	0.86–1.25
GSD C_p/C_o	4.3	3.4	3.3	2.4
GSD confidence interval	3.45–5.47	2.89–3.95	2.67–3.84	2.00–2.72
VG	12.9	4.6	5.6	2.1
log (VG) confidence interval	1.81–3.46	1.13–1.96	1.08–2.41	0.48–1.00
r	0.79	0.86	0.92	0.87
r confidence interval	0.68–0.86	0.79–0.90	0.88–0.95	0.82–0.91
% within a factor of 2	53%	47%	68%	72%

Table 11
Performance measures for the daytime, transition, and nighttime period ensemble means modeling objective at the 16-km distance.

	ISC2	AERMOD	CALPUFF	RATCHET
Daytime tests				
GM C_p/C_o	1.6	0.72	0.94	1.10
GM confidence interval	1.18–2.27	0.54–0.96	0.75–1.19	0.90–1.41
GSD C_p/C_o	3.7	3.4	2.6	2.7
GSD confidence interval	3.11–4.54	2.60–4.39	2.15–3.21	2.21–3.24
VG	6.81	5.04	2.54	2.73
log (VG) confidence interval	1.44–2.68	1.09–2.23	0.60–1.35	0.63–1.42
r	0.41	0.27	0.55	0.57
r confidence interval	0.11–0.57	0.02–0.53	0.33–0.72	0.34–0.74
% within a factor of 2	40%	56%	69%	72%
Transition period tests				
GM C_p/C_o	0.4	0.29	0.20	0.61
GM confidence interval	0.24–0.59	0.18–0.47	0.15–0.28	0.39–0.94
GSD C_p/C_o	6.3	6.8	3.8	6.2
GSD confidence interval	4.67–8.31	4.91–9.00	2.99–4.59	4.70–7.72
VG	72.31	169.10	69.42	33.82
log (VG) confidence interval	3.02–5.85	3.79–6.46	3.41–5.12	2.76–4.38
r	0.40	0.22	0.60	0.32
r confidence interval	0.11–0.60	−0.13 to 0.49	0.35–0.76	0.07–0.54
% within a factor of 2	37%	30%	30%	27%
Nighttime period tests				
GM C_p/C_o	1.2	1.2	0.90	1.1
GM confidence interval	0.89–1.72	0.86–1.51	0.73–1.09	0.93–1.33
GSD C_p/C_o	3.8	3.5	2.5	2.2
GSD confidence interval	2.82–5.07	2.84–4.08	2.11–2.83	1.80–2.62
VG	6.0	4.6	2.3	1.8
log (VG) confidence interval	1.07–2.79	1.09–2.02	0.57–1.10	0.35–0.95
r	0.74	0.82	0.91	0.92
r confidence interval	0.60–0.85	0.73–0.89	0.87–0.94	0.87–0.95
% within a factor of 2	54%	53%	68%	76%

Table 12
Significant differences in model performance measures for the day, transition, and nighttime ensemble means modeling objective. An "X" indicates a significant difference.

Model	8-km data			16-km data		
	GM	VG	r	GM	VG	r
Daytime						
ISC2-AERMOD	X			X		
ISC2-CALPUFF	X	X	X	X	X	
ISC2-RATCHET		X			X	
AERMOD-CALPUFF		X	X		X	
AERMOD-RATCHET	X	X		X		
CALPUFF-RATCHET	X			X		
Transition						
ISC2-AERMOD						
ISC2-CALPUFF		X	X	X		
ISC2-RATCHET		X				
AERMOD-CALPUFF			X			X
AERMOD-RATCHET				X		
CALPUFF-RATCHET	X		X	X		
Nighttime						
ISC2-AERMOD	X	X				
ISC2-CALPUFF			X		X	X
ISC2-RATCHET	X	X			X	X
AERMOD-CALPUFF			X		X	X
AERMOD-RATCHET		X			X	X
CALPUFF-RATCHET	X	X				

about the performance of one type of model over the other for a specific application.

The steady-state models generally did not underestimate the high-end concentrations at the distances studied, and therefore provide a sound basis for regulatory compliance modeling. Based on the overall performance of ISC2, assessment models that rely on the Gaussian plume model are not necessarily inferior to the current state-of-the-art models in terms of meeting regulatory performance objectives.

There was a general tendency for the steady-state models to predict relatively higher concentrations at the 16-km distance compared to the 8-km distance. This effect is important because it manifests itself at substantially shorter distances (16 km) than what is defined by the EPA as the near-field environment (≤50 km). The EPA requires AERMOD for the near-field environment for demonstration of regulatory compliance, unless compelling reasons are provided to justify the use of an alternative model. Thus, estimated maximum hourly-average concentrations at distances >16 km are likely to be overestimated based on these results. Other investigators (Dresser and Huizer, 2011) found AERMOD to underestimate near-field maximum one- and three-hour average SO_2 concentrations based on data from the Martins Creek Power Plant. However, only eight samplers were used in the study and it is possible (if not likely) that the true maximum concentration in the model domain was not captured. In the WVTS, it was less likely that the maximum concentration within a sampling arc went undetected.

Finally, a compelling reason to use steady-state models for regulatory compliance demonstration is the fact that they are simpler to run, require less user judgment, and are less prone to error than Lagrangian puff models. The CALMET/CALPUFF model simulation in this paper required numerous iterations using different values of RMAX1, RMAX2, and other parameters so that the wind field matched what was expected. In a prospective analysis, it is unlikely tracer or other validation data would be available to test model performance and adjust model parameters accordingly to improve model performance. The need for consistency and assurance that estimated concentrations are not underestimated are legitimate reasons for using steady-state models for regulatory compliance determination.

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