BEFORE THE ENVIRONMENTAL QUALITY COUNCIL
STATE OF WYOMING

In the Matter of:	)	
Basin Electric Power Cooperative	)	Docket No. 10-2802
Air Quality Permit No. MD-6047	)	
BART Permit: Laramie River Station	)	

RESPONSE TO BASIN ELECTRIC'S MOTION FOR SUMMARY JUDGMENT

Basin Electric's BART Modeling Refinement submittal, 7/28/08

EXHIBIT 7

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Basin Electric Power Cooperative
Laramie River Station

B&V Project 145423.0033
B&V File 30.0000
July 24, 2008

Mr. Dave Finley
State of Wyoming
Department of Environmental Quality
Air Quality Division Administrator
122 West 25th Street
Herschler Building
Cheyenne, WY 82002

JUL 2008
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AIR QUALITY
DIVISION

Subject: Best Available Retrofit Technology Modeling Refinements

Mr. Finley,

On April 3, 2008, WDEQ requested additional BART modeling analyses for Basin Electric Power Cooperative's Laramie River Station. Specifically, the WDEQ request was for individual unit modeling for the baseline scenario as well as unit specific analyses of the selective catalytic reduction (SCR) control technology—or NO_x control technologies being reviewed as BART for the LRS units. Coincident with completing the requested analysis, Basin further investigated additional refinements to the LRS BART modeling analyses which included nitrate repartitioning and more realistic ammonia background concentrations. These refined BART modeling analyses supplement the previous report submitted on February 14, 2008. On behalf of Basin Electric please find enclosed three copies of the refined visibility modeling report for the Laramie River Station and one external hard drive containing the revised electronic modeling files.

If you have any questions regarding the contents of this submittal please call me at 913-458-9062. For specific questions regarding the Laramie River BART analysis please contact Bob Eriksen of Basin Electric at (701) 355-5654.

Very truly yours,

BLACK & VEATCH

Kyle Lucas

Kyle Lucas
Air Project Manager

Enclosures

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Black & Veatch Project: 145423

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Introduction

In a conference call held on April 3, 2008, the Wyoming Department of Environmental Quality (WDEQ) requested additional modeling analyses be performed for the Laramie River Station (LRS). Specifically, the WDEQ request was for individual unit modeling for the baseline scenario as well as unit specific analyses of the selective catalytic reduction (SCR) control technology—or NO_x control technologies being reviewed as BART for the LRS units. Subsequent to the April conference call with WDEQ, Basin further investigated additional refinements to the BART CALPUFF air dispersion modeling analyses which included nitrate repartitioning and more realistic ammonia background concentrations based on monitored values in western Wyoming as well as at several western Class I areas. In addition to the individual unit modeling requested by WDEQ, these two refinements are described in more detail below.

Additionally, the submittal of the Basin LRS BART analysis in September 2007 contained 2006 cost information. The cost for control equipment and other associated expenses have continued to increase and can no longer be considered representative. Therefore, the costs for NO_x control technologies were updated from the November 2006 timeframe to December 2007 costs.

This submittal document contains to two parts—updated cost information for the control technologies as well as updated visibility modeling results.

Part 1 – Technology Cost Update

In an effort to provide a more accurate visibility cost impact, the cost impact analysis for the control scenario evaluated for BART were updated to a 2007 dollar basis to capture recent escalation in equipment and other associated expenses between the last submitted cost estimation values (2006). The cost data submitted in the September 2007 transmittal to WDEQ was based on the results from the cost impact analysis performed using November 2006 values. Since then, it has been observed that there is an increase in the cost for control equipment. This increase is attributable to the surge in demand for such control equipment in both the domestic and international markets. The inability of the manufacturer's supply capacity to meet this demand has resulted in a spike in these equipment costs.

The cost escalation was based on published material escalation rates recorded between 2006 and 2007. The primary escalation factor utilized was the Chemical Engineering Plant Cost Index (CEPCI). CEPCI is an index published by the Chemical Engineering magazine to track process plant construction costs from one time period to another. The CEPCI consists of a series of sub-indices for specific plant equipment categories, which is then calculated using assigned weightage to produce a composite index value. Using the sub-indices in CEPCI for specific plant equipments, the cost impact analysis for the control technologies evaluated for LRS were escalated to the December 2007 time frame.

The cost data and updated cost analysis tables are included in Attachment 1 of this document.

Part 2 – Visibility Analysis

To date, Basin has previously submitted two BART modeling analyses. To clarify the contents of these analyses, as well as for this submittal, a summary of each has been provided:

September 25, 2007

Modeling analyses were performed to provide LRS plant-wide regional haze (visibility) impacts at the Badlands and Wind Cave Class I areas. The analyses were based on a constant 2 ppb background ammonia concentration and no nitrate repartitioning.

February 14, 2008

Modeling analyses were performed to provide LRS plant-wide regional haze (visibility) impacts at two aforementioned Class I areas. The analysis corrected two discrepancies in the September 2007 modeling. Specifically, the update included corrected upper air meteorological station locations and a ZFACE height change. The analysis was based on a constant 2 ppb background ammonia concentration and no nitrate repartitioning.

July 24, 2008

Two main modeling analyses were performed to provide LRS plant-wide and unit specific regional haze (visibility) impacts at two Class I areas for the baseline scenario, the units with Overfired air (OFA), selective non-catalytic reduction (SNCR) control technology, and SCR. The first analysis, believed to be the more representative of ammonia chemistry of the area, was based on refinements which included using the nitrate repartitioning methodology and monthly variable background ammonia concentrations. The second analyses, was conducted utilizing the methodologies and modeling options from the previous submittals--the analyses included a 2 ppb constant background ammonia concentration.

The modeling analyses using the constant ammonia background is at the request of the WDEQ while the analyses based on the refinements contained in this submittal using the aforementioned nitrate repartitioning and the variable ammonia background, supersedes the original September 2007 and February 2008 BART modeling analyses as Basin believes these analyses are more representative. Therefore, the purpose of this document is to first describe the two refinements in modeling methodology used and to provide supplemental information on the background ammonia data. Secondly, the document will summarize the LRS plant-wide and unit specific modeling using nitrate repartitioning and a variable ammonia background. Lastly, the document will summarize the requested WDEQ modeling using the constant ammonia background concentration.

BART CALPUFF Modeling Refinements

Subsequent to the April conference call with WDEQ, Basin further investigated additional refinements to the BART CALPUFF air dispersion modeling analyses which included nitrate repartitioning and more realistic ammonia background concentrations based on monitored values in western Wyoming as well as at several western Class I areas.

Nitrate Repartitioning

The first refinement for the LRS BART visibility analyses was to better account for the amount of particulate nitrate (NO_3) by limiting the available ammonia when individual unit puffs overlap. The original visibility modeling did not incorporate repartitioning of available ammonia (MNITRATE = 0). The refinements did not allow each overlapping puff(s) to use the full ammonia background value but instead only a portion of the ammonia available (MNITRATE = 1). This concept is reflected in Section 6.0 of the WDEQ protocol. It is important to note that this refinement noted as nitrate repartitioning is not the ammonia limiting method commonly referred to as ALM.

Ammonia Background Concentration

As described in Section 7.1 of the BART application, the air dispersion modeling analyses presented were conducted in accordance with the *BART Air Modeling Protocol Individual Source Visibility Assessments for BART Control Analyses* dated September 2006, (hereinafter referred to as the WDEQ Protocol). Specifically, the LRS BART modeling was performed using the same high fixed background ammonia level of 2 ppb that was used for the initial modeling performed by WDEQ. Section 5.0 of the WDEQ protocol notes that the 2 ppb ammonia concentration is *"...based upon monitoring data from nearby states and IWAQM guidance. Experience suggests that 2.0 ppb is* *conservative in that it is unlikely to significantly limit nitrate formation in the model computations."* However, at the time of the WDEQ protocol development there was limited real-time or historic ambient concentration information for ammonia within the modeling domain and at the individual Class I areas from sources such as CASNET. As a result, there was limited information to use to verify whether the assumed 2 ppb ammonia background concentration was representative. In fact, colder temperatures and limited agriculture activity, among other variables, could limit the amount of ammonia present in the ambient atmosphere, thus limiting the ammonia available to chemically react to form sulfates and nitrates to reduce visibility.

The WDEQ Protocol (Section 3.1) further indicates that "ammonia is not believed to be a significant contributor to visibility impairment in most cases in Wyoming…". Other regional BART modeling guidance also considered a high initial ammonia value but also noted that the issue would be later reviewed as noted in the *CALMET/CALPUFF Protocol for BART Exemption Screening Analysis for Class I Areas in the Western United States* dated August 15, 2006, (hereinafter referred to as the WRAP Protocol). Section 3.1.2.6 of WRAP protocol indicates that the 1 ppb value would be initially used and the issue revisited at a later time:

> *Thus, based on the fact that western Class I areas tend to be either more arid or forest land than grassland we proposed to initially use a 1 ppb background ammonia value for the CALPUFF runs. We will then revisit the background ammonia values for the Class I areas for the post processing step and provide the CALPUFF output to the States so they can investigate alternative background ammonia values if desired.*

Similar to WDEQ, no additional information regarding refined ammonia background concentrations was available from the WRAP in supplemental guidance or modified BART modeling protocols.

However, additional studies have been complete which report lower background ammonia concentrations as well as provide modeling results which clearly suggest ammonia concentrations less than 1 ppb could significantly affect the visibility impacts.

Therefore, an investigation was undertaken to locate and identify more realistic ammonia background values. A 15-month monitoring study, located in the Upper Green River Basin of western Wyoming southwest of Bridge Wilderness Area, was initiated in December 2006 by Shell Exploration & Production Company to characterize ammonia concentrations throughout the year. The findings of this study were presented at the Air & Waste Management Association (AWMA) Aerosol & Atmospheric Optics: Visual Air Quality and Radiation in Moab, Utah on May 1, 2008. The extended abstract for this presentation has been included as Attachment 2. As the abstract indicates, "standard operating procedures, technical instructions, and a QAPP for instrument installation, operation and maintenance, field sampling, filter handling, and laboratory analyses were developed and submitted to WDEQ". The results of study indicate that ammonia concentrations are variable throughout the year, are below or near detectable limits from December through late February, peak in August at levels less than WDEQ's assumed constant 2 ppb ammonia level, and have an annual mean value of 0.24 ppb. Table 1 includes the monthly mean ammonia values (referenced from Figure 2 of the abstract) for illustration of the low background ammonia values.

Table 1
Monitored Variable Monthly Ammonia Background Concentration[1]

Month	Background Ammonia Concentration (ppb)
January	< 0.1
February	< 0.1
March	0.2
April	0.2
May	0.3
June	0.3
July	0.8
August	0.8
September	0.3
October	0.2
November	0.1
December	< 0.1

[1] The Wyoming ammonia data is from the extended abstract presented at the Air & Waste Management Association (AWMA) Aerosol & Atmospheric Optics: Visual Air Quality and Radiation in Moab Utah on May 1, 2008.

Similarly, other facilities undergoing Prevention of Significant Deterioration (PSD) air permitting further investigated more realistic ammonia background concentrations. The Sithe Global Power, LLC's Desert Rock Energy Facility and the Toquop Energy Project visibility analyses located in the southwestern U.S. used variable monthly background ammonia concentrations which were approved by the regulating agencies as being representative of regional background concentrations. For reference, these background ammonia concentrations are presented in Table 2. Additionally, the aforementioned ammonia data and supporting information for the values contained in the Desert Rock Energy Facility and the Toquop Energy Project visibility analyses have been included in Attachment 3. These data were based on ammonia background concentrations monitored at several western class I areas. Attachment 3 also contains the Colorado Department of Public Health and Environment's *CALMET/CALPUFF BART Protocol for Class I Federal Area Individual Source Attribution Visibility Impairment Modeling Analysis* dated October 24, 2005. This document contains information on ammonia sensitivity tests completed which indicate that background ammonia values do vary and that the model is sensitive to background ammonia values less than 1.0 ppb.

Table 2
Variable Monthly Ammonia
Background Concentration[1]

Month	Background Ammonia Concentration (ppb)
January	0.2
February	0.2
March	0.2
April	0.5
May	0.5
June	1.0
July	1.0
August	1.0
September	1.0
October	0.5
November	0.5
December	0.5

[1] The ammonia data is from the Sithe Global Power, LLC's Desert Rock Energy Facility and the Toquop Energy Project visibility analyses.

Additionally, based on a conference call with Mark Sather of EPA Region 6 it was determined that EPA has conducted an ammonia monitoring study from December 2006 through January 2008 in the Four-corner's area of New Mexico. The EPA goal of this study is to establish a baseline for the area and to set the background ammonia concentrations to be used in visibility studies, PSD permitting activities, and BART analyses. The study used five monitoring sites scattered throughout the Four-Corners area. From discussions with EPA the data in the 4 corners area generally ranges from a non-detectable level to 0.6 ppb with the annual average background approximately 0.2 ppb. EPA is currently completing a technical review for journal publication with completion of the review anticipated at the end of July.

The aforementioned supplemental data from the Shell study in Wyoming, the Desert Rock Energy Facility and the Toquop Energy Project's, and EPA Region 6's monitoring study each indicate that the background ammonia in the western United States is variable and the ammonia values monitored less than WDEQ's 2 ppb constant value. Based on this information, refinements to LRS's BART modeling have been completed to reflect the monthly ammonia values from the study in Wyoming. The results of this update are presented below. It should be noted that Basin considers these refinements and the resulting visibility impacts more realistic and representative than those results previously submitted.

Visibility Summary with Nitrate Repartitioning and Variable Ammonia

Based on the aforementioned refinements in background ammonia concentrations and nitrate repartitioning, revised CALPUFF visibility modeling was performed for the following scenarios:

- Facility and unit specific Baseline
- Facility and unit specific Scenario 1 (OFA)
- Facility and unit specific Scenario 4 (SNCR)
- Facility and unit specific Scenario 5 (SCR)

The modeling summarized in this report is for the LRS on a plant-wide basis and for each of the three LRS units on an individual unit basis. It is important to note that all other modeling options as described in the BART application were unchanged. For simplicity, the following results discuss the differences between the OFA scenario and the SNCR and SCR scenarios. The OFA scenario was used as the new baseline as Basin is currently proceeding with the installation of this control technology as BART for NO_x as indicated in the submittal in September 2007. The visibility modeling results are contained in Attachment 4.

The results of the refined visibility modeling for the LRS plant, assuming the same control technology is installed on all three units, are illustrated in Tables 1 through 3 and 13 of Attachment 4. These tables summarize the scenarios and the maximum visibility (deciview) impact seen at any of the two Class I areas at any time over the 2001 to 2003 period. The results of this analysis, using the aforementioned refinements, indicates a decrease in visibility impact at each of the two Class I areas from those visibility impacts indicated in the BART application document.

The maximum visibility (deciview) improvement seen at either of the two Class I areas at any time over the 2001 to 2003 period is illustrated in Table 13 for each scenario.

The expected degree of visibility improvement for each control scenario on a plant-wide basis was determined by the difference in the maximum visibility improvement for each receptor at each of the Class I areas. Again, it is important to note that the control technology associated with the OFA scenario formulated the LRS's baseline case, as well as the new baseline case for the individual unit analyses described later. Additionally, the cost-effectiveness for the potential BART control technologies from the BART application were used to calculate visibility improvement cost-effectiveness in $/deciview ($/dv).

These maximum visibility improvements between the OFA and the SNCR and SCR control scenarios range from 0.35 dv to 0.68 dv of expected visibility improvement above the OFA scenario. The results indicate that adding additional SNCR or SCR NO_x control technology beyond the consent decree does not yield visibility improvement greater than 1.0 dv at any Class I area and in fact results indicate that visibility improvement at Badlands is less than 0.5 dv.

Based on the visibility improvements modeled and the total annual cost evaluated in the impact analysis stage of the BART application document, the cost-effectiveness for visibility improvement (annual cost per improvement in visibility, $/dv), was determined for LRS over the aforementioned range of visibility improvement. The resulting cost for installation of SNCR or SCRs at LRS ranges from $42.4 million/dv to $97.6 million/dv.

The results of the refined visibility modeling for Unit 1, Unit 2, and Unit 3 individually are illustrated in Tables 4-6, 7-9, 10-12, and Table 13 Attachment 4, respectively. These tables summarize the scenarios and the maximum visibility (deciview) impact seen at either of the two Class I areas at any time over the 2001 to 2003 period. Again, it is important to note that individual unit impacts at a specific class I area cannot be added to equal the combined LRS plant-wide impact at the same class I area because each impact may not have occurred during the same 24 hour period or at the same receptor location.

The maximum visibility (deciview) improvement seen at either of the two Class I areas at any time over the 2001 to 2003 period is illustrated in Tables 13. Again, the expected degree of visibility improvement for each control scenario for each unit was determined by the difference in the maximum visibility improvement for each receptor at each of the sixteen Class I areas. Furthermore, the same methodology previously described for the LRS's cost-effectiveness in ($/dv) was used here for each unit.

These maximum visibility improvements between the OFA scenario and the SNCR or SCR control scenario for each unit are lower than the results utilizing the less realistic constant ammonia background of 2 ppb described in the next section. The visibility improvements are summarized below.

- Unit 1 improvements range from 0.07 dv to 0.19 dv.
- Unit 2 improvements range from 0.10 dv to 0.19 dv
- Unit 3 improvements range from 0.09 dv to 0.22 dv

The results again indicate that adding additional SNCR or SCR NO_x control technology beyond the OFA scenario does not yield visibility improvement greater than 0.5 dv at any Class I area. Based on the visibility improvement modeled and the total annual cost evaluated in the impact analysis stage of the BART application document, the cost-effectiveness for visibility improvement (annual cost per improvement in visibility, $/dv), was determined for each unit. The resulting cost for installation of SNCRs or SCRs for each unit is summarized below.

SNCR

- Unit 1 cost range is $54.6 million/dv to $99.5 million/dv.
- Unit 2 cost range is $55.8 million/dv to $73.7 million/dv.
- Unit 3 cost range is $43.6 million/dv to $85.6 million/dv.

SCR

- Unit 1 cost range is $78.1 million/dv to $130.7 million/dv.
- Unit 2 cost range is $78.1 million/dv to $114.0 million/dv.
- Unit 3 cost range is $70.5 million/dv to $130.7 million/dv.

Attachment 4 contains a LRS plant and unit summary of the 98th percentile visibility impact for the three modeled technology scenarios and provides information on the number of days above 0.5 dv threshold for each class I area.

Visibility Summary with Nitrate Repartitioning and Variable Ammonia

The individual unit's impacts for the SNCR and SCR control scenarios indicate a slight improvement in visibility from the OFA scenario. Specifically, individual improvements are less than half of the 0.5 dv threshold. For the LRS facility the visibility improvements are slightly greater than 0.5 dv but these minor visibility improvements for class I areas outside of the state of Wyoming using these technologies are cost prohibitive.

Basin recognizes that WDEQ has requested additional visibility modeling be conducted using a constant ammonia background value of 2 ppb. While Basin does not believe analyses conducted using the constant ammonia background (2 ppb) is representative, analyses have been conducted based on the aforementioned modeling methodology and described scenarios for both the LRS plant and individual units and these results are summarized in the next section as well as contained in Attachment 5.

Visibility Summary with Constant Ammonia

Based on the aforementioned request from WDEQ for individual unit modeling for the baseline scenario as well as the SCR control technology this modeling as well as modeling representing Scenarios 1 (LRS units with OFA) and 4 (SNCR) were performed.

The following CALPUFF visibility modeling was performed for the following scenarios:

- Facility and unit specific baseline
- Facility and unit specific Scenario 1 (OFA)
- Facility and unit specific Scenario 4 (SNCR)
- Facility and unit specific Scenario 5 (SCR)

Again, the OFA scenario was modeled and used as the new baseline scenario as Basin is currently proceeding with the installation of this control technology as BART for NO_X as indicated in the submittal in September 2007. The modeling summarized in this section of this report is for the LRS facility as well as each of the three LRS units on an individual unit basis. It is important to note that all other modeling options and modeling methodologies as described in the BART application were unchanged. For simplicity, the result tables illustrate the visibility impacts of the baseline scenario and the three scenarios—Scenario 1 (OFA), Scenario 4 (SNCR), and Scenario 5 (SCR) scenario. The visibility modeling results are contained in Attachment 5.

The results of the refined visibility modeling for the LRS plant's NOx control scenarios, assuming the same control technology is installed on all three units, are illustrated in Tables 1 through 3 and Table 13 of Attachment 5. These tables summarize the scenarios and the maximum visibility (deciview) impact seen at any of the two Class I areas at any time over the 2001 to 2003 period. The results of this analysis indicate visibility improvement for all three control technologies at both affected federal Class I areas through the years 2001 to 2003. It should be noted that because LRS is currently in the process of installing OFA systems, the visibility improvement from the OFA scenario to either the SNCR or SCR control technology scenario is less than 1.0 dv. The maximum improvement which is less than 1.0 dv is attributed to a costly SCR control technology scenario for each unit, which exceeds the targeted NO_x presumptive limit of 0.23 lb/MBtu.

These maximum visibility improvements between the OFA scenario and the SNCR or SCR control scenario range from 0.57 dv to 0.97 dv of expected visibility improvement above the OFA scenario. The results indicate that adding additional SCNR or SCR NO_x control technology beyond the OFA scenario does not yield visibility improvement greater than 1.0 dv at any Class I area and on a individual unit basis shows a potential visibility improvement of 0.36 dv but this is less than 0.5 dv threshold.

Based on the visibility improvement modeled and the total annual cost evaluated in the impact analysis stage (Step 4) of the BART process, the cost-effectiveness for visibility improvement (annual cost per improvement in visibility, $/dv), was determined for LRS over the aforementioned range of visibility improvement. The resulting cost for installation of SNCRs or SCRs at LRS ranges from $37.1 million/dv to $62.0 million/dv.

As noted in the application the total annual cost for the implementation of the recommended control technologies to meet the presumptive emissions levels is approximately 2.7 million $/yr. The maximum modeled visibility improvements for the recommended control scenario at each federal Class I area through the 2001 to 2003 time period is 0.2 dv. From this analysis, the cost-effectiveness for maximum visibility improvement from LRS is 8.9 million $/dv which is significantly less than the costs to install either SNCR or SCR control technology shown in this analysis.

The results of the refined visibility modeling for Unit 1, Unit 2, and Unit 3 are illustrated in Tables 4-6, 7-9, 10-12, and Table 13 of Attachment 5, respectively. These tables summarize the scenarios and the maximum visibility (deciview) impact seen at either of the two Class I areas at any time over the 2001 to 2003 period. The visibility impacts illustrated in the tables represent the maximum visibility impact at each of the Class I areas. It is important to note that individual unit impacts at a specific class I area cannot be added to equal the combined LRS plant-wide impact at the same class I area because each impact may not have occurred during the same 24 hour period or at the same receptor location.

The maximum visibility (deciview) improvement seen at either of the two Class I areas at any time over the 2001 to 2003 period is illustrated in Table 13. Again, the expected degree of visibility improvement for each control scenario for each unit was determined by the difference in the maximum visibility improvement for each receptor at each of the Class I areas. Furthermore, the same methodology previously described for the LRS's cost-effectiveness in ($/dv) was used here for each unit.

These maximum visibility improvements between the OFA scenario and the SNCR and SCR control scenario for each unit are less than that of the combine LRS analysis and are all less than 0.5 dv. The visibility improvements are summarized below.

- Unit 1 improvements range from 0.21 dv to 0.36 dv
- Unit 2 improvements range from 0.21 dv to 0.36 dv
- Unit 3 improvements range from 0.20 dv to 0.36 dv

The results again indicate that adding additional SNCR or SCR NO_x control technology beyond the OFA scenario does not yield visibility improvement greater than 0.5 dv at any Class I area. Based on the visibility improvement modeled and the total annual cost evaluated in the impact analysis stage of the BART process, the cost-effectiveness for visibility improvement (annual cost per improvement in visibility, $/dv), was determined for each unit. The resulting cost for installation of SNCRs and SCRs for each unit is summarized below.

SNCR

- Unit 1 cost range is $33.3 million/dv to $35.6 million/dv.
- Unit 2 cost range is $33.3 million/dv to $35.6 million/dv.
- Unit 3 cost range is $32.3 million/dv to $37.4 million/dv.

SCR

- Unit 1 cost range is $42.2 million/dv to $54.5 million/dv.
- Unit 2 cost range is $41.8 million/dv to $55.3 million/dv.
- Unit 3 cost range is $42.5 million/dv to $57.9 million/dv.

Attachment 5 contains a LRS plant and unit summary of the 98th percentile visibility impact for the three modeled technology scenarios and provides information on the number of days above 0.5 dv threshold for each class I area.

Additional Considerations

The minimal visibility improvements discussed in this document for either the variable or constant ammonia cases do not merit the large capital expenditure required to install SNCR or SCR. In addition to the prohibitive cost associated with SNCR and SCR, there are other important reasons that OFA should be considered BART for the LRS units. First, these state-of-the-art combustion controls (OFA technology) were used to form the basis for the BART presumptive limits for NO_x in the BART guidelines. Furthermore, these state-of-the-art combustion controls are currently being planned by Basin for installation to meet BART requirements based on the findings of the September 2007 analysis. Second, if one considers the potential visibility improvements gained (for either variable or constant ammonia) from utilizing the baseline scenario in lieu of the OFA scenario, the individual unit results again indicate that adding additional SNCR or SCR NO_x control technology does not yield visibility improvement greater than 0.5 dv at either Class I area. Lastly, installation of SNCR or SCR requires ammonia to reduce NO_x emissions. Specifically, in a SCR system, ammonia is injected into the flue gas stream just upstream of a catalytic reactor. The ammonia molecules in the presence of the catalyst dissociate NO_x into nitrogen and water. Any unreacted ammonia passes through the reactor and out the stack as ammonia emissions or ammonia slip. In an SNCR system, the ammonia is injected directly into the boiler to react with NO_x. In either case, this additional ammonia would then be available to add to the ammonia background concentration, chemically react to form nitrates and sulfates, and potentially further increase the visibility impacts at the Class I areas. The additional ammonia slip was not considered in this analysis. Therefore, OFA should be considered BART for NO_x control on the LRS units.

Conclusion

As noted in this document, Basin's further investigation of additional refinements to the February 2008 BART CALPUFF air dispersion modeling analyses to yield more realistic regional haze impacts was warranted. These analyses included nitrate repartitioning and more realistic ammonia background concentrations based on a year of monitored values in western Wyoming. The modeling refinements contained in this submittal supersedes the original February 2008 BART modeling analyses.

The conclusions of this study re-iterate and support the overall findings of the February 2008 submittal that installation of an SNCR or SCR system at the LRS provides minimal visibility improvement and would require significant capital expenditure and modifications that will impact many areas such as air heater performance, SO_3 emissions, and ash handling. The results from the analyses further substantiate that the addition of these technologies does not yield a benefit nor meet the intended goal of BART. Both the total annual costs evaluated and the cost-effectiveness ($/dv) are prohibitive for the SNCR and SCR technologies given the minimal improvements realized.

Therefore, given the minimal visibility improvement to the two Class I areas in the BART analysis, the recommended BART NO_x control for LRS is still the installation of an OFA system for all three units.

Attachment 1

Table 6-1
Impact Analysis and Cost Effectiveness Results (LRS 1)

All Feasible Technologies	Emission Performance Level (lb/mmBtu)	Expected Emission Rate (lb/yr)	Expected Emission Rate (ton/yr)	Expected Emission Reductions (tons/year)	Capital Costs (1,000$)	Total Annualized Cost (1,000$)	Cost Effectiveness ($/ton)	Incremental Cost Effectiveness ($/ton)	Energy Impacts (1,000$)	Non-Air Impacts (1,000$)
NO_x Control Technologies										
Overfire Air (OFA) System	0.23	10,767,320	5,384	936	5,326	625	668	–	140	–
New LNB	0.23	10,767,320	5,384	936	15,631	1,360	1,453	–	–	–
SNCR/SCR Hybrid (Cascade)	0.20	9,362,667	4,681	1,639	44,869	7,429	4,534	–	77	–
New LNB with OFA	0.15	7,022,165	3,511	2,809	22,096	1,944	692	704	–	–
New LNB with OFA and SNCR	0.12	5,617,732	2,809	3,511	43,441	7,365	2,098	–	77	–
Selective Catalytic Reduction (SCR)	0.07	3,277,010	1,639	4,681	123,101	15,787	3,372	7,392	414	1

Notes:

1. Dominant controls are shown in bold
2. All costs are in 2007$
3. Incremental costs are based on:
   a) New LNB with OFA incremental cost relative to OFA
   b) SCR incremental cost relative to New LNB with OFA

Table 6-2
Impact Analysis and Cost Effectiveness Results (LRS 2)

All Feasible Technologies	Emission Performance Level (lb/mmBtu)	Expected Emission Rate (lb/yr)	Expected Emission Rate (ton/yr)	Expected Emission Reductions (tons/year)	Capital Costs (1,000$)	Total Annualized Cost (1,000$)	Cost Effectiveness ($/ton)	Incremental Cost Effectiveness ($/ton)	Energy Impacts (1,000$)	Non-Air Impacts (1,000$)
NO$_x$ Control Technologies										
Overfire Air (OFA) System	0.23	10,708,280	5,354	931	5,326	625	671	--	140	--
New LNB	0.23	10,708,280	5,354	931	15,631	1,360	1,461	--	--	--
SNCR/SCR Hybrid (Cascade)	0.20	9,311,548	4,656	1,630	44,959	7,429	4,559	--	77	--
New LNB with OFA	0.15	6,983,661	3,492	2,793	22,096	1,944	696	708	--	--
New LNB with OFA and SNCR	0.12	5,586,929	2,793	3,492	43,441	7,365	2,109	--	77	--
Selective Catalytic Reduction (SCR)	0.07	3,259,042	1,630	4,656	123,101	15,787	3,391	7,433	414	1

Notes:

1. Dominant controls are shown in bold
2. All costs are in 2007$
3. Incremental costs are based on:
    - a) New LNB with OFA incremental cost relative to OFA
    - b) SCR incremental cost relative to New LNB with OFA

Table 6-3
Impact Analysis and Cost Effectiveness Results (LRS 3)

All Feasible Technologies	Emission Performance Level (lb/mmBtu)	Expected Emission Rate (lb/yr)	Expected Emission Rate (ton/yr)	Expected Emission Reductions (tons/year)	Capital Costs (1,000$)	Total Annualized Cost (1,000$)	Cost Effectiveness ($/ton)	Incremental Cost Effectiveness ($/ton)	Energy Impacts (1,000$)	Non-Air Impacts (1,000$)
NO_x Control Technologies										
Overfire Air (OFA) System	0.23	10,986,072	5,493	955	5,326	625	654	--	140	--
New LNB	0.23	10,986,072	5,493	955	15,631	1,360	1,424	--	--	--
SNCR/SCR Hybrid (Cascade)	0.20	9,553,106	4,777	1,672	44,969	7,429	4,444	--	77	--
New LNB with OFA	0.15	7,164,829	3,582	2,866	22,096	1,944	678	690	--	--
New LNB with OFA and SNCR	0.12	5,731,863	2,866	3,582	43,441	7,365	2,056	--	77	--
Selective Catalytic Reduction (SCR)	0.07	3,343,687	1,672	4,777	123,101	15,767	3,305	7,245	414	1

Notes:

1. Dominant controls are shown in bold
2. All costs are in 2007$
3. Incremental costs are based on:
   a) New LNB with OFA incremental cost relative to OFA
   b) SCR incremental cost relative to New LNB with OFA

BEPC Laramie River BART Engineering Analysis - Cost Analysis (Revision) - in 2007$

Technology: Overfire Air System

Date: 5/6/2008

Cost Item	$	Remarks/Cost Basis		
CAPITAL COST				
Direct Costs				
Purchased equipment costs				
Complete OFA System	$2,561,000	vendor quote, 10/06		
CO Monitoring System	$50,000	B&V Estimate		
Subtotal capital cost (CC)	$2,611,000			
Taxes	$104,000	(CC) X	4.0%	
Freight	$131,000	(CC) X	5.0%	
Total purchased equipment cost (PEC)	$2,846,000			
Direct installation costs				
Foundation & supports	$0	(PEC) X	0.0%	
Handling & erection	$569,000	(PEC) X	20.0%	
Electrical	$427,000	(PEC) X	15.0%	
Piping	$57,000	(PEC) X	2.0%	
Insulation	$0	(PEC) X	0.0%	
Painting	$0	(PEC) X	0.0%	
Demolition	$71,000	(PEC) X	2.5%	
Relocation	$0	(PEC) X	0.0%	
Total direct installation costs (DIC)	$1,124,000			
Site preparation	$0	N/A		
Buildings	$0	N/A		
Total direct costs (DC) = (PEC) + (DIC)	$3,970,000			
Indirect Costs				
Engineering	$397,000	(DC) X	10.0%	
Owner's cost	$79,000	(DC) X	2.0%	
Construction management	$199,000	(DC) X	5.0%	
Start-up and spare parts	$79,000	(DC) X	2.0%	
Performance test	$50,000	Engineering estimate		
Contingencies	$397,000	(DC) X	10.0%	
Total indirect costs (IC)	$1,201,000			
Allowance for Funds Used During Construction (AFDC)	$155,000	[(DC)+(IC)] X 6.00%		1 years (project time length)
Total Capital Investment (TCI) = (DC) + (IC) + (AFDC)	$5,326,000			
ANNUAL COST				
Direct Annual Costs				
Fixed annual costs				
Maintenance materials	$10,000	B&V cost estimate		
Maintenance labor	$12,000	B&V cost estimate, 6 man weeks/yr		
Total fixed annual costs	$22,000			
Variable annual costs				
Replacement power due to efficiency hit	$140,000	Engineering estimates, 0.2% efficiency drop, and 0.015 $/kWh		
Total variable annual costs	$140,000			
Total direct annual costs (DAC)	$162,000			
Indirect Annual Costs				
Cost for capital recovery	$463,000	(TCI) X	8.70%	CRF at 6% interest & 20 year life
Total indirect annual costs (IDAC)	$463,000			
Total Annual Cost (TAC) = (DAC) + (IDAC)	$625,000			

BEPC Laramie River BART Engineering Analysis - Cost Analysis (Revision) - in 2007$

Technology: New Low NOx Burners

Date: 5/6/2008

Cost Item	$	Remarks/Cost Basis		
CAPITAL COST				
Direct Costs				
Purchased equipment costs				
Complete new burners	$8,446,000	vendor quote, 10/06		
Subtotal capital cost (CC)	$8,446,000			
Taxes	$338,000	(CC) X	4.0%	
Freight	$422,000	(CC) X	5.0%	
Total purchased equipment cost (PEC)	$9,206,000			
Direct installation costs				
Foundation & supports	$0	(PEC) X	0.0%	
Handling & erection	$1,841,000	(PEC) X	20.0%	
Electrical	$921,000	(PEC) X	10.0%	
Piping	$0	(PEC) X	0.0%	
Insulation	$0	(PEC) X	0.0%	
Painting	$0	(PEC) X	0.0%	
Demolition	$230,000	(PEC) X	2.5%	
Relocation	$0	(PEC) X	0.0%	
Total direct installation costs (DIC)	$2,992,000			
Site preparation	$0	N/A		
Buildings	$0	N/A		
Total direct costs (DC) = (PEC) + (DIC)	$12,198,000			
Indirect Costs				
Engineering	$610,000	(DC) X	5.0%	
Owner's cost	$244,000	(DC) X	2.0%	
Construction management	$610,000	(DC) X	5.0%	
Start-up and spare parts	$244,000	(DC) X	2.0%	
Perfomance test	$50,000	Engineering estimate		
Contingencies	$1,220,000	(DC) X	10.0%	
Total indirect costs (IC)	$2,978,000			
Allowance for Funds Used During Construction (AFDC)	$455,000	[(DC)+(IC)] X	6.00%	1 years (project time length)
Total Capital Investment (TCI) = (DC) + (IC) + (AFDC)	**$15,631,000**			
ANNUAL COST				
Direct Annual Costs				
Fixed annual costs				
N/A	$0	Similar annual costs as current LNB		
Total fixed annual costs	$0			
Variable annual costs				
N/A	$0	Similar annual costs as current LNB		
Total variable annual costs	$0			
Total direct annual costs (DAC)	$0			
Indirect Annual Costs				
Cost for capital recovery	$1,360,000	(TCI) X	8.70%	CRF at 6% interest & 20 year life
Total indirect annual costs (IDAC)	$1,360,000			
Total Annual Cost (TAC) = (DAC) + (IDAC)	**$1,360,000**			

BEPC Laramie River BART Engineering Analysis - Cost Analysis (Revision) - in 2007$

Technology: New Low NOx Burners with OFA System

Date: 5/6/2008

Cost Item	$	Remarks/Cost Basis		
CAPITAL COST				
Direct Costs				
Purchased equipment costs				
Complete new burners	$8,446,000	vendor quote, 10/06		
Complete OFA System	$2,561,000	vendor quote, 10/06		
CO Monitoring System	$150,000	ref. quote		
Subtotal capital cost (CC)	$11,157,000			
Taxes	$446,000	(CC) X	4.0%	
Freight	$558,000	(CC) X	5.0%	
Total purchased equipment cost (PEC)	$12,161,000			
Direct installation costs				
Foundation & supports	$0	(PEC) X	0.0%	
Handling & erection	$2,432,000	(PEC) X	20.0%	
Electrical	$1,216,000	(PEC) X	10.0%	
Piping	$243,000	(PEC) X	2.0%	
Insulation	$243,000	(PEC) X	2.0%	
Painting	$0	(PEC) X	0.0%	
Demolition	$304,000	(PEC) X	2.5%	
Relocation	$122,000	(PEC) X	1.0%	
Total direct installation costs (DIC)	$4,560,000			
Site preparation	$0	N/A		
Buildings	$0	N/A		
Total direct costs (DC) = (PEC) + (DIC)	$16,721,000			
Indirect Costs				
Engineering	$1,672,000	(DC) X	10.0%	
Owner's cost	$334,000	(DC) X	2.0%	
Construction management	$669,000	(DC) X	4.0%	
Start-up and spare parts	$334,000	(DC) X	2.0%	
Performance test	$50,000	Engineering estimate		
Contingencies	$1,672,000	(DC) X	10.0%	
Total indirect costs (IC)	$4,731,000			
Allowance for Funds Used During Construction (AFDC)	$644,000	[(DC)+(IC)] X	6.00%	1 years (project time length)
Total Capital Investment (TCI) = (DC) + (IC) + (AFDC)	**$22,096,000**			
ANNUAL COST				
Direct Annual Costs				
Fixed annual costs				
Maintenance materials	$10,000	B&V cost estimate		
Maintenance labor	$12,000	B&V cost estimate, 6 man weeks/yr		
Total fixed annual costs	$22,000			
Variable annual costs				
Replacement power due to efficiency hit	$0	Engineering estimates, 0.2% efficiency drop, and 0.015 $/kWh		
Total variable annual costs	$0			
Total direct annual costs (DAC)	$22,000			
Indirect Annual Costs				
Cost for capital recovery	$1,922,000	(TCI) X	8.70%	CRF at 6% interest & 20 year life
Total indirect annual costs (IDAC)	$1,922,000			
Total Annual Cost (TAC) = (DAC) + (IDAC)	**$1,944,000**			

BEPC Laramie River BART Engineering Analysis - Cost Analysis (Revision) - in 2007$

Technology: New Low NOx Burners with OFA and SNCR

Date: 5/6/2008

Cost Item	$	Remarks/Cost Basis			
CAPITAL COST					
Direct Costs					
Purchased equipment costs					
Complete new burners	$8,446,000	vendor quote, 10/06			
Complete OFA System	$2,561,000	vendor quote, 10/06			
Complete SNCR System	$7,072,000	vendor quote, 10/06			
Initial urea inventory	$67,000	45,000 gal. urea initial inventory			
CO Monitoring System	$150,000	ref. quote			
Subtotal capital cost (CC)	$18,296,000				
Taxes	$732,000	(CC) X	4.0%		
Freight	$915,000	(CC) X	5.0%		
Total purchased equipment cost (PEC)	$19,943,000				
Direct installation costs					
Foundation & supports	$598,000	(PEC) X	3.0%		
Handling & erection	$3,989,000	(PEC) X	20.0%		
Electrical	$2,991,000	(PEC) X	15.0%		
Piping	$399,000	(PEC) X	2.0%		
Insulation	$199,000	(PEC) X	1.0%		
Painting	$0	(PEC) X	0.0%		
Demolition	$499,000	(PEC) X	2.5%		
Relocation	$399,000	(PEC) X	2.0%		
Total direct installation costs (DIC)	$9,074,000				
Site preparation	$0	N/A			
Buildings	$0	N/A			
Total direct costs (DC) = (PEC) + (DIC)	$29,017,000				
Indirect Costs					
Engineering	$2,902,000	(DC) X	10.0%		
Owner's cost	$1,451,000	(DC) X	5.0%		
Construction management	$2,902,000	(DC) X	10.0%		
Start-up and spare parts	$1,451,000	(DC) X	5.0%		
Performance test	$100,000	Engineering estimate			
Contingencies	$4,353,000	(DC) X	15.0%		
Total indirect costs (IC)	$13,159,000				
Allowance for Funds Used During Construction (AFDC)	$1,265,000	[(DC)+(IC)] X	6.00%	1 years (project time length)	
Total Capital Investment (TCI) = (DC) + (IC) + (AFDC)	$43,441,000				
ANNUAL COST					
Direct Annual Costs					
Fixed annual costs					
Operating labor	$107,000		1 FTE and	106,893 $/yr	Fully-loaded labor rate
Maintenance materials and labor	$871,000	(DC) X	3.0%		
Total fixed annual costs	$978,000				
Variable annual costs					
Replacement power due to efficiency hit	$0	Engineering estimates, 0.2% efficiency drop, and 0.015 $/kWh			
Reagent	$2,352,000		1,894 lb/hr and	315 $/ton	
Auxiliary power	$77,000		648 kW and	0.015 $/kWh	
Water	$179,000		200 gpm and	2 $/1,000 gal	
Total variable annual costs	$2,608,000				
Total direct annual costs (DAC)	$3,586,000				
Indirect Annual Costs					
Cost for capital recovery	$3,779,000	(TCI) X	8.70%	CRF at 6% interest & 20 year life	
Total indirect annual costs (IDAC)	$3,779,000				
Total Annual Cost (TAC) = (DAC) + (IDAC)	$7,365,000				

BEPC Laramie River BART Engineering Analysis - Cost Analysis (Revision) - in 2007$

Technology: SNCR/SCR Hybrid

Date: 5/8/2008

Cost Item	$	Remarks/Cost Basis			
CAPITAL COST					
Direct Costs					
Purchased equipment costs					
Reagent storage, handling, injection & controls	$7,000,000	vendor quote, 10/06			
Complete SCR cost	$13,077,000	from ref. cost			
Initial urea inventory	$67,000	45,000 gal. urea initial inventory			
Subtotal capital cost (CC)	$20,144,000				
Taxes	$806,000	(CC) X	4.0%		
Freight	$1,007,000	(CC) X	5.0%		
Total purchased equipment cost (PEC)	$21,957,000				
Direct installation costs					
Foundation & supports	$2,196,000	(PEC) X	10.0%		
Handling & erection	$2,196,000	(PEC) X	10.0%		
Electrical	$2,196,000	(PEC) X	10.0%		
Piping	$659,000	(PEC) X	3.0%		
Insulation	$110,000	(PEC) X	0.5%		
Painting	$44,000	(PEC) X	0.2%		
Demolition	$878,000	(PEC) X	4.0%		
Relocation	$878,000	(PEC) X	4.0%		
Total direct installation costs (DIC)	$9,157,000				
Site preparation	$0	N/A			
Buildings	$0	N/A			
Total direct costs (DC) = (PEC) + (DIC)	$31,114,000				
Indirect Costs					
Engineering	$2,178,000	(DC) X	7.0%		
Owner's cost	$1,556,000	(DC) X	5.0%		
Construction management	$3,111,000	(DC) X	10.0%		
Start-up and spare parts	$933,000	(DC) X	3.0%		
Performance test	$100,000	Engineering estimate			
Contingencies	$4,667,000	(DC) X	15.0%		
Total indirect costs (IC)	$12,545,000				
Allowance for Funds Used During Construction (AFDC)	$1,310,000	[(DC)+(IC)] X	6.00%	1 years (project time length)	
Total Capital Investment (TCI) = (DC) + (IC) + (AFDC)	$44,969,000				
ANNUAL COST					
Direct Annual Costs					
Fixed annual costs					
Operating labor	$107,000		1 FTE and	106,893 $/yr	Fully-loaded labor rate
Maintenance labor and materials	$933,000	(DC) X	3.0%		
Total fixed annual costs	$1,040,000				
Variable annual costs					
Reagent	$2,221,000		1,894 lb/hr and	315 $/ton	
Auxiliary and ID fan power	$77,000		648 kW and	0.015 $/kWh	
Water	$179,000		200 gpm and	2 $/1,000 gal	
Total variable annual costs	$2,477,000				
Total direct annual costs (DAC)	$3,517,000				
Indirect Annual Costs					
Cost for capital recovery	$3,912,000	(TCI) X	8.70%	CRF at 6% interest & 20 year life	
Total indirect annual costs (IDAC)	$3,912,000				
Total Annual Cost (TAC) = (DAC) + (IDAC)	$7,429,000				

BEPC Laramie River BART Engineering Analysis - Cost Analysis (Draft)

Technology: Selective Catalytic Reduction

Date: 5/6/2008

Cost Item	$	Remarks/Cost Basis			
CAPITAL COST					
Direct Costs					
Purchased equipment costs					
Anhydrous Ammonia System	$2,481,000	from ref. cost			
Expansion Joints	$1,887,000	from ref. cost			
SCR Reactor & Ductwork	$4,871,000	from ref. cost			
Catalyst	$4,487,000	from vendor quote			
Sonic Horns	$115,000	from ref. cost			
Hoists & Conveyors	$182,000	from ref. cost			
Elevator	$1,200,000	from ref. cost			
ID Fans	$6,334,000	B&V Estimate			
Ash Handling	$176,000	from ref. cost			
NOx Monitoring System	$440,000	from ref. cost			
Electrical	$2,398,000	from ref. cost			
Piping	$822,000	from ref. cost			
Support Steel	$4,723,000	from ref. cost			
Instrumentation and Controls	$1,309,000	from ref. cost			
SubTotal capital cost (CC)	$31,425,000	from ref. cost			
Taxes	$1,257,000	(CC) X	4.0%		
Freight	$1,571,000	(CC) X	5.0%		
Total purchased equipment cost (PEC)	$34,253,000				
Direct Installation costs					
Foundation & supports	$11,988,550	(PEC) X	35.0%		
Handling & erection	$11,988,550	(PEC) X	35.0%		
Electrical	$8,563,250	(PEC) X	25.0%		
Piping	$1,712,650	(PEC) X	5.0%		
Insulation	$3,425,300	(PEC) X	10.0%		
Painting	$342,530	(PEC) X	1.0%		
Demolition	$3,425,300	(PEC) X	10.0%		
Relocation	$2,397,710	(PEC) X	7.0%		
Total direct installation costs (DIC)	$43,844,000				
Site preparation	$2,000,000	Engineering estimate			
Buildings	$500,000	Engineering estimate			
Total direct costs (DC) = (PEC) + (DIC)	$80,597,000				
Indirect Costs					
Engineering	$5,642,000	(DC) X	7.0%		
Owner's cost	$4,030,000	(DC) X	5.0%		
Construction Management	$8,060,000	(DC) X	10.0%		
Start-up and spare parts	$2,418,000	(DC) X	3.0%		
Performance test	$100,000	Engineering estimate			
Contingencies	$12,090,000	(DC) X	15.0%		
Total Indirect costs (IC)	$32,340,000				
Allowance for Funds Used During Construction (AFDC)	$10,164,000	[(DC)+(IC)] X	6.0%	for	3 year(s)
Total Capital Investment (TCI) = (DC) + (IC) + (AFDC)	$123,101,000				
ANNUAL COST					
Direct Annual Cost					
Fixed annual costs					
Operating labor	$107,000	1	FTE and	106,893 $/yr	Fully-loaded labor rate
Maintenance materials and labor	$2,418,000	(DC) X	3.0%		
Yearly Emissions Test	$25,000	Engineering estimate			
Catalyst Activity Testing	$5,000	Engineering estimate			
Fly Ash Sampling and Analysis	$20,000	Engineering estimate			
Total fixed annual costs	$2,575,000				
Variable annual costs					
Reagent	$1,030,000	581	lb/hr and	450 $/ton	
Auxiliary and ID fan power	$414,000	4,769	kW and	0.015 $/kWh	
Catalyst replacement	$1,057,000	199	m3 and	5,300 $/m3	3yr replacement rate
Catalyst disposal	$1,000	213,993	lb and	10 $/ton	
Total variable annual costs	$2,502,000				
Total direct annual costs (DAC)	$5,077,000				
Indirect Annual Costs					
Cost for capital recovery	$10,710,000	(TCI) X	8.70%	CRF at 6% interest & 20 year life	
Total indirect annual costs (IDAC)	$10,710,000				
Total Annual Cost (TAC) = (DAC) + (IDAC)	$15,787,000				

Attachment 2

NH_3 Monitoring in the Upper Green River Basin, Wyoming

Extended Abstract #70

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INTRODUCTION

A long term ammonia air monitoring study was initiated in December, 2006 at Boulder, Wyoming, by Shell Exploration & Production Company. The monitoring site is located in the Upper Green River Basin of western Wyoming southwest of the Bridger Wilderness, a Class I area with an IMPROVE monitoring site. This region is experiencing rapid development of natural gas resources with possible consequences of air quality and visibility impacts in the Bridger Wilderness. Only very limited short-term ammonia measurements were previously available for this region. Thus, the primary objective of this study is to characterize the local airborne nitrogen budget and, specifically, ammonia concentrations and concentrations of related gases and particles in the basin for at least one year. Gaseous and particulate samples were collected twice per week (integrated 3-day and 4-day samples) beginning December 15, 2006 and will continue through May, 2008. Samples were collected using coated annular denuders and stacked filters in a University Research Glassworks (URG) sampler. The Colorado State University Atmospheric Science Department provided laboratory-prepared sample media and laboratory analysis for gas and particle concentrations. Standard operating procedures, technical instructions, and a QAPP for instrument installation, operation and maintenance, field sampling, filter handling, and laboratory analyses were developed and submitted to Wyoming Department of Environmental Quality – Air Quality Division.

MONITORING AND LABORATORY PROCEDURES

Table 1 lists the instrumentation used and parameters monitored for the Boulder station ammonia study. Scheduled denuder and filter changes were performed twice per week, providing three- to four-day integrated samples for the duration of the study period. Ammonia concentrations and the concentrations of related gases and particles were measured using coated annular denuders and stacked filters in a University Research Glassworks (URG) sampler. The Colorado State University Atmospheric Science Department provided laboratory-prepared sample media and laboratory analysis for gas and particle concentrations. The two-channel sampler operated continuously, the air flow being controlled by a programmable pump with a mass flow sensor, and subsequent volumetric gas flow meters. The sampling method requires that metered air is drawn through a $PM_{2.5}$ size selective cyclone inlet, then through a series of annular denuders and filters. The denuders are coated with an acid-based substrate to collect ammonia gas. A second denuder is coated with NaCl to collect gaseous nitric acid. A subsequent stack of two filters is utilized to collect particles. A nylon filter collects particles, and a second, acid-coated filter collects any ammonia volatilized from collected, semi-volatile ammonium nitrate particles. The nylon filter retains any nitric acid volatilized from particulate ammonium nitrate. Following field exposure, the denuders, filters, and field data logs are sent to the CSU lab for chemical extraction and analysis. Total sampler air volume from the data sheet is then used to calculate concentrations.

Table 1: Instrumentation and Monitored Parameters Boulder, Wyoming Air Quality Station

Component	Instrumentation	Height	Frequency	Parameters
GASEOUS	URG denuders	1.5m	3-day and 4-day integrated samples	Ammonia, NH_3 Nitric Acid, HNO_3
PARTICULATE	URG stacked filters	1.5m	3-day and 4-day integrated samples	Ammonium, NH_4^+ Nitrate, NO_3^- Sulfate, SO_4^{2-}

RESULTS

Figure 1 shows a timeline of gaseous and particulate concentrations from December, 2006 – January, 2008. Figure 2 plots the monthly mean, standard deviation, minimum, and maximum NH_3 concentrations. NH_3 concentrations are below 1 ppbv for most of the monitoring period, peaking in August, 2007 at 1.55 ppbv. Elevated NH_3 concentrations here coincide with warmer summer months. A shift in ammonium nitrate equilibrium toward the gas phase might be responsible for some of this increase, although an increase in total reduced nitrogen (ammonium + ammonia) during the summer suggests that changes in emissions and or transport patterns are likely also important contributors.

Figure 1: Timeline of measured concentrations.

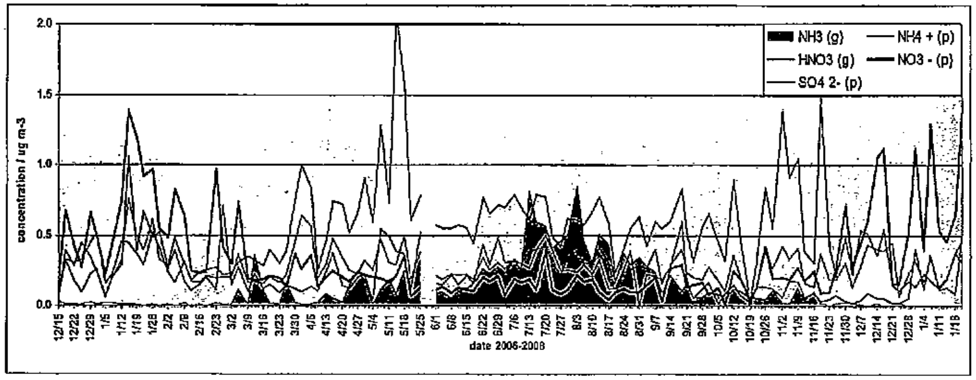
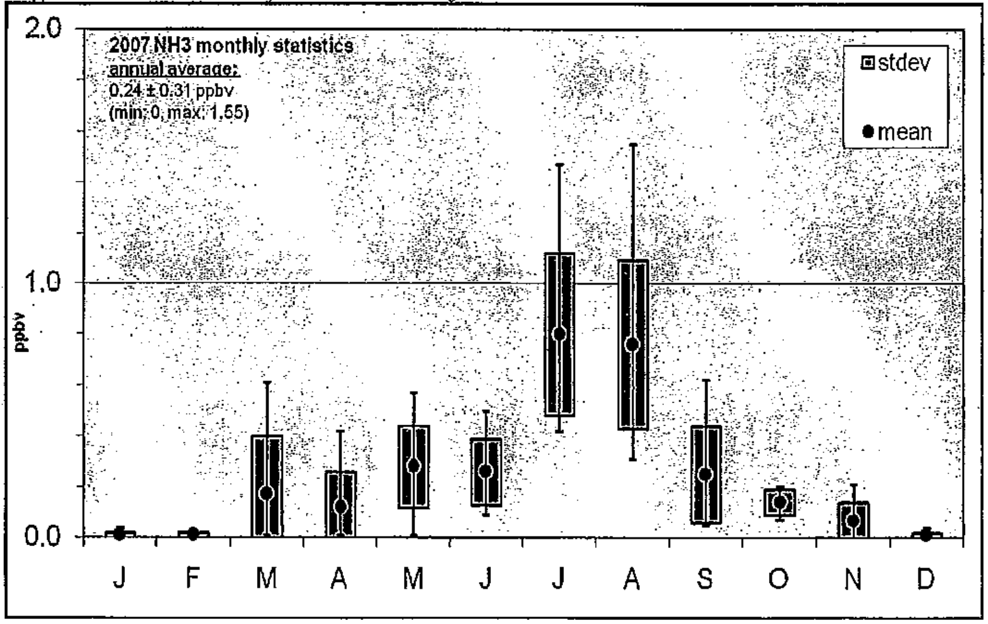


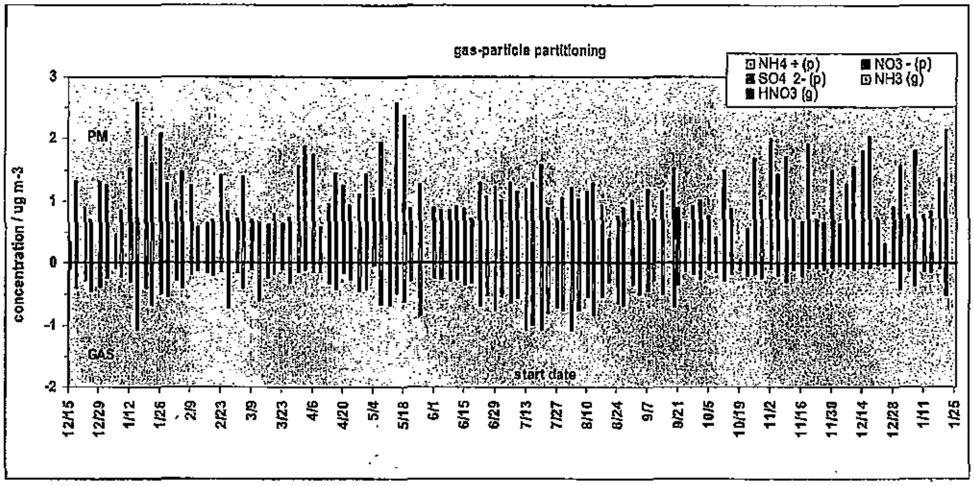
Figure 2: 2007 monthly and annual NH_3 concentration data



Three events stand out: high particulate NO_3^- in January, 2007; high particulate NO_3^- in December, 2007 – January, 2008; and high particulate SO_4^{-2} in May, 2007. The winter nitrate events are interesting as all reduced nitrogen is present as particle phase ammonium while considerable nitric acid remains in the gas phase. Sufficient increases in ammonia emissions during this period could have substantially increased $PM_{2.5}$ concentrations by further ammonium nitrate formation.

Figure 3 displays a timeline of the gas/particle partitioning of the measured species for the same time period. Particulate sulfate (red) dominates throughout most of the year. Reduced nitrogen (green bars) shows an increased partitioning into the gas phase (ammonium to ammonia). Increased particulate nitrate in late winter is consistent with thermodynamic expectations: ammonium nitrate formation is favored at lower temperatures and higher relative humidities.

Figure 3: Timeline of gas-particle partitioning. Concentrations in µg/m^3, top bar stack for particles, bottom bar stack for gases.



RESIDENCE TIME ANALYSIS

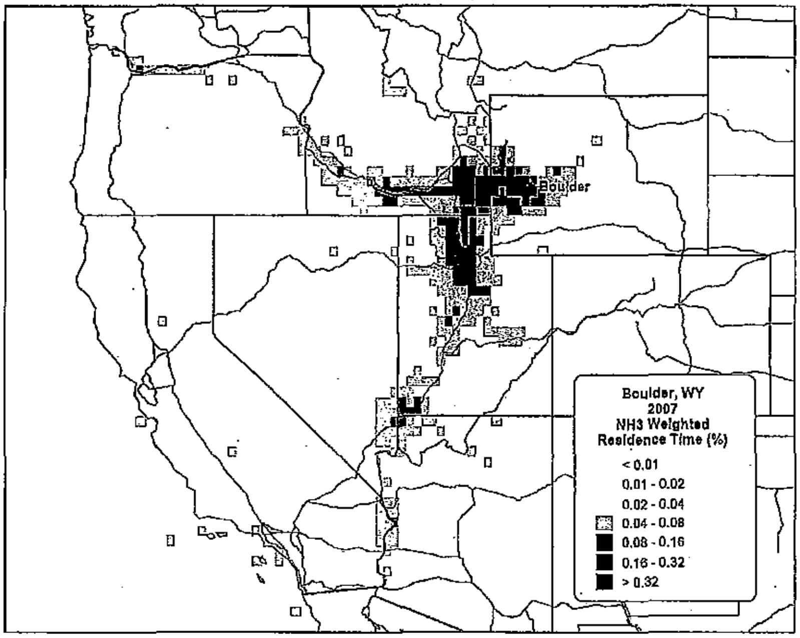
Ammonia weighted back trajectories were used to identify the geographic source areas most likely to contribute to the highest measured ammonia days. Back trajectory analyses use interpolated measured or modeled meteorological fields to estimate the most likely central path over geographical areas that provided air to a receptor at a given time. The method essentially follows a parcel of air backward in hourly steps for a specified length of time. Back trajectories account for the impact of wind direction and wind speed on delivery of emissions to the receptor, but do not account for chemical transformation, dispersion and deposition of emissions.

Trajectories were generated using the Hybrid-Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model developed by the National Oceanic and Atmospheric Administration's (NOAA) Air Resources Laboratory (ARL). Detailed information regarding the trajectory model and these data sets can be found on NOAA's Web site (http://www.arl.noaa.gov/ready/hysplit4.html).

Three back trajectories were generated per day, including end times of 0400, 1200 and 2000 MST and end heights of 100 m. Each hourly point along a 72-hour back trajectory paths was weighted with measured ammonia concentration corresponding to the end date of each trajectory. The ammonia values associated with each hourly point were then summed and normalized into 1/4 degree horizontal grid cells of latitude and longitude.

Figure 4 presents a map of the ammonia weighted residence time for 2007. One path of influence follows the Snake River from Idaho to the Columbia River. This is a significant agriculture region. Another distinct path is from the South-Southwest along I-15 to Nevada then along the Colorado River. In addition to the major urban areas of Salt Lake City and Las Vegas, this pathway includes the agriculture regions of Star Valley north of Salt Lake City, the Wasatch front in Utah, and the Colorado River Basin.

Figure 4: NH_3 weighted residence time analysis for 2007.



SUMMARY

A 15 month study in the Upper Green River Basin of Wyoming measuring ammonia and nitric acid gasses and ammonium, nitrate, and sulfate particles has been completed. The results of the study show that in the Upper Green River Basin of Wyoming 2007 ammonia concentrations are (1) quite variable throughout the year, (2) are below or near detectable limits from December through late February, (3) peak in August at 1.55 ppbv, and (4) have a yearly mean value of 0.24 ppbv. NH_3 weighted Residence time analysis indicates that much of the NH_3 present is transported into the region from agriculture and urban areas to the West and Southwest.

Attachment 3

- Summary
- BRAVO ion Paper dated May 2004
- LAWFR final report dated August 22, 2003
- Ammonia Data
- Addendum to Modeling Protocol for the Proposed Desert Rock Generating Station dated January 2006
- Colorado Department of Public Health and Environment – CALMET/CALPUFF Modeling Protocol dated October 24, 2005 (Ammonia Sensitivity Tests)

Summary

The attached documents were sent to the National Park Service in conjunction with their approval of the monthly ammonia data for the Desert Rock and the Toquop PSD projects. One document is a modeling protocol addendum for Desert Rock project that explains the procedure; it was provided to the reviewing agencies on January 19, 2006. The ammonia data used as part of the justification is also attached, along with two papers discussing measurement techniques for Big Bend and Grand Canyon National Parks..

BRAVO ion Paper dated May 2004

TECHNICAL PAPER

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Aerosol Ion Characteristics During the Big Bend Regional Aerosol and Visibility Observational Study

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ABSTRACT

The ionic compositions of particulate matter with aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) and size-resolved aerosol particles were measured in Big Bend National Park, Texas, during the 1999 Big Bend Regional Aerosol and Visibility Observational study. The ionic composition of $PM_{2.5}$ aerosol was dominated by sulfate (SO_4^{2-}) and ammonium (NH_4^+). Daily average SO_4^{2-} and NH_4^+ concentrations were strongly correlated ($R^2 = 0.94$). The molar ratio of NH_4^+ to SO_4^{2-} averaged 1.54, consistent with concurrent measurements of aerosol acidity. The aerosol was observed to be comprised of a submicron fine mode consisting primarily of ammoniated SO_4^{2-} and a coarse particle mode containing nitrate (NO_3^-). The NO_3^- appears to be primarily associated with sea salt particles where chloride has been replaced by NO_3^-, although formation of calcium nitrate ($Ca(NO_3)_2$) is important, too, on several days. Size-resolved aerosol composition results reveal that a size cut in particulate matter with aerodynamic diameter ≤1 μm would have provided a much better separation of fine and coarse aerosol modes than the standard $PM_{2.5}$ size cut utilized for the study. Although considerable nitric acid exists in the gas phase at Big Bend, the aerosol is sufficiently acidic and temperatures sufficiently high that even significant future reductions in $PM_{2.5}$ SO_4^{2-} are unlikely to be offset by formation of particulate ammonium nitrate in summer or fall.

IMPLICATIONS

Aerosol particles in Big Bend National Park during summer and fall include an external mixture of submicron, acidic partially ammoniated SO_4^{2-} particles and supermicron sodium nitrate or $Ca(NO_3)_2$ particles. The NO_3^- is present as a result of reactions of nitric acid or its precursors with sea salt or soil dust. The division between the two aerosol modes is at ~1 μm, such that $PM_{2.5}$ samples include a significant part of the coarse mode tail. The acidity of the SO_4^{2-} aerosol and the importance of sodium nitrate and $Ca(NO_3)_2$ particles should be considered when examining aerosol hygroscopicity and aerosol contributions to regional haze.

INTRODUCTION

The Big Bend Regional Aerosol and Visibility Observational (BRAVO) study was conducted in the region surrounding Big Bend National Park during 4 months from July to October, 1999. Despite its remote location, Big Bend National Park frequently experiences poor visibility caused by long-range pollutant transport.[1] Big Bend National Park, located on the Rio Grande River on the Texas–Mexico border, is designated a Class I area.[2,3] The Interagency Monitoring of Protected Visual Environments (IMPROVE) network and earlier networks have included measurements at Big Bend since 1982.

A 1996 study found that sulfate (SO_4^{2-}) was the major contributor to fine particle mass and the largest contributor to visibility degradation in Big Bend National Park.[4] The highest fine particulate SO_4^{2-} concentrations were observed in summer and autumn; however, no information was available from this earlier study regarding the size distribution or acidity of the SO_4^{2-} aerosol. The size of the SO_4^{2-} particles has a strong effect on their light-scattering efficiency. Likewise, the acidity of the SO_4^{2-} aerosol strongly affects its hygroscopicity and, hence, the amount of water on the particles at a given humidity. More acidic forms of SO_4^{2-} (e.g., ammonium bisulfate [NH_3HSO_4], letovicite, or sulfuric acid [H_2SO_4]) take up liquid water at much lower relative humidities than ammonium sulfate (($(NH_4)_2SO_4$)).[5–7] Addition of water to SO_4^{2-}-containing particles is an important factor governing their masses and scattering efficiencies and, therefore, their impact on visibility degradation.

Organic carbon and soil-derived aerosol particles were observed to contribute significantly to visibility degradation in Big Bend National Park as well, although their contributions were typically much smaller than that observed for SO_4^{2-}.[1] The highest contributions of organic carbon are observed during the spring when agriculture-related biomass burning in Mexico is suspected to be a primary source.[4,8] The presence of soil and dust particles was associated with local emissions as well as with suspected Saharan dust episodes in July and August.[4]

To improve understanding of the visibility-degrading properties and sources of aerosol particles in Big Bend

National Park, the 4-month BRAVO study was conducted during summer and fall 1999. As part of BRAVO, a series of special aerosol characterization studies was conducted in the park itself to provide detailed information about the physical and chemical properties of the aerosol particles. These included a determination of the particle size distribution,[9] characterization of the organic composition of the aerosol,[10] and a detailed investigation of aerosol ionic chemical composition. The objective of this work is to examine the aerosol ionic chemical composition, focusing on examination of aerosol acidity, major ion concentrations in particulate matter with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$), and aerosol ion size distributions.

EXPERIMENTAL PROCEDURES

The BRAVO study (www2.nature.nps.gov/ait/studies/bravo/index.html) was conducted during July 1–October 31, 1999. A network of ~40 sites was used to measure aerosol properties following the IMPROVE protocol. More detailed measurements of aerosol composition were conducted at the K-Bar ranch site inside Big Bend National Park.

Concentrations of aerosol ions at the K-Bar site were measured in daily 24-hr $PM_{2.5}$ samples collected with an annular denuder/filter-pack system manufactured by URG. Ambient air was drawn through a cyclone (D_{50} = 2.5 μm) and through two coated annular denuders (242 mm) in series to collect the gaseous species of interest. Sodium chloride (NaCl [0.1%]) coated the first denuder for collection of nitric acid (HNO_3), and the second denuder was coated with 0.5 g citric acid in 50 mL of methanol to collect ambient ammonia (NH_3). Pre-filter collection of NH_3 helps preserve acidic aerosol samples.[11] The remaining airstream was then filtered through 47-mm diameter Teflon and nylon filters in series. The Teflon filter (Gelman Teflo, 2-μm pore size) was used to collect particulate matter (PM). The nylon membrane filter (Gelman Nylasorb) was used to capture any HNO_3 volatilized from PM on the Teflon filter. Samples were collected from 8:00 a.m. to 8:00 p.m. central daylight time with a nominal flow rate of 10 L/min. Flow was controlled by a mass flow controller and the actual sample volume was monitored using a dry gas meter with appropriate correction for system pressure drop. Two URG systems were operated to permit rapid daily sample changeover, collection of replicate samples (on selected days), and regular collection of system blanks.

Daily 24-hr impactor samples were also collected using a Micro-Orifice Uniform Deposit Impactor (MOUDI). The largest eight stages of the MOUDI were used, corresponding to the following aerodynamic diameter size ranges: 18–10 μm, 10–5.6 μm, 5.6–3.2 μm, 3.2–1.8 μm, 1.8–1 μm, 1–0.56 μm, 0.56–0.32 μm, and 0.32–0.18 μm. Additionally, there was an initial stage that collected particles with aerodynamic diameter >18 μm. The MOUDI stages used in the study were selected to provide good coverage of the expected ion size distributions and to avoid potential clogging issues associated with use of stages with smaller size cuts. Samples were collected on greased aluminum foil impaction surfaces[12] to reduce particle bounce. The MOUDI impactor was operated 6 days each week, with the seventh day used for impactor cleaning and collection of a sampler blank.

Analysis of the collected aerosol samples focused on quantification of the main ionic species: chloride (Cl^-), SO_4^{2-}, nitrate (NO_3^-), sodium (Na^+), ammonium (NH_4^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}). $PM_{2.5}$ and denuder samples were extracted and analyzed on-site to minimize potential artifacts (e.g., neutralization) associated with sample storage and shipping. Samples were loaded and unloaded in an NH_3-free glove box to further minimize potential artifact neutralization. Ion analysis was completed on two Dionex DX-500 ion chromatographs set up in a trailer at the field site. A Dionex AG4A-SC guard column, an AS4A-SC separation column, and a self-regenerating anion suppressor were used to measure anion concentrations. Cations were measured using a Dionex CG12A guard column, a CS12A separation column, and a self-regenerating cation suppressor. Detection was by conductivity in both cases. Both ion chromatographs were calibrated daily using a series of standards prepared from analytical-grade salts. Replicate injections and analysis of independent National Institute of Science and Technology-traceable standards were used to establish measurement precision and accuracy.

$PM_{2.5}$ and denuder samples were generally extracted twice per week, with cation and anion analyses usually conducted once per week. Denuders were extracted with 10 mL deionized water freshly prepared on-site. The nylon membrane filter was extracted using 6 mL of ion chromatographic anion eluent (1.8 mM sodium carbonate (Na_2CO_3)/1.7 mM $NaHCO_3$). Each Teflo filter was extracted with 5.85 mL of 10^{-4} N perchloric acid ($HClO_4$) solution with 150 μL of ethanol added first to wet the filter. pH measurements (Orion model 250A portable pH meter equipped with a Ross Sure-Flow combination pH electrode calibrated with pH 4 and 7 buffers and a series of H_2SO_4 solutions) of the $PM_{2.5}$ extracts were made immediately after extraction to measure strong aerosol acidity. The background acidity from the $HClO_4$ extract solution inhibits dissolution of carbon dioxide (CO_2) and other weak acids to permit measurement of sample strong acidity. The hydrogen ion (H^+) concentration of a filter blank was subtracted from each filter extract concentration to determine the aerosol strong acidity contribution.

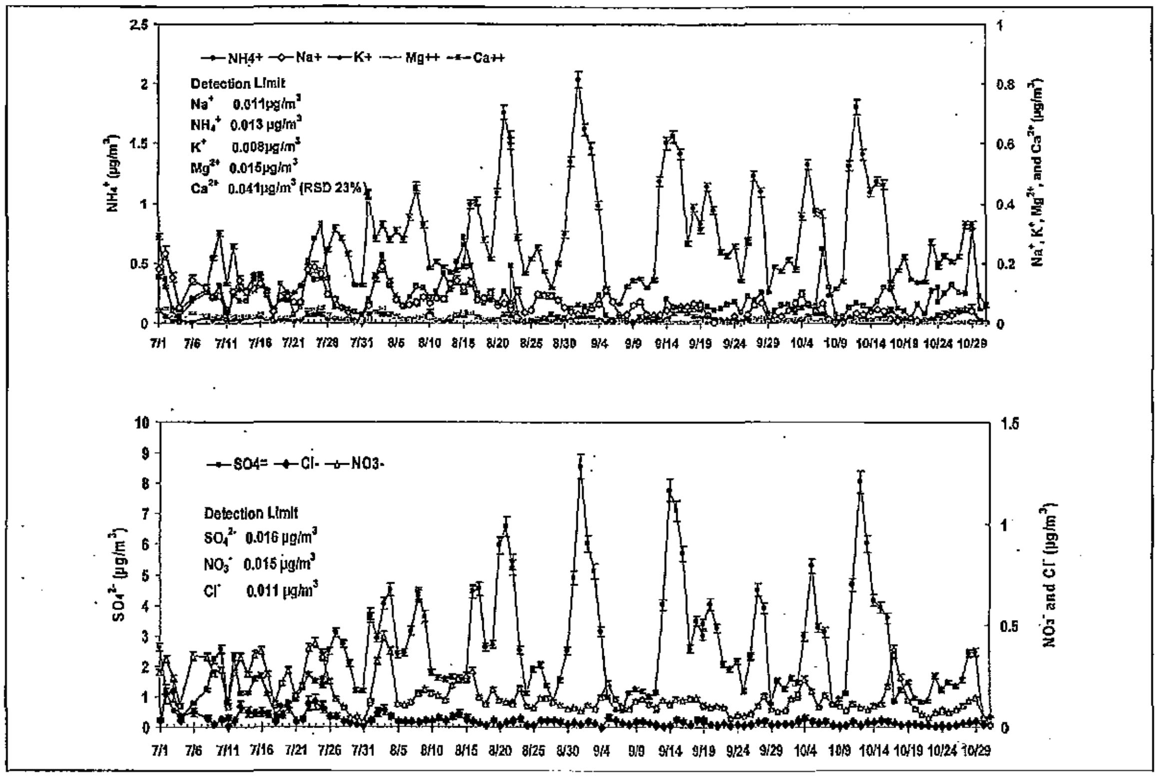

Figure 1. Timelines of major $PM_{2.5}$ ion concentrations. The error bars represent measurement precision (1 standard deviation).

MOUDI samples were stored frozen until later analysis in the laboratory at Colorado State University. Samples from 41 study days (plus several blanks) were analyzed. This subset of sample periods was selected based on interesting $PM_{2.5}$ aerosol composition measurements (e.g., high SO_4^{2-}, high NO_3^-, and suspected sea-salt days) and other BRAVO study results (particle size distributions and thermodynamic modeling studies). MOUDI impactor substrates were extracted by sonication in deionized water ($HClO_4$ was not needed because acidity measurements were not made on these samples) and analyzed using the same ion chromatograph systems and approaches outlined previously.

Analysis of sample replicates and blanks permitted establishment of measurement precision and detection limits. Precisions for the major measured aerosol species (NO_3^-, SO_4^{2-}, NH_4^+, and H^+) were good with relative standard deviations (RSDs) in the range of 3–5%. RSDs for trace aerosol ions were higher, ranging from 12 to 23%. RSDs for replicate denuder measurements of HNO_3 and NH_3 were each 9%. RSDs for replicate sample analyses of MOUDI extracts were all below 6%.

$PM_{2.5}$ NO_3^- concentrations are reported as the sum of NO_3^- measured on the Teflo and the backup nylon filter. Further details of all sampling and analysis protocols, including copies of study Standard Operating Procedures are presented by Lee and Collett.[13]

RESULTS AND DISCUSSION

Study timelines of the major $PM_{2.5}$ ions and a statistical summary of concentrations of $PM_{2.5}$ ion components and gases are presented in Figure 1 and Table 1, respectively. SO_4^{2-} and NH_4^+ were the dominant ionic species in daily $PM_{2.5}$, with smaller contributions from NO_3^-, Na^+, and

Table 1. Statistical summary of $PM_{2.5}$ and gas compositions (µg/m³) measured using the URG sampler.

Species	Mean	Min	Max	Standard Deviation
HNO_3 (g)	0.545	1.555	0.084	0.341
NH_3 (g)	0.156	0.003	0.624	0.131
Cl^- (p)	0.033	0.002	0.177	0.029
SO_4^{2-} (p)	2.391	0.289	8.568	1.751
NO_3^- (p)	0.159	0.015	0.451	0.093
Na^+ (p)	0.063	0.002	0.234	0.047
NH_4^+ (p)	0.651	0.102	2.037	0.415
K^+ (p)	0.018	0.002	0.055	0.011
Mg^{2+} (p)	0.013	0.001	0.052	0.012
Ca^{2+} (p)	0.082	0.003	0.329	0.068
H^+ (p) (nmol/m³)	13.08	0	75.56	14.27

other species. SO_4^{2-} concentrations were highest in the period from August to October, reaching as high as 8.5 μg/m^3. Daily average SO_4^{2-} and NH_4^+ concentrations were strongly correlated (R^2 = 0.94) as shown in Figure 2. $PM_{2.5}$ NO_3^- and SO_4^{2-} concentrations showed little correlation (R^2 = 0.05).

The aerosol was usually acidic, with an average $PM_{2.5}$ NH_4^+ to SO_4^{2-} molar ratio of 1.54 (standard deviation of 0.3). The ratios of NH_4^+ to SO_4^{2-} showed a trend consistent with the aerosol acidity measurements (see Figure 3). A high correlation between SO_4^{2-} and H^+ was observed (R^2 = 0.9) as shown in Figure 4. The average acidity measured during BRAVO was 13 nmol H^+/m^3 with a range of 0–75.6 nmol/m^3. These values are similar to aerosol acidities measured in previous midwestern U.S. studies in Portage, WI (average = 8 nmol/m^3, range = 0–78 nmol/m^3), St. Louis, MO (10, 0–122 nmol/m^3), and Chicago, IL (7.7, 0–78 nmol/m^3),[14–17] but somewhat lower than measured at eastern U.S. sites in Kingston, TN (36.1, 0–290 nmol/m^3) and Boston, MA (17.9, 1.3–84 nmol/m^3).[18,19] The most acidic BRAVO aerosol was observed during August, September, and the beginning of October, with 24-hr average concentrations in the range of 40–80 nmol/m^3 of H^+ on several days.

Both NO_3^- and NH_4^+ can partition between the gas and particle phases. The sum of gaseous NH_3 and particulate NH_4^+ comprise N in the minus three oxidation state (N(-III)). Likewise, the sum of gaseous HNO_3 and particulate NO_3^- comprise N(V). N(V) and N(-III) were found to exhibit quite different distributions between the particle and gas phases (see Figure 5). The average ratio for HNO_3(g)/N(V) was 0.73 and for NH_3(g)/N(-III) was 0.22. (These ratios do not reflect NO_3^- or NH_4^+ contained in particles with aerodynamic diameters larger than 2.5 μm.)

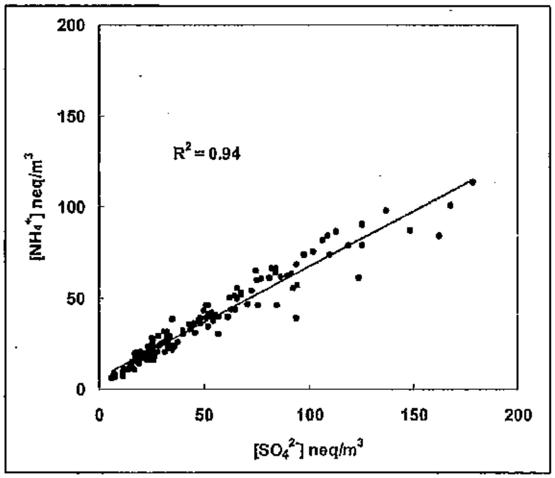

Figure 2. Relationship between NH_4^+ and SO_4^{2-} concentrations in BRAVO $PM_{2.5}$ aerosol.

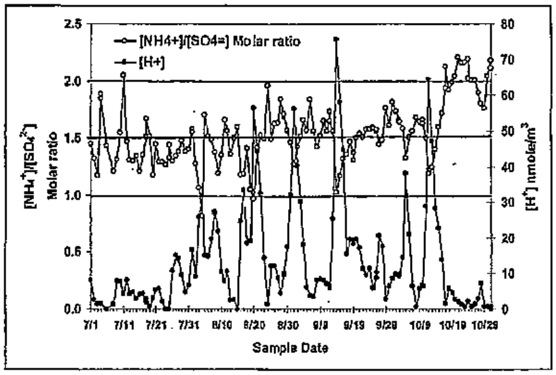

Figure 3. Timelines of the molar ratio of NH_4^+/SO_4^{2-} and the $PM_{2.5}$ H^+ concentration. As reference, horizontal lines are included at NH_4^+/SO_4^{2-} molar ratios of 1, 1.5, and 2 corresponding to the compositions of $(NH_4)_2SO_4$, letovicite, and NH_4HSO_4, respectively.

The implication is that most of the available N(-III) has been taken up into particles, while the majority of N(V) remains in the gas phase, representing potential for formation of additional particulate NO_3^-.

Back trajectory analysis revealed that days with high HNO_3 concentrations featured quite different transport from days with high $PM_{2.5}$ NO_3^-. High HNO_3 days were generally also high SO_4^{2-} days and typically featured transport from a sector extending east-southeast to northeast of Big Bend National Park. High $PM_{2.5}$ NO_3^- days, in contrast, typically featured transport from the southeast and across the Gulf of Mexico. These transport differences suggest that $PM_{2.5}$ NO_3^- concentrations are governed not by HNO_3 availability but by some other factor that promotes NO_3^- particle formation.

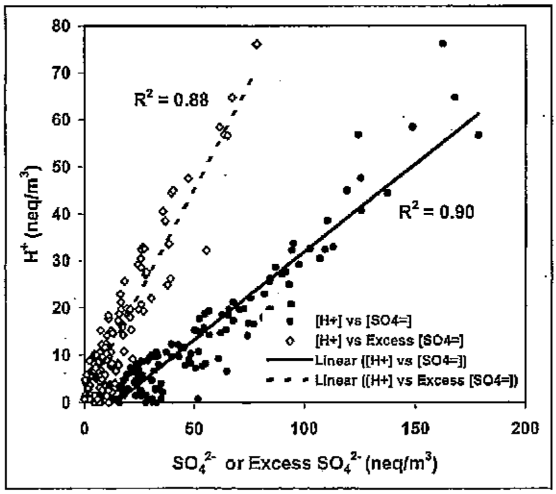

Figure 4. Relationships between H^+ and SO_4^{2-} and between H^+ and excess SO_4^{2-} in BRAVO $PM_{2.5}$ aerosol.

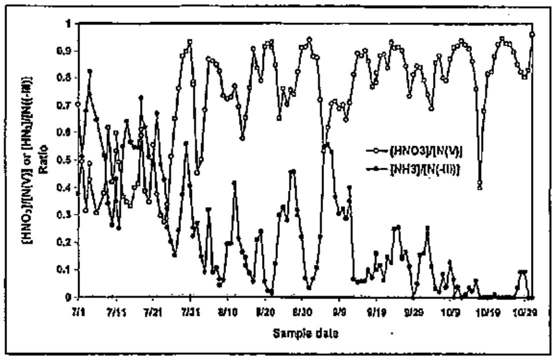

Figure 5. Timelines of ratios of HNO_3/N(V) and NH_3/N(-III). The particle components of N(V) and N(-III) in these ratios only include material measured in the $PM_{2.5}$ fraction.

Comparison of $PM_{2.5}$ Na^+ and Cl^- concentrations (see Figure 6) reveals that the observed Cl^-/Na^+ equivalent ratio (average ~0.33) is much lower than expected for sea salt (~1.16).[20] The combination of apparent Cl^- loss from sea salt and the observation that $PM_{2.5}$ NO_3^- concentrations peak during periods with transport from the Gulf region, suggests that HNO_3 reaction with sea salt is important. Indeed, if we examine the daily ratios of the sum of $PM_{2.5}$ NO_3^- and Cl^- to $PM_{2.5}$ Na^+, it is found that on many days they fall close to the ratio expected in aged sea salt (see Figure 6). This is consistent with the reaction of HNO_3 with sea salt, resulting in a stoichiometric loss of volatilized hydrochloric acid.[21] The correlation between NO_3^- and Na^+ is moderate ($R^2 = 0.64$), further suggesting the presence of sea salt aerosol as an important precursor to particulate NO_3^- formation in this environment. A weaker correlation was observed between NO_3^- and Ca^{2+} ($R^2 = 0.33$), suggesting that HNO_3 condensation onto dust particles might also exert some influence on aerosol NO_3^- formation. Occurrence of this reaction can account for why some ratios of (NO_3^- + Cl^-) to Na^+ fall above the sea salt line. This becomes clearer if the data are replotted as shown in Figure 7. Here, the observed ratio of (Cl^- + NO_3^-)/Na^+ is compared with the expected Cl^-/Na^+ sea salt ratio (shown as a horizontal line) as a function of the observed Ca^{2+}/Na^+ ratio. When the Ca^{2+}/Na^+ ratio is high, indicating a greater presence of dust than sea salt, the (NO_3^- + Cl^-)/Na^+ ratio tends to fall well above the sea salt ratio line, indicating that much more NO_3^- is present than can be accounted for by HNO_3 reaction with sea salt. Presumably, this reflects formation of $Ca(NO_3)_2$ or other HNO_3-dust reaction products. Recent laboratory tests[22] have demonstrated that reaction of HNO_3 with $CaCO_3$ particles occurs with a timescale on the order of hours, even at relative humidities as low as 17%. When the Ca^{2+}/Na^+ ratio is lower than ~3, indicating increased presence of sea salt (relative to dust), the points mainly fall close to the line, indicating that most NO_3^- probably is associated with reacted sea salt particles.

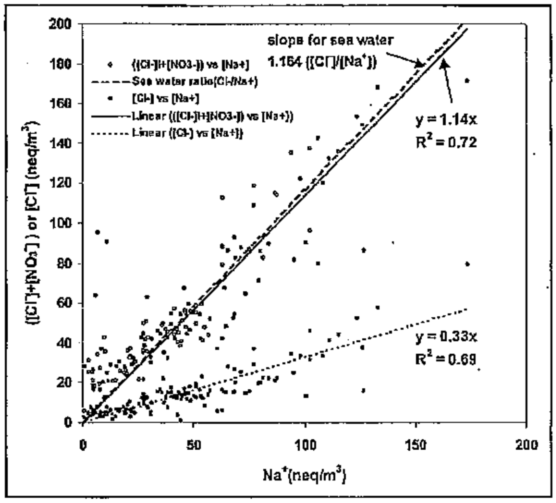

Figure 6. Relationship between Na^+ and Cl^- and between Na^+ and the sum of NO_3^- and Cl^-.

Further insight into the properties of BRAVO aerosol NO_3^-, as well as other species, is possible through examination of the MOUDI impactor results. Figure 8 depicts the average measured size distributions for SO_4^{2-}, NH_4^+, NO_3^-, Cl^-, Na^+, K^+, Mg^{2+}, and Ca^{2+}. These average distributions are representative of the general features of the distributions measured on the 41 selected MOUDI analysis days, although observed concentrations of the different ions changed (sometimes significantly) from day

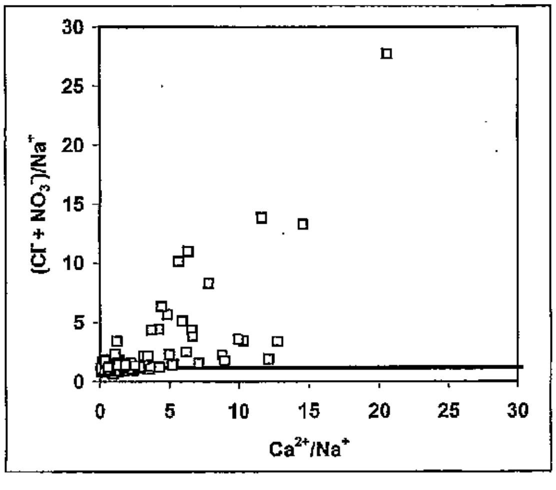

Figure 7. Comparison of the ratio of (NO_3^- + Cl^-)/Na^+ with the sea salt Cl^-/Na^+ ratio (indicated as horizontal line) as a function of the Ca^{2+}/Na^+ ratio. The figure does not include one sample at a Ca^{2+}/Na^+ ratio of 51, which also falls well above the sea salt ratio line. Units used for all species in these ratios were neq/m^3.

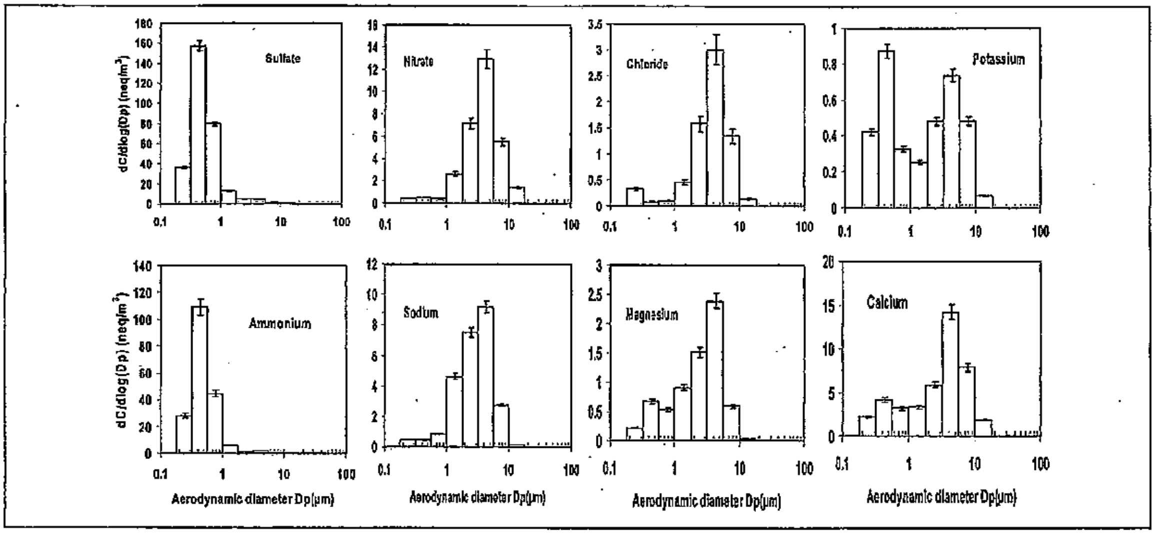

Figure 8. The average measured size distributions of inorganic ion concentrations. The error bars represent analytical precision (1 standard deviation).

to day. Integrated results for the submicron aerosol species (NH_4^+ and SO_4^{2-}) from the appropriate stages of the MOUDI impactor show excellent agreement with $PM_{2.5}$ concentrations measured using the URG sampler, providing confidence in the quality of the two data sets. A direct comparison is not possible for the other species, which are distributed over a broader size range, because of the lack of matching size cuts between the $PM_{2.5}$ sampler and MOUDI impactor, where the closest size cut is at 3.2 µm.

The MOUDI SO_4^{2-} and NH_4^+ size distributions exhibit very similar shapes, with a submicron mode typically peaked at 0.4–0.5 µm aerodynamic diameter. NO_3^-, by contrast, is found almost exclusively in a coarse particle mode, with a characteristic mode diameter of ~4–5 µm. (There are some days near the end of October where a small fine particle mode of what appears to be NH_4NO_3 was also observed; the presence of NH_4NO_3 during this period is consistent with the observation that the NH_4^+/SO_4^{2-} molar ratio climbed slightly above 2 (see Figure 3). The average NO_3^- size distribution has a shape very similar to the size distributions of sea salt components Na^+ and Cl^-, further supporting the interpretation that particulate NO_3^- in BRAVO was formed primarily as a result of HNO_3 (or other precursor nitrogen species) reaction with sea salt particles. Several days, however, were observed when the amount of NO_3^- found in coarse particles considerably exceeded the amount of Na^+. On these days, sufficient Ca^{2+} was present to account for the NO_3^-, consistent with the analysis presented in Figure 7. The bimodal nature of the average K^+ distribution is also interesting. Individual day samples in the first half of the study tended to contain mostly coarse-mode K^+, while distributions from days in September and October frequently contain both fine- and coarse-mode K^+.

The findings from the MOUDI size distribution measurements have several important implications. First, the coexistence of acidic, submicron ammoniated SO_4^{2-} particles with coarse-mode sea salt, reacted sea salt ($NaNO_3$), and dust particles indicates the aerosol is externally mixed, even within the $PM_{2.5}$ fraction. Second, the commonly made assumption that fine particle NO_3^- is present mainly as NH_4NO_3[2,3] is clearly not appropriate for BRAVO aerosol. The fact that the NO_3^- is present mainly in the form of coarse-mode $NaNO_3$ particles is important for understanding the hygroscopicity and refractive index of NO_3^- containing particles in this environment, topics addressed in some detail by Malm et al.[23] Significant formation of hygroscopic $Ca(NO_3)_2$[22] on some days is also of interest. Third, the MOUDI ion distribution measurements clearly show that a size cut at 1 µm aerodynamic diameter would provide a much better separation of the coarse and fine particle modes, a point also evident from the aerosol size distributions measured in the study and reported by Hand et al.[9] Use of a $PM_{2.5}$ size cut for the URG sampling, as well as for IMPROVE samplers running at the site, leads to inclusion of a substantial portion of the lower tail of the coarse-mode size distribution in fine particle ($PM_{2.5}$) samples.

If SO_4^{2-} concentrations at Big Bend were substantially reduced, for example, because of upwind reductions in SO_2 emissions, it is likely that the resulting aerosol would be less acidic. If the SO_4^{2-} concentrations were reduced far enough, sufficient NH_3 might be present to neutralize the SO_4^{2-} in the aerosol. Further SO_4^{2-} reductions beyond this neutralization point would leave some NH_3 available to react with HNO_3 to form particulate NH_4NO_3 (assuming total N(-III) concentrations do not change in response to SO_4^{2-} decreases). Because two NH_3 molecules

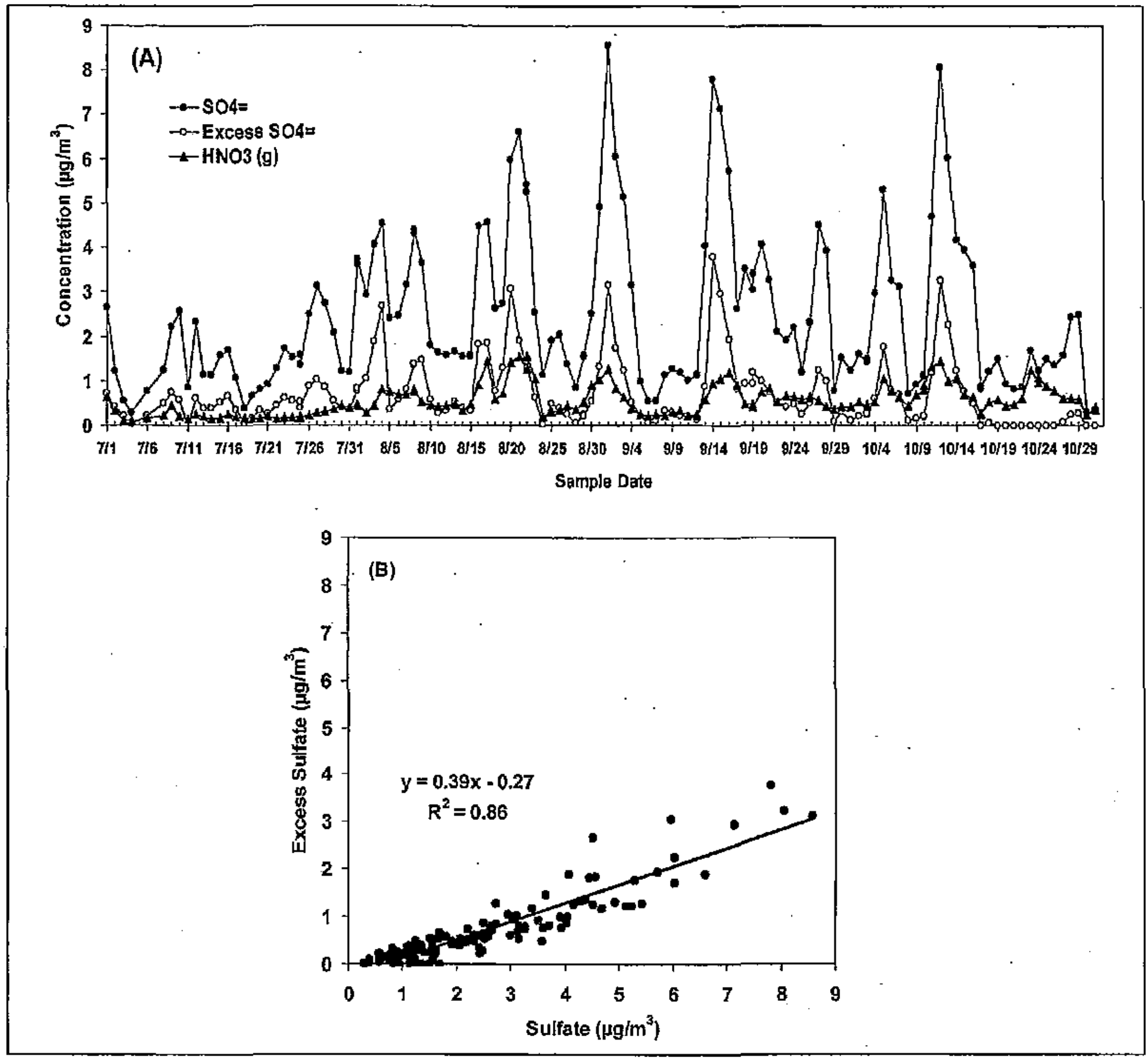

Figure 9. (a) Timelines of $PM_{2.5}$ SO_4^{2-}, excess SO_4^{2-}, and HNO_3(g) concentrations. (b) Relationship between excess SO_4^{2-} and SO_4^{2-} concentrations in BRAVO $PM_{2.5}$ aerosol.

are required to neutralize one SO_4^{2-} molecule, two NH_3 molecules can neutralize two HNO_3 molecules, and two NO_3^- molecules have greater mass than one SO_4^{2-} molecule, replacement of $(NH_4)_2SO_4$ by NH_4NO_3 has the potential under the right circumstances to actually produce an increase in $PM_{2.5}$ mass concentrations. West et al.[24] utilized model simulations of eastern U.S. aerosol composition to show that reductions in aerosol SO_4^{2-} concentrations may be up to 50% less effective in some locations at reducing annual average fine particle mass concentrations than if the role of HNO_3 is neglected. The effect was largest in winter, with up to half of the examined locations affected, but uncommon in summer because of higher temperatures that do not favor NH_4NO_3 formation. Much less is known about the potential for nonlinear responses in fine particle mass concentrations (resulting from SO_4^{2-} decreases) in western U.S. aerosol. This is in large part because of a lack of information about current western U.S. aerosol acidity and concentrations of key species including gaseous NH_3 and HNO_3.

The BRAVO data set provides an opportunity to consider whether hypothetical reductions in regional aerosol SO_4^{2-} concentrations might be less effective at decreasing $PM_{2.5}$ mass than expected because of NH_4NO_3 formation. To consider this issue, it is useful to determine the amount of "excess" SO_4^{2-} present in BRAVO aerosol, where "excess" SO_4^{2-} is defined as the concentration of SO_4^{2-} (expressed in equivalents) minus the concentration of NH_4^+ (i.e., the amount that SO_4^{2-} concentrations would have to be decreased for the aerosol to become neutralized, assuming particulate NH_4^+ concentrations remain unchanged). The BRAVO "excess" SO_4^{2-} timeline is shown in Figure 9A, along with timelines of $PM_{2.5}$ SO_4^{2-} and HNO_3(g). It is evident from the timelines that periods of high SO_4^{2-} concentration also feature high concentrations of "excess" SO_4^{2-}. This point is further made in Figure 9B where a strong correlation ($R^2 = 0.86$) is found to exist between "excess" SO_4^{2-} and SO_4^{2-}. When SO_4^{2-} concentrations are high, "excess" SO_4^{2-} concentrations are also high, indicating that considerable reductions in aerosol SO_4^{2-} concentrations could be made on these days before the aerosol became neutralized. Second, the high temperatures present during the summer and fall at Big Bend do not favor formation of NH_4NO_3, even if additional gaseous NH_3 is made available by SO_4^{2-} reductions. Last, even if all the available gaseous nitric were shifted to the particulate phase, the additional mass (see Figure 9A) would still be smaller during most periods than the SO_4^{2-} concentration decreases required to neutralize the aerosol. Accordingly, it appears that during summer and fall at Big Bend, SO_4^{2-} concentrations could be significantly decreased without much concern about nonlinear responses in fine particle mass concentrations.

ACKNOWLEDGMENTS

The authors thank D.E. Sherman, M.P. Hannigan, J.L. Hand, and J.E. Reilly for their contributions to the success of the field campaign. They are grateful to Air Resource Specialists for excellent field support before and during the campaign and to W. Malm for numerous helpful discussions. This study was funded by the National Park Service, grants CA238099001 TO 01-52 and CA238099001 TO 01-54. However, the results, findings, and conclusions expressed in this paper are solely those of the authors and are not necessarily endorsed by the management, sponsors, or collaborators of the BRAVO study. A comprehensive final report for the BRAVO study is anticipated in 2004.

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Possible future replacement of sulfate by nitrate in aerosols on the Colorado Plateau

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August 22, 2003

1. Introduction

The composition of atmospheric aerosols is determined in part by the nature of primary particle emissions and partly by the production of secondary atmospheric pollutants that condense to form particulate matter. Two important secondary pollutants are sulfates and nitrates, formed from the atmospheric oxidation of emissions of gaseous sulfur dioxide and nitrogen oxides, respectively (Seinfeld and Pandis, 1998).

Because the sulfuric acid produced by atmospheric oxidation of SO_2 has a very low equilibrium vapor pressure, it tends to partition mainly into atmospheric particles. This may happen either by condensation onto pre-existing particles or by new particle formation. In most environments sulfates are found primarily as constituents of submicron aerosol particles. They may be present as sulfuric acid or as partly or fully neutralized sulfate salts. Typically these are ammonium sulfate salts in the form of ammonium sulfate, ammonium bisulfate, letovicite, etc....

Nitric acid, produced by atmospheric oxidation of gaseous nitrogen oxides, is a gas phase species. In the presence of gaseous ammonia, however, the nitric acid and ammonia can combine to form particulate ammonium nitrate salts. This is a reversible reaction with an equilibrium that is strongly dependent on temperature and relative humidity (Seinfeld and Pandis, 1998); low temperatures and high humidities favor the formation of ammonium nitrate aerosol.

Understanding the propensity for ammonium nitrate aerosol formation also requires understanding the presence of acidic sulfate in the aerosol. For a system containing sulfuric acid, ammonia, and nitric acid, thermodynamic constraints favor the formation of ammonium sulfate salts prior to equilibrium formation of ammonium nitrate. In other words, if there is insufficient ammonia to fully neutralize the sulfate (a 2:1 molar ratio is required since two ammonia molecules pair with one sulfate to form fully neutralized $(NH_4)_2SO_4$), nitrate is not expected to coexist with the sulfate in submicron particles. If excess ammonia is available, however, ammonium nitrate can form.

As a result of decreasing SO_2 emissions in the U.S., attention has begun to focus increasingly on the nitrate fraction of atmospheric aerosols. In particular, concern has been expressed about the potential for replacement of sulfate by nitrate in fine aerosol particles. If sulfate concentrations at a receptor site with an acidic aerosol were substantially reduced, due for example to upwind reductions in SO_2 emissions, it is likely that the resulting aerosol would be less acidic. If the sulfate concentrations were reduced far enough, sufficient ammonia might be present to neutralize the sulfate in the aerosol. Further sulfate reductions beyond this neutralization point would leave some ammonia available to react with nitric acid to form particulate ammonium nitrate (assuming total N(-III) concentrations do not change in response to sulfate decreases). Because two ammonia molecules are required to neutralize one sulfate molecule, two ammonia molecules can neutralize two nitric acid molecules, and two nitrate molecules have greater mass than one sulfate molecule, replacement of $(NH_4)_2SO_4$ by NH_4NO_3 has the potential under the right circumstances to actually produce an increase in $PM_{2.5}$ mass concentrations.

West et al. (2000) utilized model simulations of eastern U.S. aerosol composition to show that reductions in aerosol sulfate concentrations may be up to 50% less effective at reducing annual average fine particle mass concentrations than if the role of nitric acid is neglected. The reduced effectiveness comes from increased formation of ammonium nitrate. The effect was largest in winter, with up to half of the examined locations affected, but uncommon in summer due to higher temperatures which do not favor NH_4NO_3 formation.

Much less is known about the potential for nonlinear responses in fine particle mass concentrations (resulting from sulfate decreases) in western U.S. aerosol. This is in large part due to a lack of information about current western U.S. aerosol acidity and concentrations of key species including gaseous ammonia and nitric acid. Although the IMPROVE monitoring network makes routine measurements of aerosol composition at many locations in the western U.S., it does not measure concentrations of all the aerosol and gas phase species needed to examine the aerosol/gas partitioning of nitrate and the sensitivity of this partitioning to sulfate concentrations. These issues are, however, sometimes addressed in special studies sponsored by the National Park Service and other agencies..

The ionic composition of aerosol particles was studied in detail at Big Bend N.P. during the 1999 BRAVO study. During this study we found that the submicron aerosol was generally quite acidic, due to a lack of sufficient ammonia to fully neutralize the aerosol sulfate. While some nitrate was found in the BRAVO aerosol, particle size-resolved composition measurements demonstrated that this nitrate was associated with larger sea salt and soil dust particles and not associated with the acidic submicron aerosol. A large amount of gaseous nitric acid was also observed throughout most of the study, illustrating the potential for submicron ammonium nitrate formation in the event that sulfate concentrations were reduced and/or ammonia concentrations were increased.

The BRAVO data set provides an opportunity to consider whether hypothetical reductions in regional aerosol sulfate concentrations might be less effective than expected due to NH_4NO_3 formation. In order to consider this issue, it is useful to determine the amount of "excess" sulfate present in BRAVO aerosol, where "excess" sulfate is defined as the concentration of sulfate minus the concentration of ammonium (i.e., the amount that sulfate concentrations would have to be decreased for the aerosol to become neutralized, assuming particulate ammonium concentrations remain unchanged). The

BRAVO "excess" sulfate timeline is shown in Figure 1a, along with timelines of $PM_{2.5}$ sulfate and $HNO_3(g)$. It is evident from the timelines that periods of high sulfate concentration also feature high concentrations of "excess" sulfate. This point is further made in Figure 1b where a strong correlation ($R^2 = 0.86$) is found to exist between "excess" sulfate and sulfate. When sulfate concentrations are high, "excess" sulfate concentrations are also high, indicating that considerable reductions in aerosol sulfate concentrations could be made on these days before the aerosol became neutralized. Second, the high temperatures present during the summer and fall at Big Bend do not favor formation of NH_4NO_3, even if additional gaseous ammonia is made available by sulfate reductions. Last, even if all the available gaseous nitric were shifted to the particulate phase, the additional mass (see Figure 1a) would still be small during most periods relative to the sulfate concentration decreases required to neutralize the aerosol. Accordingly, it appears that during summer and fall at Big Bend sulfate concentrations could be significantly decreased without much concern about nonlinear responses in fine particle mass concentrations.

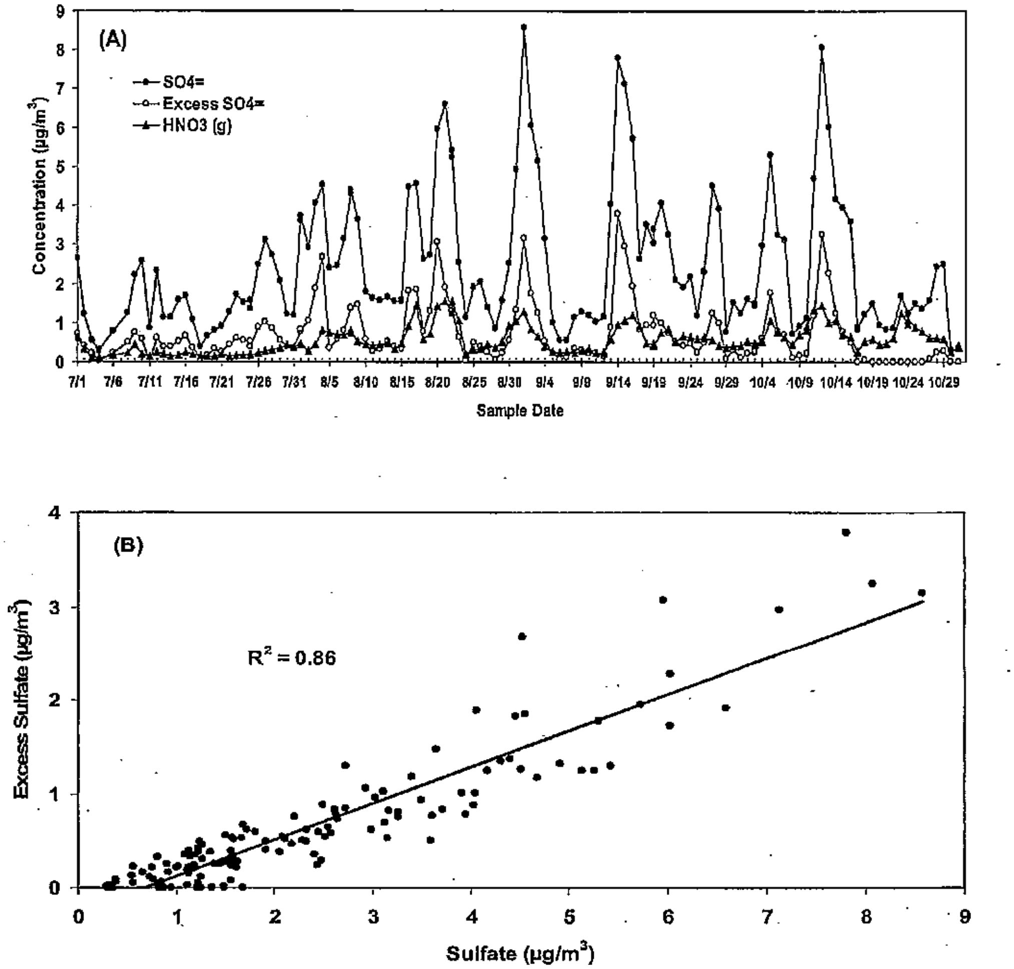


Figure 1. $PM_{2.5}$ aerosol composition measured at Big Bend N.P. during the 1999 BRAVO experiment.

Because measurements of all of these components are not routinely made throughout the western U.S. it is not easy to determine the extent to which the situation at Big Bend is representative of the situation at other western U.S. locations. Nor are these results directly applicable to consideration of other seasons at Big Bend. Some western U.S. locations may well have aerosol compositions that are close to the neutral point where reductions in sulfate would more quickly translate into possible increases in aerosol nitrate.

In order to consider the potential for nitrate replacement of sulfate in fine aerosol elsewhere in the interior western U.S., a one month study of aerosol composition was conducted at Grand Canyon National Park in spring 2003. Preliminary findings from that study, sponsored by the National Park Service and Land and Water Fund of the Rockies (LAWFR, now Western Resource Advocates), are presented here.

2. Experimental description

2.1 Site selection

The region selected for the study was the Colorado Plateau. This region is home to the so-called *Golden Circle* of National Parks, including Bandelier, Bryce Canyon, Canyonlands, Grand Canyon, Mesa Verde and Petrified Forest. The IMPROVE network intensively monitors many aerosol characteristics in this region. According to the May 2000 IMPROVE report (Malm, 2000), light extinction in this region is caused primarily by sulfate, organic species, and soil. Nitrate is a smaller contributor at present, experiencing its highest concentrations in spring, but nitrate concentrations have been increasing at some sites (Malm, 2000).

Although Mesa Verde was originally considered for the LAWFR measurement campaign, a decision was made to conduct the measurements at Grand Canyon, due to complementary work already planned there under sponsorship of NPS/IMPROVE. By conducting measurements at Grand Canyon, we were able to (1) sample for a month, rather than the 3 weeks originally proposed, (2) collect $PM_{2.5}$ samples at time resolutions of 24 hours rather than the 48 hr samples originally proposed, and to add high time resolution (15 min) measurements of $PM_{2.5}$ aerosol composition. Measurements at Grand Canyon were targeted for spring, because that is the season when the park historically has the highest $PM_{2.5}$ nitrate concentrations, based on IMPROVE data (see Figure 2). Grand

Canyon nitrate concentrations peak in May, so the study was scheduled for May 2003. As seen in Figure 2, May is historically also the month featuring the 2nd highest aerosol fine mass concentrations. The site utilized for the study was the existing IMPROVE site GRCA2 (Site Name: Hance Camp at Grand Canyon NP Longitude (dd): -111.9841 Latitude (dd): 35.9731 Elevation (m): 2267). This site is located in a meadow approximately 200 m south of East Rim Drive and approximately 1.2 miles south of the Grandview point turnoff.

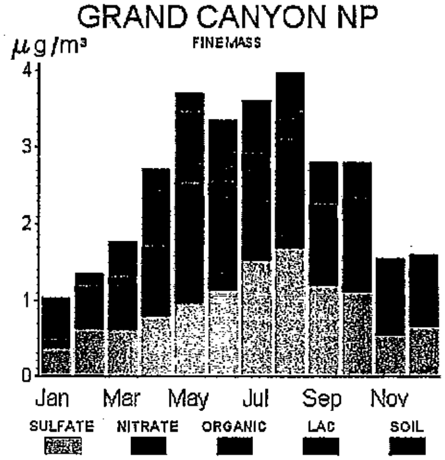


Figure 2. IMPROVE data showing seasonal trends in $PM_{2.5}$ aerosol concentrations at Grand Canyon (source: http://vista.cira.colostate.edu/improve/Data/GraphicViewer/seasonal.htm).

2.2 Measurements

Three types of measurements were made at Grand Canyon during the study. $PM_{2.5}$ composition, along with concentrations of gaseous nitric acid and ammonia, was measured using a URG annular denuder/filter pack system. Size-resolved aerosol composition was measured using a Micro Orifice Uniform Deposit Impactor (MOUDI). Semi-continuous measurements of $PM_{2.5}$ aerosol composition were made using a Particle Into Liquid Sampler (PILS) coupled to two Dionex ion chromatographs.

Several URG systems were operated in parallel to test measurement precision and different filter sampling and extraction protocols as part of the NPS/IMPROVE study. We focus here on results from the first module, operated to collect 24 hr samples (08:00-08:00 local time). This module contained a $PM_{2.5}$ cyclone, a carbonate-coated annular denuder for nitric acid collection, a phosphorous acid-coated annular denuder for ammonia collection, a nylon filter for particle collection, a second nylon filter for collection of any nitric acid lost from the first filter, and a final phosphorous acid-coated annular denuder for collection of any ammonia lost from particles collected on the nylon filter.

Ion size distributions were measured over sequential 48 hr sampling periods (08:00-08:00) using a Multi Orifice Uniform Deposit Impactor (MOUDI). The MOUDI was operated with eight stages with size cuts ranging from 0.18 to10 µm aerodynamic diameter. An inlet stage collected particles with aerodynamic diameter > 18 µm and a Teflon after-filter collected particles with diameters below 0.18 µm. Impaction surfaces were aluminum, with a silicone grease coating to reduce particle bounce.

Denuders were extracted on-site with deionized water. Filters and impaction substrates were frozen for later extraction and analysis in our lab at CSU. URG module 1 filters were extracted with deionized water (first nylon filter) or an alkaline sodium bicarbonate/sodium carbonate solution (2nd nylon filter). Aluminum impaction substrates and the MOUDI after-filter were extracted with deionized water. All filters were sonicated during extraction. Ion analysis was completed on two Dionex DX-500 ion chromatographs. A Dionex AG4A-SC guard column, AS4A-SC separation column and a self-regenerating anion suppressor were used to measure anion (NO_3^-, Cl^-, and SO_4^{2-}) concentrations. Cations (Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}) were measured using a Dionex CG12A guard column, CS12A separation column and a self-regenerating cation suppressor. Detection was by conductivity in both cases. Both ion chromatographs used for URG and MOUDI sample analysis were calibrated daily using a series of standards prepared from analytical grade salts. Replicate injections and analysis of independent NIST traceable standards were used to establish measurement precision and accuracy.

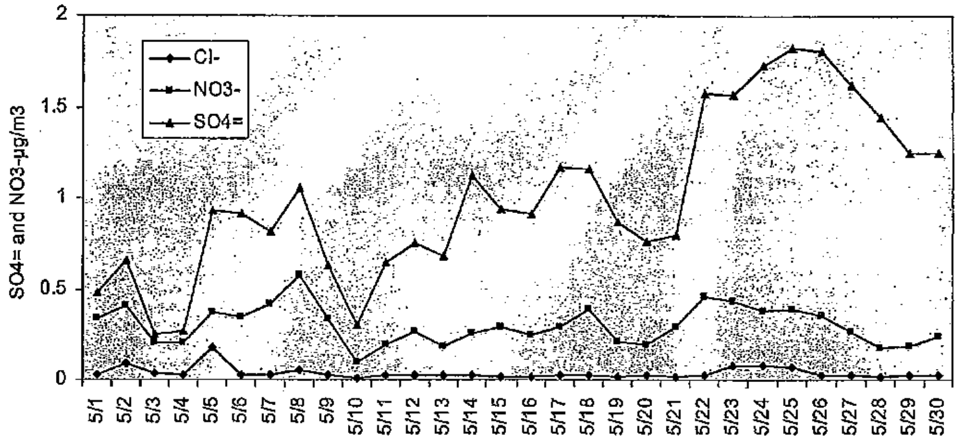
URG annular denuders and a $PM_{2.5}$ cyclone (URG) were also used upstream of the PILS. The first denuder was coated with Na_2CO_3 for removal of acidic gases and the second denuder was coated with phosphorous acid to remove basic gases. The overall principle of PILS is to collect particles that comprise the $PM_{2.5}$ aerosol mass into a small continuous flow of high purity water. The liquid stream is then continually drawn to two ion chromatography systems for measurement of aerosol anions and cations using the same separation, suppression and detection schemes outlined above. Calibration of the PILS IC's was checked approximately every 4-5 days.

3. Results and discussion

Measurements using the URG and MOUDI samplers were made at Grand Canyon beginning at 08:00 on May 1st and ending at 08:00 on May 31st. PILS data are available for a slightly shorter time period. Concentrations of $PM_{2.5}$ aerosol observed during the study were typical of previous May concentrations measured by IMPROVE.

Figure 3 depicts timelines of $PM_{2.5}$ ion concentrations. Concentrations are expressed as mass concentrations in $\mu g/m^3$. On a mass concentration basis, sulfate is observed to be the dominant anion while ammonium is the dominant cation. Sulfate concentrations during the month-long study range over approximately a factor of ten, from ~0.2 to nearly 2 $\mu g/m^3$. Nitrate concentrations are observed to range between approximately 0.1 and 0.5 $\mu g/m^3$. In addition to ammonium, both Ca^{2+} and Na^+ are important contributors to cation concentrations.

Figure 4 depicts timelines of the concentrations of the most important ions in units of nanoequivalents per cubic meter (neq/m^3). These concentration units incorporate the charge on each species (e.g., one mole of sulfate equals two equivalents), permitting ready analysis of the charge balance in the aerosol. The highest concentration species is ammonium, closely followed by sulfate. This result indicates that more than sufficient ammonium is typically present in the aerosol to neutralize the sulfate.


Grand Canyon timeline of PM2.5 anions

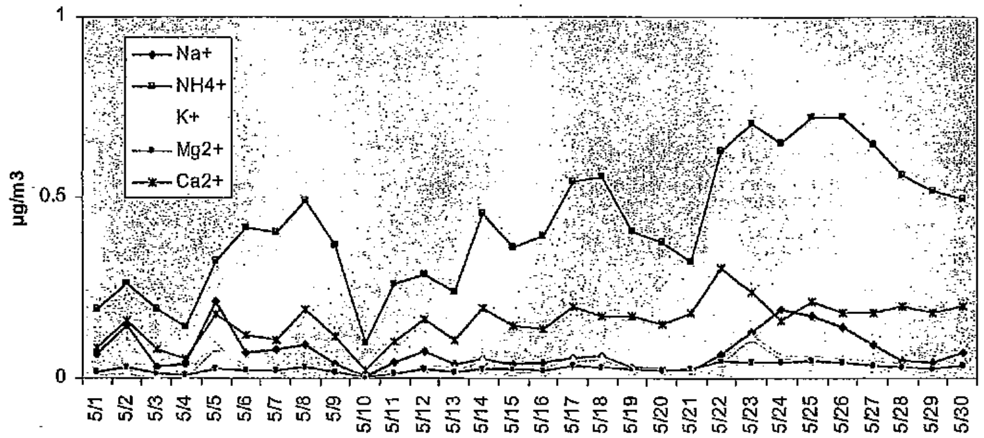

Grand Canyon timelines of PM2.5 cations

Figure 3. Timelines of $PM_{2.5}$ ion concentrations measured using the URG sampler at Grand Canyon.

A comparison of ammonium concentrations vs. sulfate concentrations (Figure 5) shows this result again. When ammonium concentrations are compared to the sum of nitrate and sulfate concentrations, however, it is clear that there is frequently insufficient ammonium present to balance the sum of nitrate and sulfate. This finding suggests that other forms of nitrate and sulfate, e.g. products of the reaction of nitric or sulfuric acid (or their precursors) with soil dust or sea salt, may be present.

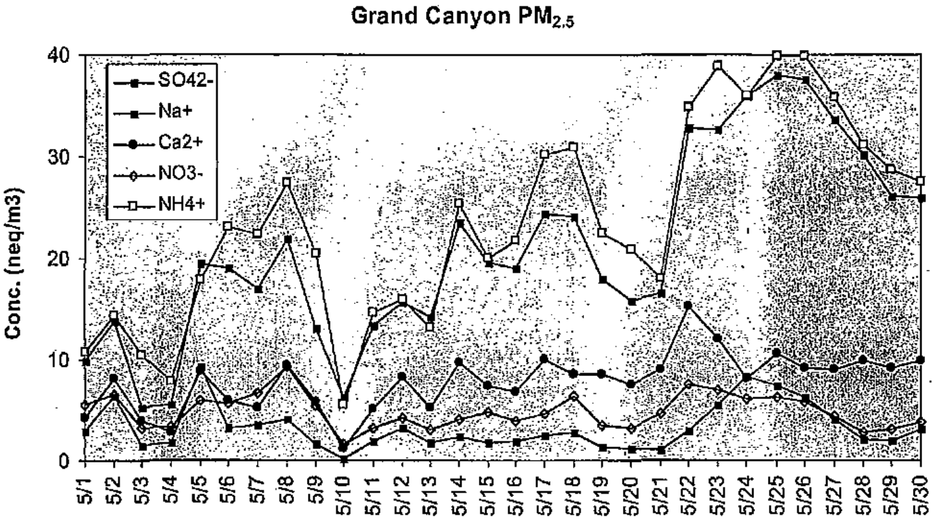


Figure 4. Timelines of major $PM_{2.5}$ ion concentrations in neq/m^3.

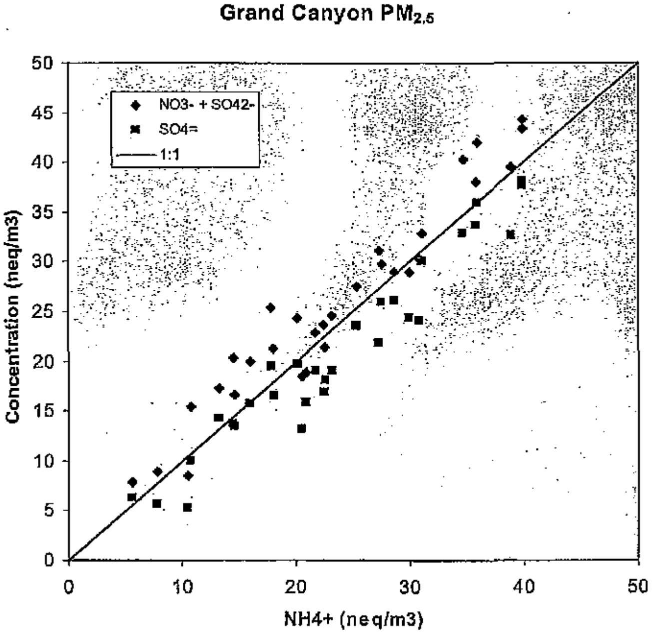


Figure 5. Comparison of $PM_{2.5}$ concentrations of nitrate, sulfate, and ammonium.

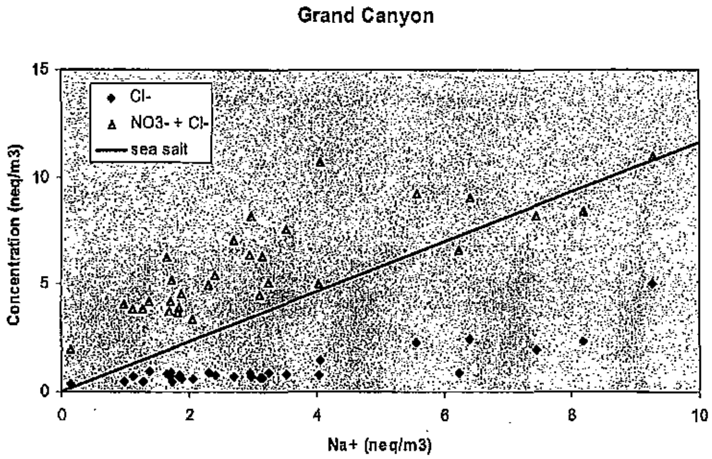


Figure 6. $PM_{2.5}$ concentrations of Cl^- or $Cl^- + NO_3^-$ vs. Na^+ in Grand Canyon aerosol. The sea salt line defines a Cl^- to Na^+ ratio of 1.164.

If we assume the Na^+ measured at Grand Canyon is associated with sea salt, we observe that there is a deficiency of Cl^- (also observed at Big Bend). If we sum NO_3^- and Cl^- concentrations, we find there is usually more nitrate than can be explained by the amount of missing chloride and the ratio of nitrate plus chloride to Na^+ falls above the Cl^-/Na^+ ratio in sea salt (Figure 6). Nitrate concentrations are correlated with Na^+ (See Fig. 7), but the correlation improves

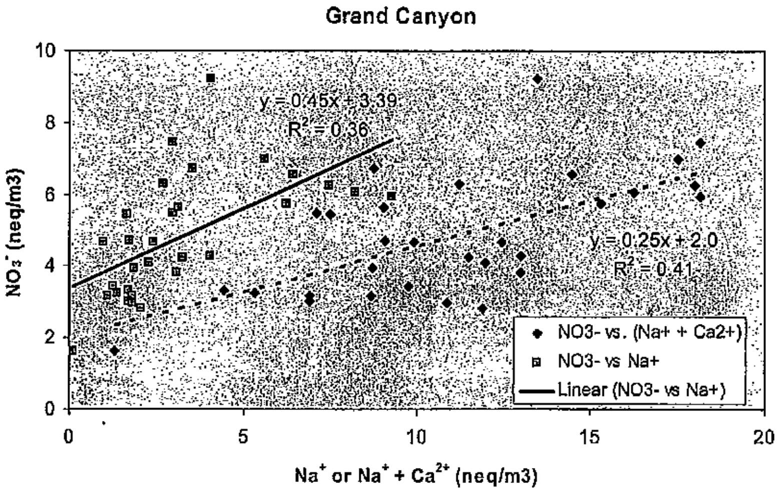
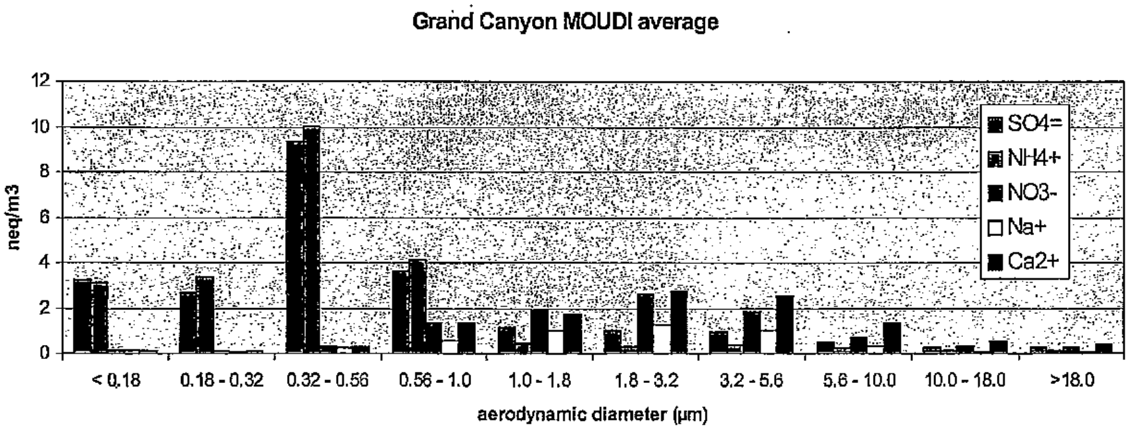


Figure 7. Correlations between $PM_{2.5}$ NO_3^- and Na^+ or Na^+ plus Ca^{2+} in Grand Canyon aerosol.

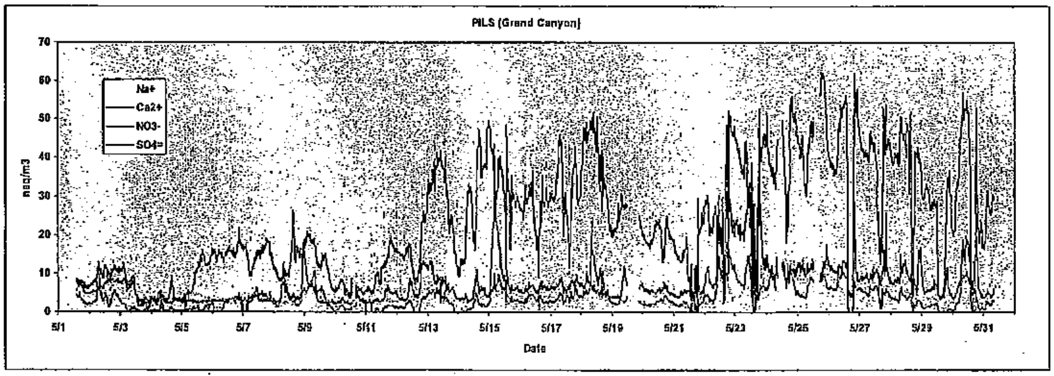
somewhat if nitrate is correlated against the sum of Na^+ and Ca2$^+$, again suggesting reaction of nitric acid with soil dust might be important here.

Figure 8 depicts the average size distributions of the major anions and cations as measured from the 48 hr MOUDI impactor samples. Several points are clear from



analyzing these distributions. **Figure 8. Study average major ion size distributions measured at Grand Canyon using the MOUDI impactor.**

First, the aerosol fine particle mode consists mainly of particles with aerodynamic diameters less than 1 µm and a composition of fully neutralized $(NH_4)_2SO_4$. Second, nitrate is contained mainly in a coarse particle mode, with most particles possessing aerodynamic diameters above 1 µm. Third, the size distributions of nitrate and Na^+ are similar, but nitrate concentrations on average exceed Na^+ concentrations in essentially all particle sizes. Fourth, Ca^{2+} exhibits an average size distribution quite similar to the average nitrate size distribution, with concentrations that are also similar. Last, there is also sulfate present in coarse mode particles. Since the amount of sulfate in these particles exceeds the amount of ammonium, it appears likely that the coarse sulfate is associated, like nitrate, with soil dust or reacted sea salt. Ion size distributions from most 48 hr sampling periods show features generally similar to those discussed above for the study average size distributions.



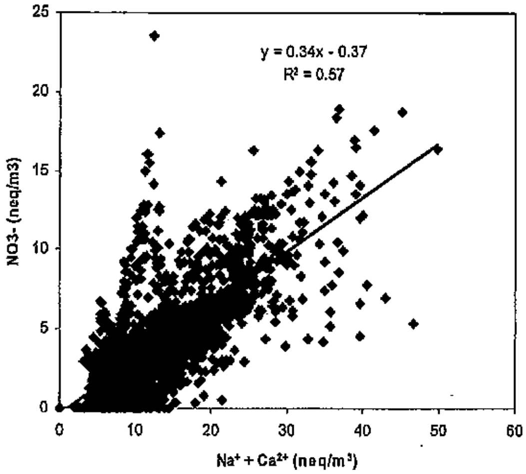


Figure 9. PILS timelines (15-min resolution) of selected $PM_{2.5}$ ions (top panel) and PILS nitrate vs. the sum of PILS Na^+ and Ca^{2+} (lower panel).

As mentioned above, high time resolution (15 minute) measurements of Grand Canyon $PM_{2.5}$ aerosol composition were made using a PILS sampler coupled to two ion chromatographs. Figure 9 depicts timelines of ion concentrations (neq/m^3) measured by this approach. The timelines show some correlation between changes in nitrate and changes in Na^+ ($r^2 = 0.36$) and Ca^{2+} ($r^2 = 0.49$). An improved correlation is seen when plotting nitrate vs. the sum of Na^+ and Ca^{2+} ($r^2 = 0.57$) as shown in Figure 10. Nitrate concentrations are observed to increase with increasing Na^+ and Ca^{2+} concentrations, presumably reflecting increased reaction with advected sea salt and soil dust. The average ratio of nitrate to the sum of Na^+ and Ca^{2+} is approximately one-third.

In order to examine the potential for further particle formation at Grand Canyon, it is useful to consider the concentrations of key precursor species in the gas phase. Figure 10 presents timelines of the mass concentrations of gaseous sulfur dioxide, ammonia, and nitric acid, measured using the URG annular denuders. The highest concentration is observed for nitric acid, with values approaching 1 μg/m^3 late in May. Concentrations of sulfur dioxide are generally below 0.4 μg/m^3, while NH_3 concentrations increase from ~ 0.2 μg/m^3 early in May to ~ 0.6 μg/m^3 at the end of the study.

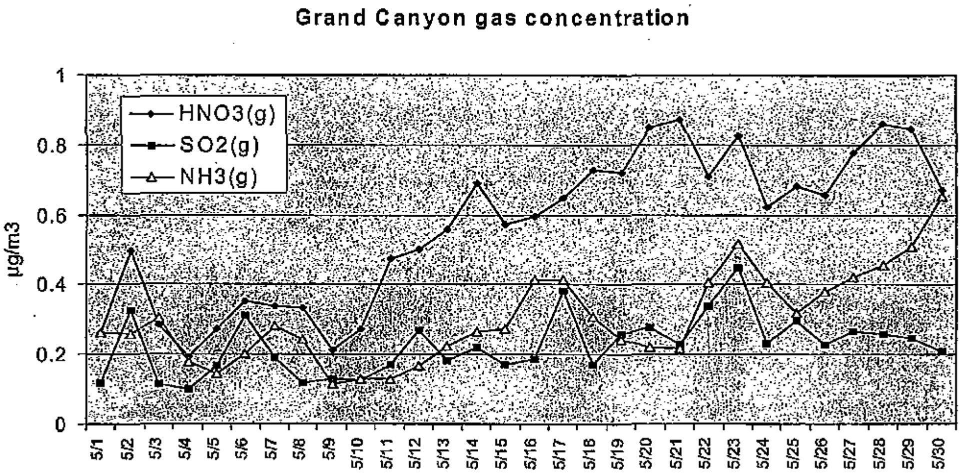


Figure 10. Timelines of mass concentrations of key gases measured at Grand Canyon using URG annular denuders.

Figure 11 depicts the ratios of each of these gases to the sum of the gas and its counterpart $PM_{2.5}$ aerosol concentration throughout the study. For example, the ratio of gaseous nitric acid to the sum of gaseous nitric acid and $PM_{2.5}$ nitrate (this sum is designated as N(V), nitrogen in the +5 oxidation state) ranges between approximately 0.4 and 0.8. The higher values occur later in the month. Beginning May 10 and continuing until the end of the study, 60-80% of the total N(V) resides in the gas phase (neglecting contributions from nitrate in particles with aerodynamic diameters > 2.5 µm). This indicates a significant potential for increasing nitrate's contribution to particle mass.

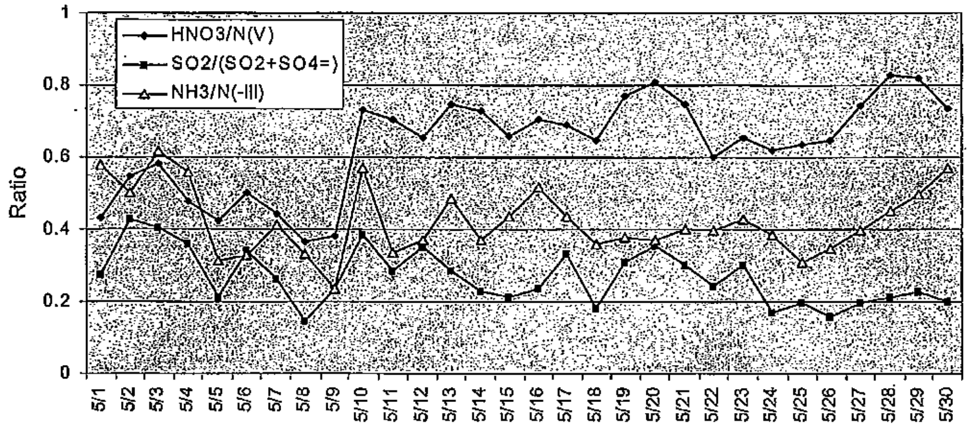


Figure 11. Timelines of the fraction of key species present in the gas phase at Grand Canyon. $HNO_3/N(V)$ denotes the ratio of nitric acid to the sum of nitric acid and $PM_{2.5}$ nitrate. $SO_2/SO_2+SO_4^{=}$ denotes the ratio of sulfur dioxide to the sum of sulfur dioxide and $PM_{2.5}$ sulfate. $NH_3/N(-III)$ denotes the ratio of gaseous ammonia to the sum of ammonia and $PM_{2.5}$ ammonium.

The likelihood of nitrate entering particles, due for example to changes in particulate sulfate concentrations, can be examined using an aerosol thermodynamic model. We conducted this analysis using the model ISORROPIA v. 1.5 (Nenes et al., 1998. 1999). This model treats gas-particle equilibria for a system containing ammonium, nitrate, sulfate, sodium, and chloride. Soil components (e.g., Ca^{2+} and Mg^{2+}) are not included. In addition, the version of the model used here permits only one (internally mixed) aerosol composition. In other words, it cannot predict variations in aerosol composition with size or between particles of the same size. Inputs to the model simulation include: total sulfate (as H_2SO_4), total ammonium (gaseous ammonia + particulate ammonium, as NH_3), total nitrate (gaseous nitric acid plus particulate nitrate, as HNO_3), total Cl^- (as HCl), Na^+, relative humidity (RH) and temperature. Where particulate concentrations were called for, we used measured $PM_{2.5}$ concentrations. Average temperature values measured during each 24 hr sample were input for temperature. Because RH values were not immediately available for the study period, we performed a sensitivity analysis, looking at RH values of 20% (a typical May value for the Grand Canyon area) and a higher value of 50%.

The model was applied to examine the predicted equilibrium composition of $PM_{2.5}$ aerosol at Grand Canyon and to watch how this predicted composition changes as sulfate concentrations are reduced. The intent of this evaluation was primarily to determine the likelihood of NH_4NO_3 formation that might occur in response to future reductions in aerosol sulfate and associated nonlinearities in fine particle mass reductions. The main finding from these analyses is that significant formation of NH_4NO_3 is unlikely, even as available gaseous ammonia increases in response to sulfate decreases. The lack of NH_4NO_3 formation can primarily be attributed to the relatively high temperatures and low humidities characteristic of this region in spring and summer.

Figure 12 depicts the results of the aerosol composition simulations for RH=50%. Panels are included showing $PM_{2.5}$ mass, gaseous ammonia, $PM_{2.5}$ ammonium sulfate, gaseous nitric acid, $PM_{2.5}$ sodium sulfate, and $PM_{2.5}$ sodium nitrate. Five lines are included in each panel, showing how predicted $PM_{2.5}$ mass on each day changes from current conditions (100% sulfate) to hypothetical scenarios where the particulate sulfate concentration is reduced to levels equal to 75%, 50%, 25%, and 0% of the current value. All other species inputs were held constant. As sulfate is initially reduced, it is apparent that $PM_{2.5}$ mass also decreases, accompanied by decreases in particulate ammonium sulfate and increases in gaseous ammonia. This pattern changes only at large sulfate reductions in excess of 50%. For example, the simulations for May 2nd and May 5th predict that when sulfate is reduced from 50 to 25% of its present value, a slight increase in $PM_{2.5}$ mass is observed. The mass increase is accompanied by a decrease in gaseous nitric acid. The predicted mass increase on these two days does, in fact, reflect replacement of sulfate by nitrate, but it is replacement of Na_2SO_4 by $NaNO_3$ that occurs (see bottom two panels in Figure 12), not replacement of $(NH_4)_2SO_4$ by NH_4NO_3. Reductions of gaseous nitric acid and replacement of sodium sulfate by sodium nitrate become more common in the simulations as sulfate is further reduced to 0% of its current value. These predictions, however, must be judged cautiously. The nitrate replacement effect at extreme sulfate reduction levels is magnified by the absence of Ca^{2+} in the ISORROPIA simulations. Because Ca^{2+} is not included, gas phase nitric acid concentrations are overpredicted by the model which pairs sulfate, not nitrate, with Na^+. In the absence of available Na^+ or any Ca^{2+}, the simulation forces all nitrate into the gas phase. Even aside from this limitation of the ISORROPIA simulations, however, it is clear that sulfate replacement by nitrate is unlikely except at extreme levels of sulfate reduction.

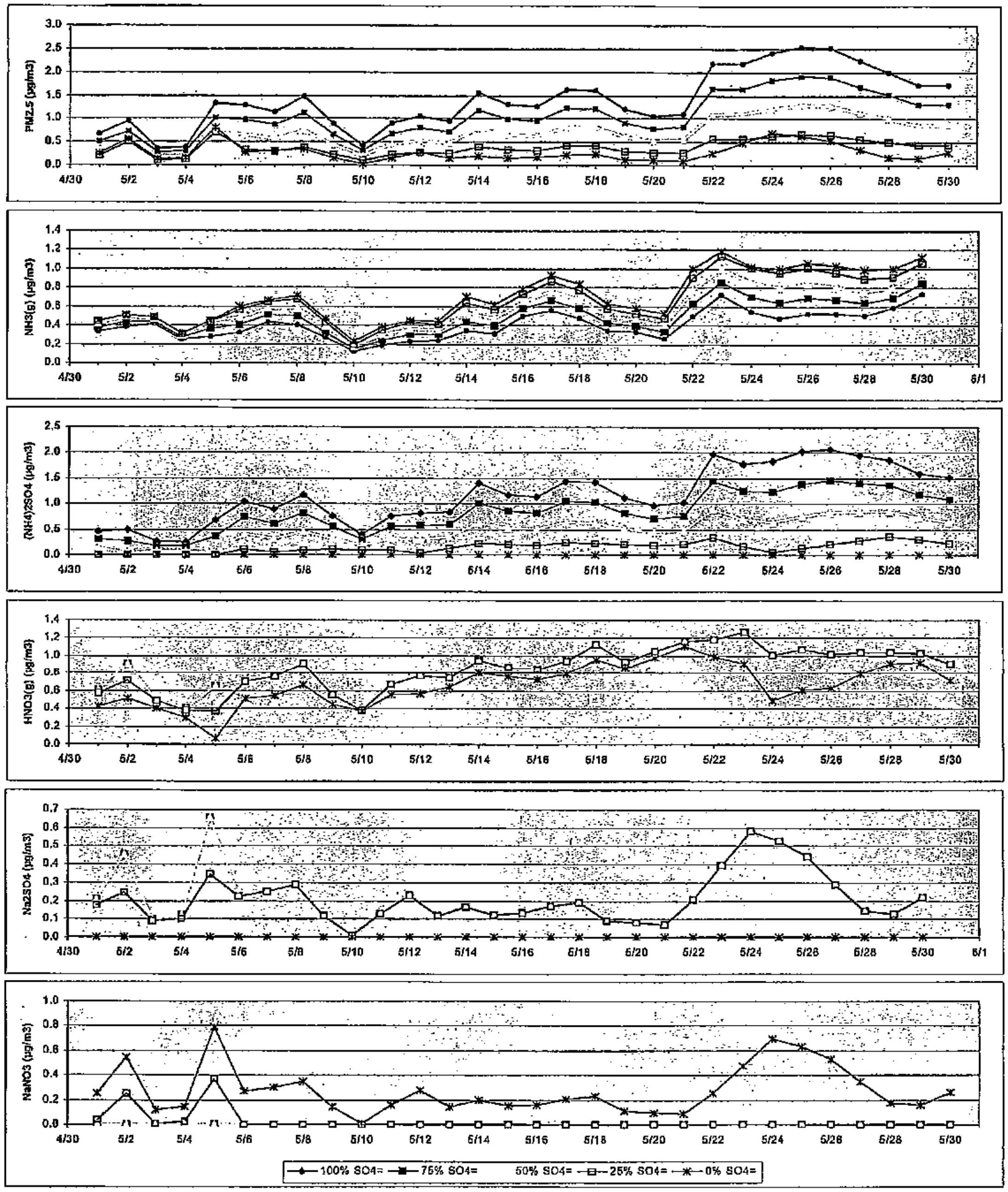


Figure 12. Timelines of aerosol and gas composition at Grand Canyon predicted by simulations using the ISORROPIA aerosol thermodynamic model. Predictions are shown

for sulfate at its current level (100% sulfate) and for sulfate reduced to 75%, 50%, 25%, and 0% of its current level.

The absence of a tendency for the atmosphere to readily form NH_4NO_3 in May at Grand Canyon suggests that significant reductions in regional sulfate can be achieved without great concern about potential sulfate replacement by nitrate or increases in $PM_{2.5}$ mass. Only at extreme levels of sulfate reduction, exceeding 75%, do the model simulations suggest any significant movement of nitrate from the gas phase into particles and the effect predicted here is probably exaggerated by the absence of Ca^{2+} in the model's treatment of aerosol thermodynamics.

While we must be cautious in trying to extend these conclusions to other locations, it seems most likely that a similar picture would emerge at other sites on the Colorado Plateau with similar climates if data were available. This hypothesis should be tested by additional measurements at another key location such as Mesa Verde. It would also be worth examining the behavior of the system under winter conditions. May was selected for the current study because that is when $PM_{2.5}$ nitrate concentrations have been observed to peak at Grand Canyon. Based on our observations, it appears that the relatively high nitrate concentrations present at this time of year are due to reactions of gaseous nitric acid with sea salt and soil dust. We do not know what form Grand Canyon nitrate exists in during the colder winter months, but a secondary seasonal peak is observed at Grand Canyon in December (see Fig. 2). Certainly the chances of NH_4NO_3 formation are greater then and the system might also be more sensitive to additional ammonium nitrate formation in response to increases in gaseous ammonia associated with any reductions in aerosol sulfate. For these reasons, we recommend that a future study be conducted in the region during winter to evaluate aerosol composition and its sensitivity to changes in ambient sulfate levels.

4. Summary

Measurements of aerosol composition at Grand Canyon in May 2003 indicate the ionic fraction of the aerosol is a complex mixture of submicron ammonium sulfate and supermicron nitrate and sulfate salts. The coarse mode nitrate and sulfate appear to be present mainly in the form of calcium or sodium salts, products of reaction of nitric or sulfuric acid (or their precursors) with sea salt and soil dust. Sulfate concentrations generally were several times nitrate concentrations on a mass basis; the sulfate to nitrate ratio for 24 hr samples ranged from approximately 1.2 to 8.2. An aerosol thermodynamic model (ISORROPIA) was applied to predict how gas-particle partitioning of nitrate and fine particle mass concentrations might change if aerosol sulfate concentrations were reduced at Grand Canyon due, for example, to future reductions in upwind sulfur dioxide emissions. The simulations suggest that sulfate replacement by nitrate in the aerosol is likely only in response to large sulfate concentration decreases, on the order of 75% or more. It is recommended that additional research be conducted to determine whether this finding is representative of other locations on the Colorado Plateau or other seasons of the year.

5. Acknowledgments and disclaimer

This work was supported by the National Park Service and by Land and Water Fund of the Rockies (recently renamed Western Resource Advocates). The support of Western Resource Advocates was made possible by an Environmental Science Program Grant from Environmental Defense. We are grateful to the IMPROVE team at UC Davis for their help with site logistics and project planning. We are also grateful to S. Kreidenweis, J. Carrillo, and B. Ayres of CSU and W. Malm of NPS for their assistance in project planning and sample analysis. The data presented here are still undergoing quality review and are, therefore, subject to revision.

6. References

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Seinfeld, J. H. and Pandis, S. N. (1998) *Atmospheric Chemistry and Physics – from Air Pollution to Climate Change*, John Wiley, New York.

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Ammonia Data

		µg/m3	Temp(K)	Pressure(atm)	ppmV	ppbv
Example	NH3	10	298.5	1	0.0143865	14
Site	Date	µg/m3	Temp(K)	Pressure(atm)	ppmV	ppbv
Big Bend N.P	7/1/99	0.4324897	300	0.88897	0.0007034	0.703
	7/2/99	0.3177803	300	0.88897	0.0005169	0.517
	7/3/99	0.2601676	300	0.88897	0.0004232	0.423
	7/4/99	0.4781967	300	0.88897	0.0007778	0.778
	7/5/99	0.2937857	300	0.88897	0.0004778	0.478
	7/6/99	0.3776515	300	0.88897	0.0006142	0.614
	7/7/99	0.3030271	300	0.88897	0.0004929	0.493
	7/8/99	0.2378276	300	0.88897	0.0003868	0.387
	7/9/99	0.2814694	300	0.88897	0.0004578	0.458
	7/10/99	0.2675793	300	0.88897	0.0004352	0.435
	7/11/99	0.2480806	300	0.88897	0.0004035	0.403
	7/12/99	0.2164813	300	0.88897	0.0003521	0.352
	7/13/99	0.3393498	300	0.88897	0.0005519	0.552
	7/14/99	0.4946789	300	0.88897	0.0008046	0.805
	7/15/99	0.520837	300	0.88897	0.0008471	0.847
	7/16/99	0.4607102	300	0.88897	0.0007493	0.749
	7/17/99	0.3346344	300	0.88897	0.0005443	0.544
	7/18/99	0.2834199	300	0.88897	0.000461	0.461
	7/19/99	0.3049095	300	0.88897	0.0004959	0.496
	7/20/99	0.187097	300	0.88897	0.0003043	0.304
	7/21/99	0.2299045	300	0.88897	0.0003739	0.374
	7/22/99	0.6235008	300	0.88897	0.0010141	1.014
	7/23/99	0.3894045	300	0.88897	0.0006334	0.633
	7/24/99	0.2682514	300	0.88897	0.0004363	0.436
	7/25/99	0.1848315	300	0.88897	0.0003006	0.301
	7/26/99	0.153428	300	0.88897	0.0002495	0.250
	7/27/99	0.1399494	300	0.88897	0.0002276	0.228
	7/28/99	0.2270115	300	0.88897	0.0003692	0.369
	7/29/99	0.3423145	300	0.88897	0.0005568	0.557
	7/30/99	0.3983273	300	0.88897	0.0006479	0.648
	7/31/99	0.2140239	300	0.88897	0.0003481	0.348
	8/1/99	0.3603876	300	0.88897	0.0005862	0.586
	8/2/99	0.2592449	300	0.88897	0.0004217	0.422
	8/3/99	0.1421023	300	0.88897	0.0002311	0.231
	8/4/99	0.0704523	300	0.88897	0.0001146	0.115
	8/5/99	0.3580124	300	0.88897	0.0005823	0.582
	8/6/99	0.0694992	300	0.88897	0.000113	0.113
	8/7/99	0.1067945	300	0.88897	0.0001737	0.174
	8/8/99	0.0783037	300	0.88897	0.0001274	0.127
	8/9/99	0.055428	300	0.88897	9.015E-05	0.090
	8/10/99	0.1090983	300	0.88897	0.0001774	0.177
	8/11/99	0.1243592	300	0.88897	0.0002023	0.202
	8/12/99	0.3259212	300	0.88897	0.0005301	0.530
	8/13/99	0.1151523	300	0.88897	0.0001873	0.187
	8/14/99	0.0865252	300	0.88897	0.0001407	0.141
	8/15/99	0.0793586	300	0.88897	0.0001291	0.129
	8/16/99	0.0947912	300	0.88897	0.0001542	0.154
	8/17/99	0.0608606	300	0.88897	9.899E-05	0.099

		µg/m3	Temp(K)	Pressure(atm)	ppmV	ppbv
Example	NH3	10	298.5	1	0.0143865	14
	8/18/99	0.1819116	300	0.88897	0.0002959	0.296
	8/19/99	0.1676753	300	0.88897	0.0002727	0.273
	8/20/99	0.0655813	300	0.88897	0.0001067	0.107
	8/21/99	0.0412588	300	0.88897	6.711E-05	0.067
	8/22/99	0.0329118	300	0.88897	5.353E-05	0.054
	8/23/99	0.0976835	300	0.88897	0.0001589	0.159
	8/24/99	0.1744019	300	0.88897	0.0002837	0.284
	8/25/99	0.2601731	300	0.88897	0.0004232	0.423
	8/26/99	0.2461532	300	0.88897	0.0004004	0.400
	8/27/99	0.3533519	300	0.88897	0.0005747	0.575
	8/28/99	0.2494415	300	0.88897	0.0004057	0.406
	8/29/99	0.2097213	300	0.88897	0.0003411	0.341
	8/30/99	0.2091272	300	0.88897	0.0003401	0.340
	8/31/99	0.1029207	300	0.88897	0.0001674	0.167
	9/1/99	0.0717892	300	0.88897	0.0001168	0.117
	9/2/99	0.1166805	300	0.88897	0.0001898	0.190
	9/3/99	0.1724441	300	0.88897	0.0002805	0.280
	9/4/99	0.2748442	300	0.88897	0.000447	0.447
	9/5/99	0.354151	300	0.88897	0.000576	0.576
	9/6/99	0.244154	300	0.88897	0.0003971	0.397
	9/7/99	0.1810427	300	0.88897	0.0002945	0.294
	9/8/99	0.1752375	300	0.88897	0.000285	0.285
	9/9/99	0.1563287	300	0.88897	0.0002543	0.254
	9/10/99	0.1759587	300	0.88897	0.0002862	0.286
	9/11/99	0.1198776	300	0.88897	0.000195	0.195
	9/12/99	0.1971267	300	0.88897	0.0003206	0.321
	9/13/99	0.0838616	300	0.88897	0.0001364	0.136
	9/14/99	0.0883098	300	0.88897	0.0001436	0.144
	9/15/99	0.0946431	300	0.88897	0.0001539	0.154
	9/16/99	0.092398	300	0.88897	0.0001503	0.150
	9/17/99	0.0715884	300	0.88897	0.0001164	0.116
	9/18/99	0.0757026	300	0.88897	0.0001231	0.123
	9/19/99	0.1464696	300	0.88897	0.0002382	0.238
	9/20/99	0.1491567	300	0.88897	0.0002426	0.243
	9/21/99	0.0637126	300	0.88897	0.0001036	0.104
	9/22/99	0.1034005	300	0.88897	0.0001682	0.168
	9/23/99	0.0830731	300	0.88897	0.0001351	0.135
	9/24/99	0.2123768	300	0.88897	0.0003454	0.345
	9/25/99	0.1209784	300	0.88897	0.0001968	0.197
	9/26/99	0.1170312	300	0.88897	0.0001903	0.190
	9/27/99	0.2425912	300	0.88897	0.0003946	0.395
	9/28/99	0.1398417	300	0.88897	0.0002274	0.227
	9/29/99	0	300	0.88897	0	0.000
	9/30/99	0.024167	300	0.88897	3.931E-05	0.039
	10/1/99	0.0774498	300	0.88897	0.000126	0.126
	10/2/99	0.099696	300	0.88897	0.0001622	0.162
	10/3/99	0.1499461	300	0.88897	0.0002439	0.244
	10/4/99	0.1130874	300	0.88897	0.0001839	0.184
	10/5/99	0.0415091	300	0.88897	6.751E-05	0.068

		µg/m3	Temp(K)	Pressure(atm)	ppmV	ppbv
Example	NH3	10	298.5	1	0.0143865	14
	10/6/99	0.0184388	300	0.88897	2.999E-05	0.030
	10/7/99	0.0834712	300	0.88897	0.0001358	0.136
	10/8/99	0.0090958	300	0.88897	1.479E-05	0.015
	10/9/99	0.0417177	300	0.88897	6.785E-05	0.068
	10/10/99	0.0247477	300	0.88897	4.025E-05	0.040
	10/11/99	0.0531778	300	0.88897	8.649E-05	0.086
	10/12/99	0	300	0.88897	0	0.000
	10/13/99	0.0121699	300	0.88897	1.979E-05	0.020
	10/14/99	0.0380807	300	0.88897	6.194E-05	0.062
	10/15/99	0.0292747	300	0.88897	4.761E-05	0.048
	10/16/99	0.0740632	300	0.88897	0.0001205	0.120
	10/17/99	0	300	0.88897	0	0.000
	10/18/99	0	300	0.88897	0	0.000
	10/19/99	0	300	0.88897	0	0.000
	10/20/99	0	300	0.88897	0	0.000
	10/21/99	0.0027914	300	0.88897	4.54E-06	0.005
	10/22/99	0	300	0.88897	0	0.000
	10/23/99	0	300	0.88897	0	0.000
	10/24/99	0	300	0.88897	0	0.000
	10/25/99	0	300	0.88897	0	0.000
	10/26/99	0	300	0.88897	0	0.000
	10/27/99	0.0206089	300	0.88897	3.352E-05	0.034
	10/28/99	0.08372	300	0.88897	0.0001362	0.136
	10/29/99	0.0835952	300	0.88897	0.000136	0.136
	10/30/99	0	300	0.88897	0	0.000
	10/31/99	0	300	0.88897	0	0.000
Yosemite N.P	7/14/02	2.1985058	295	0.8238	0.0037943	3.794
	7/15/02	1.9506237	295	0.8238	0.0033665	3.367
	7/16/02	1.7508617	295	0.8238	0.0030218	3.022
	7/17/02	1.7557416	295	0.8238	0.0030302	3.030
	7/18/02	1.573602	295	0.8238	0.0027158	2.716
	7/19/02	1.5980512	295	0.8238	0.002758	2.758
	7/20/02	1.753371	295	0.8238	0.0030261	3.026
	7/21/02	1.8919999	295	0.8238	0.0032654	3.265
	7/22/02	1.6646199	295	0.8238	0.0028729	2.873
	7/23/02	1.9746935	295	0.8238	0.0034081	3.408
	7/24/02	2.0045247	295	0.8238	0.0034596	3.460
	7/25/02	1.3116232	295	0.8238	0.0022637	2.264
	7/26/02	1.1842875	295	0.8238	0.0020439	2.044
	7/27/02	1.7255472	295	0.8238	0.0029781	2.978
	7/28/02	2.3236657	295	0.8238	0.0040104	4.010
	7/29/02	1.8024083	295	0.8238	0.0031107	3.111
	7/30/02	2.050771	295	0.8238	0.0035394	3.539
	7/31/02	1.7444775	295	0.8238	0.0030108	3.011
	8/1/02	1.4579433	295	0.8238	0.0025162	2.516
	8/2/02	1.7315657	295	0.8238	0.0029885	2.988
	8/3/02	2.9744911	295	0.8238	0.0051336	5.134
	8/4/02	1.5258905	295	0.8238	0.0026335	2.633
	8/5/02	1.2852996	295	0.8238	0.0022183	2.218

		µg/m3	Temp(K)	Pressure(atm)	ppmV	ppbv
Example	NH3	10	298.5	1	0.0143865	14
	8/6/02	1.3241604	295	0.8238	0.0022853	2.285
	8/7/02	1.0156514	295	0.8238	0.0017529	1.753
	8/8/02	1.2774439	295	0.8238	0.0022047	2.205
	8/9/02	1.5729415	295	0.8238	0.0027147	2.715
	8/10/02	1.5653678	295	0.8238	0.0027016	2.702
	8/11/02	1.4846665	295	0.8238	0.0025624	2.562
	8/12/02	1.670329	295	0.8238	0.0028828	2.883
	8/13/02	1.8929517	295	0.8238	0.003267	3.267
	8/14/02	1.5154399	295	0.8238	0.0026155	2.615
	8/15/02	1.6386779	295	0.8238	0.0028282	2.828
	8/16/02	1.4608394	295	0.8238	0.0025212	2.521
	8/17/02	1.2867552	295	0.8238	0.0022208	2.221
	8/18/02	1.5953123	295	0.8238	0.0027533	2.753
	8/19/02	1.3997464	295	0.8238	0.0024158	2.416
	8/20/02	0.990909	295	0.8238	0.0017102	1.710
	8/21/02	1.368196	295	0.8238	0.0023613	2.361
	8/22/02	1.5655903	295	0.8238	0.002702	2.702
	8/23/02	1.6097282	295	0.8238	0.0027782	2.778
	8/24/02	1.3738666	295	0.8238	0.0023711	2.371
	8/25/02	1.2220733	295	0.8238	0.0021091	2.109
	8/26/02	1.0614	295	0.8238	0.0018318	1.832
	8/27/02	1.7295178	295	0.8238	0.0029849	2.985
	8/28/02	2.1110297	295	0.8238	0.0036434	3.643
	8/29/02	1.9778178	295	0.8238	0.0034135	3.413
	8/30/02	1.3502569	295	0.8238	0.0023304	2.330
	8/31/02	1.7537224	295	0.8238	0.0030267	3.027
	9/1/02	1.5608312	295	0.8238	0.0026938	2.694
	9/2/02	1.1308022	295	0.8238	0.0019516	1.952
	9/3/02	1.39328	295	0.8238	0.0024046	2.405
	9/4/02	1.5717609	295	0.8238	0.0027127	2.713
Bondville, IL	2/1/03	0.4248991	276	0.97404	0.0005803	0.580
	2/2/03	0.6646827	276	0.97404	0.0009077	0.908
	2/3/03	1.4290753	276	0.97404	0.0019516	1.952
	2/4/03	0.4464631	276	0.97404	0.0006097	0.610
	2/5/03	0.2427664	276	0.97404	0.0003315	0.332
	2/6/03	0.2574685	276	0.97404	0.0003516	0.352
	2/7/03	0.0526125	276	0.97404	7.185E-05	0.072
	2/8/03	0.4341843	276	0.97404	0.0005929	0.593
	2/9/03	0.3726877	276	0.97404	0.000509	0.509
	2/10/03	0.2071454	276	0.97404	0.0002829	0.283
	2/11/03	0.183113	276	0.97404	0.0002501	0.250
	2/12/03	0.2752659	276	0.97404	0.0003759	0.376
	2/13/03	0.8017485	276	0.97404	0.0010949	1.095
	2/14/03	0.3139462	276	0.97404	0.0004287	0.429
	2/15/03	0.1208578	276	0.97404	0.0001651	0.165
	2/16/03	0.1170747	276	0.97404	0.0001599	0.160
	2/17/03	0.0312416	276	0.97404	4.267E-05	0.043
	2/18/03	0.0790236	276	0.97404	0.0001079	0.108
	2/19/03	0.302582	276	0.97404	0.0004132	0.413

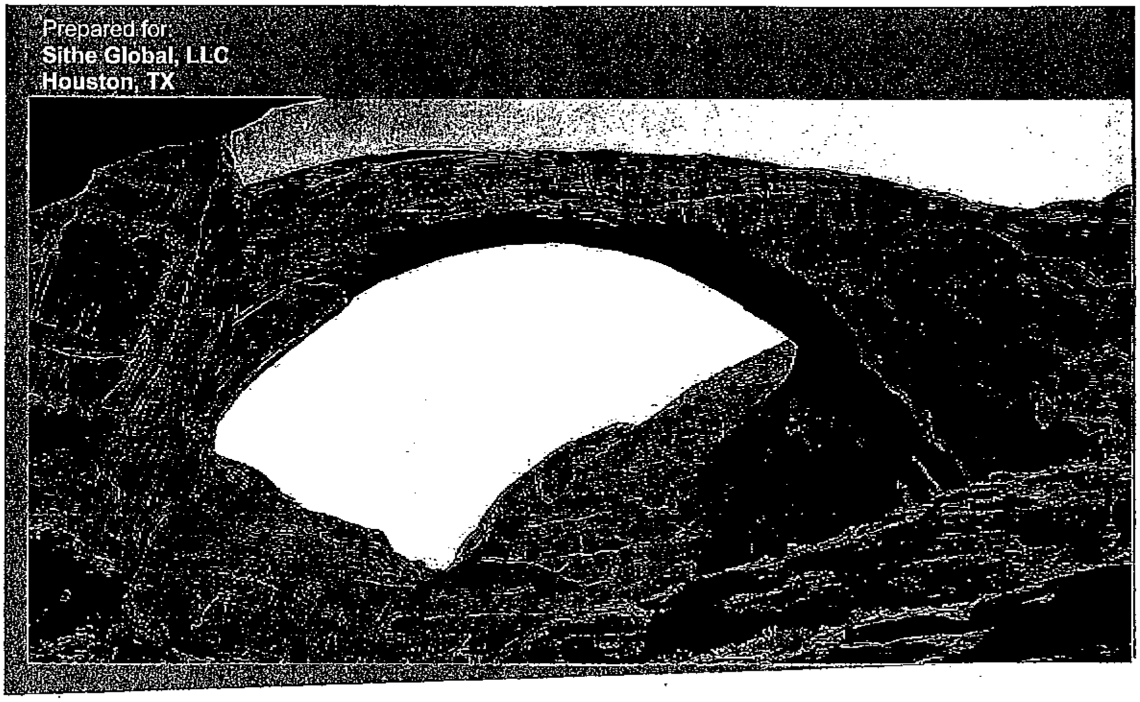
		µg/m3	Temp(K)	Pressure(atm)	ppmV	ppbv
Example	NH3	10	298.5	1	0.0143865	14
	2/20/03	0.5118587	276	0.97404	0.000699	0.699
	2/21/03	0.1143403	276	0.97404	0.0001561	0.156
	2/22/03	0.1639139	276	0.97404	0.0002239	0.224
	2/23/03	0.1392738	276	0.97404	0.0001902	0.190
	2/24/03	0.0396096	276	0.97404	5.409E-05	0.054
	2/25/03	0.0397416	276	0.97404	5.427E-05	0.054
	2/26/03	0.061876	276	0.97404	8.45E-05	0.085
	2/27/03	0.0909833	276	0.97404	0.0001243	0.124
Grand Canyon N.P	5/1/03	0.2614889	295	0.76766	0.0004843	0.484
	5/2/03	0.2567476	295	0.76766	0.0004755	0.476
	5/3/03	0.3025117	295	0.76766	0.0005603	0.560
	5/4/03	0.1763725	295	0.76766	0.0003267	0.327
	5/5/03	0.1440949	295	0.76766	0.0002669	0.267
	5/6/03	0.2002973	295	0.76766	0.000371	0.371
	5/7/03	0.2819588	295	0.76766	0.0005222	0.522
	5/8/03	0.2423621	295	0.76766	0.0004489	0.449
	5/9/03	0.1133546	295	0.76766	0.0002099	0.210
	5/10/03	0.1291995	295	0.76766	0.0002393	0.239
	5/11/03	0.1306583	295	0.76766	0.000242	0.242
	5/12/03	0.1685175	295	0.76766	0.0003121	0.312
	5/13/03	0.2227893	295	0.76766	0.0004126	0.413
	5/14/03	0.2659592	295	0.76766	0.0004926	0.493
	5/15/03	0.2742725	295	0.76766	0.000508	0.508
	5/16/03	0.4116403	295	0.76766	0.0007624	0.762
	5/17/03	0.4124989	295	0.76766	0.000764	0.764
	5/18/03	0.307847	295	0.76766	0.0005702	0.570
	5/19/03	0.2441263	295	0.76766	0.0004521	0.452
	5/20/03	0.2204024	295	0.76766	0.0004082	0.408
	5/21/03	0.2164546	295	0.76766	0.0004009	0.401
	5/22/03	0.4068385	295	0.76766	0.0007535	0.754
	5/23/03	0.5168976	295	0.76766	0.0009573	0.957
	5/24/03	0.406053	295	0.76766	0.000752	0.752
	5/25/03	0.3167727	295	0.76766	0.0005867	0.587
	5/26/03	0.3800757	295	0.76766	0.0007039	0.704
	5/27/03	0.4191143	295	0.76766	0.0007762	0.776
	5/28/03	0.4545668	295	0.76766	0.0008419	0.842
	5/29/03	0.5068734	295	0.76766	0.0009388	0.939
	5/30/03	0.6516641	295	0.76766	0.0012069	1.207
San Gorgonio	4/4/03	0.4520397	289	0.80809	0.0007792	0.779
	4/5/03	1.3682234	289	0.80809	0.0023583	2.358
	4/6/03	1.2643345	289	0.80809	0.0021793	2.179
	4/7/03	0.4853762	289	0.80809	0.0008366	0.837
	4/8/03	0.4174674	289	0.80809	0.0007196	0.720
	4/9/03	2.2028933	289	0.80809	0.003797	3.797
	4/10/03	1.7510235	289	0.80809	0.0030181	3.018
	4/11/03	1.5181289	289	0.80809	0.0026167	2.617
	4/12/03	0.7950082	289	0.80809	0.0013703	1.370
	4/13/03	0.8124928	289	0.80809	0.0014004	1.400
	4/14/03	0.1170158	289	0.80809	0.0002017	0.202

		µg/m3	Temp(K)	Pressure(atm)	ppmV	ppbv
Example	NH3	10	298.5	1	0.0143865	14
	4/16/03	1.4533051	289	0.80809	0.002505	2.505
	4/17/03	0.6370786	289	0.80809	0.0010981	1.098
	4/18/03	0.8140165	289	0.80809	0.0014031	1.403
	4/19/03	0.5264535	289	0.80809	0.0009074	0.907
	4/20/03	1.9902295	289	0.80809	0.0034304	3.430
	4/21/03	1.0913788	289	0.80809	0.0018811	1.881
	4/22/03	0.6182538	289	0.80809	0.0010656	1.066
	4/23/03	0.4664089	289	0.80809	0.0008039	0.804
	4/24/03	0.8180046	289	0.80809	0.0014099	1.410
	4/25/03	1.1954716	289	0.80809	0.0020606	2.061
	4/26/03	0.6340705	289	0.80809	0.0010929	1.093
	7/1/03	1.1508674	298	0.80809	0.0020455	2.045
	7/2/03	1.7351965	298	0.80809	0.003084	3.084
	7/3/03	1.8225929	298	0.80809	0.0032393	3.239
	7/4/03	2.2347766	298	0.80809	0.0039719	3.972
	7/5/03	1.7582609	298	0.80809	0.003125	3.125
	7/6/03	3.080472	298	0.80809	0.005475	5.475
	7/7/03	2.6699759	298	0.80809	0.0047454	4.745
	7/8/03	2.6607387	298	0.80809	0.004729	4.729
	7/9/03	2.1798461	298	0.80809	0.0038743	3.874
	7/10/03	1.897579	298	0.80809	0.0033726	3.373
	7/11/03	3.6562342	298	0.80809	0.0064983	6.498
	7/12/03	3.3857207	298	0.80809	0.0060175	6.018
	7/13/03	2.1314336	298	0.80809	0.0037882	3.788
	7/14/03	1.4775031	298	0.80809	0.002626	2.626
	7/15/03	1.9875548	298	0.80809	0.0035325	3.533
	7/16/03	2.5530809	298	0.80809	0.0045376	4.538
	7/17/03	2.4323033	298	0.80809	0.004323	4.323
	7/18/03	3.8732721	298	0.80809	0.006884	6.884
	7/19/03	4.3307939	298	0.80809	0.0076972	7.697
	7/20/03	3.5059764	298	0.80809	0.0062312	6.231
	7/21/03	3.8249028	298	0.80809	0.0067981	6.798
	7/22/03	2.9632854	298	0.80809	0.0052667	5.267
	7/23/03	4.0200089	298	0.80809	0.0071448	7.145
	7/24/03	3.6464071	298	0.80809	0.0064808	6.481
	7/25/03	3.0228622	298	0.80809	0.0053726	5.373
	7/26/03	4.0503221	298	0.80809	0.0071987	7.199
	7/27/03	4.187615	298	0.80809	0.0074427	7.443
	7/28/03	4.5617782	298	0.80809	0.0081077	8.108
	7/29/03	2.0703654	298	0.80809	0.0036797	3.680
	7/30/03	2.9100174	298	0.80809	0.005172	5.172
Briganitine	11/04/03	0.2206698	287	1	0.0003052	0.305
	11/05/03	0.4123882	287	1	0.0005704	0.570
	11/06/03	0.1521582	287	1	0.0002105	0.210
	11/07/03	0.1951034	287	1	0.0002699	0.270
	11/08/03	0.0638068	287	1	8.826E-05	0.088
	11/09/03	0.1128087	287	1	0.000156	0.156
	11/10/03	0.4815922	287	1	0.0006661	0.666
	11/11/03	0.507241	287	1	0.0007016	0.702

		µg/m3	Temp(K)	Pressure(atm)	ppmV	ppbv
Example	NH3	10	298.5	1	0.0143865	14
	11/12/03	0.3402455	287	1	0.0004706	0.471
	11/13/03	0.1226835	287	1	0.0001697	0.170
	11/14/03	0.2479913	287	1	0.000343	0.343
	11/15/03	0.4621654	287	1	0.0006393	0.639
	11/16/03	0.6210247	287	1	0.000859	0.859
	11/17/03	0.1987873	287	1	0.000275	0.275
	11/18/03	0.4813656	287	1	0.0006658	0.666
	11/19/03	0.3412621	287	1	0.000472	0.472
	11/20/03	0.0966073	287	1	0.0001336	0.134
	11/21/03	0.7662481	287	1	0.0010599	1.060
	11/22/03	0.3700046	287	1	0.0005118	0.512
	11/23/03	0.2436489	287	1	0.000337	0.337
	11/24/03	0.3630643	287	1	0.0005022	0.502
	11/25/03	0.0954852	287	1	0.0001321	0.132
	11/26/03	0.140397	287	1	0.0001942	0.194
	11/27/03	0.2768692	287	1	0.000383	0.383
	11/28/03	0.3239342	287	1	0.0004481	0.448
	11/29/03	0.044656	287	1	6.177E-05	0.062
	11/30/03	0.168285	287	1	0.0002328	0.233
Great Smoky Mts	7/20/04	0.2002726	302	0.91905	0.0003172	0.317
	7/21/04	0.2590933	302	0.91905	0.0004103	0.410
	7/22/04	0.2766246	302	0.91905	0.0004381	0.438
	7/23/04	0.2204342	302	0.91905	0.0003491	0.349
	7/24/04	0.1766765	302	0.91905	0.0002798	0.280
	7/25/04	0.2602328	302	0.91905	0.0004121	0.412
	7/26/04	0.2535956	302	0.91905	0.0004016	0.402
	7/27/04	0.2029204	302	0.91905	0.0003214	0.321
	7/28/04	0.2005491	302	0.91905	0.0003176	0.318
	7/29/04	0.2630131	302	0.91905	0.0004165	0.417
	7/30/04	0.299369	302	0.91905	0.0004741	0.474
	7/31/04	0.1985987	302	0.91905	0.0003145	0.315
	8/1/04	0.1767665	302	0.91905	0.0002799	0.280
	8/2/04	0.1138253	302	0.91905	0.0001803	0.180
	8/3/04	0.1125322	302	0.91905	0.0001782	0.178
	8/4/04	0.1895693	302	0.91905	0.0003002	0.300
	8/5/04	0.1485111	302	0.91905	0.0002352	0.235
	8/6/04	0.11655	302	0.91905	0.0001846	0.185
	8/7/04	0.1561461	302	0.91905	0.0002473	0.247
	8/8/04	0.1843826	302	0.91905	0.000292	0.292
	8/9/04	0.2053317	302	0.91905	0.0003252	0.325
	8/10/04	0.1884613	302	0.91905	0.0002985	0.298
	8/11/04	0.1340964	302	0.91905	0.0002124	0.212
	8/12/04	0.1214892	302	0.91905	0.0001924	0.192
	8/13/04	0.2019858	302	0.91905	0.0003199	0.320
	8/14/04	0.3402938	302	0.91905	0.0005389	0.539
	8/15/04	0.3212033	302	0.91905	0.0005087	0.509
	8/16/04	0.3390405	302	0.91905	0.0005369	0.537
	8/17/04	0.2429167	302	0.91905	0.0003847	0.385
	8/18/04	0.2363473	302	0.91905	0.0003743	0.374

Addendum to Modeling Protocol for the Proposed Desert Rock Generating Station dated January 2006

Prepared for:
Sithe Global, LLC
Houston, TX



Addendum to Modeling Protocol for the Proposed Desert Rock Generating Station

ENSR Corporation
January 2006
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Prepared for:
Sithe Global, LLC
Houston, TX

Addendum to Modeling Protocol for the Proposed Desert Rock Generating Station

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Reviewed By: Robert J. Paine

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1.0 Introduction

1.1 Background

In May, 2004, Steag, LLC (now Sithe Global, LLC) submitted a Prevention of Significant Deterioration (PSD) permit application to EPA Region IX associated with a modeling protocol and modeling analysis for assessing the air quality impacts of the proposed Desert Rock Generating Station. This project is a mine-mouth coal-fired power plant, to be located in northwestern New Mexico about 50 km southwest of Farmington, New Mexico, within the trust lands of the Navajo Nation. The plant will receive its coal supplies from BHP Billiton New Mexico Coal.

The modeling analysis submitted in May 2004 used the CALPUFF (Scire et al., 2000) model for both short-range and long-range transport modeling. While CALPUFF is the preferred EPA model for long-range transport (distances of at least 50 km), it is also used on a case-by-case basis for local complex winds. The results of a 1982 study focusing upon meteorological conditions in northwestern New Mexico provided evidence that the local flows exhibit complex behavior. Therefore, EPA Region 9 approved the use of the CALPUFF model with a 3-year meteorological database (2001-2003) for evaluating impacts on a consistent basis at all distances. This general modeling approach will not be changing for future modeling of the facility, except that a finer grid mesh may be employed for the local modeling near the proposed project site (including the local Class II modeling as well as Class I impacts at Mesa Verde; see Section 3-1). However, the National Park Service has elected to add three specific periods (more details in Section 3.3) to the analysis for regional haze at PSD Class I areas.

The two proposed units will exhaust to a common stack which will be built to the Good Engineering Practice (GEP) height of 279.5 meters (917 feet). For long-range transport modeling at distant (beyond 50 km) PSD Class I and sensitive Class II areas, the emissions from this main stack only were modeled in the 2004 submittal. Future modeling will use these same procedures for distant Class I and sensitive Class II areas. For short-range modeling (at distances within 50 km of the project site), emissions from fugitive sources and other intermittent and low-level combustion sources were also considered in the 2004 submittal and will be included in future local Class II modeling.

1.2 Overview of past modeling results

The short-range modeling of the project emissions (modeled for both minimum and maximum boiler loads) indicated a significant impact for two criteria pollutants: SO_2 and PM_{10}. The significant impact areas were contained within the Navajo Nation lands. A cumulative inventory was obtained for the area extending out 50 km from the distance to the Significant Impact Area (SIA).. All sources in this inventory were modeled, along with the proposed source, except for very small sources with an emission rate in tons per year (TPY) less than 0.8D (D in km) from the extent of the SIA for SO_2, and 0.3D for PM_{10}. (This exclusion of very small sources is consistent with the approach used for the cumulative inventory for PSD Class I modeling, and equates to 40 TPY for SO_2 and 15 TPY for NO_x at a distance of 50 km.) The cumulative modeling results showed compliance by a wide margin for the National Ambient Air Quality Standards (NAAQS) and the PSD increments.

Long-range modeling (for transport distances beyond 50 km) was conducted for both mandatory PSD Class I areas and also several sensitive Class II areas of interest to the National Park Service and the Forest Service. The Class II results were well below applicable thresholds for increment consumption and increment significance levels. The Class I results were significant for SO_2 only. A modeling analysis with a cumulative inventory was conducted, after an inventory was requested from New Mexico, Colorado, Utah, and Arizona. For two nearby sources (San Juan Generating Station and Four Corners Power Plant), increment-expanding emissions were also considered. The modeling results showed compliance for total SO_2 increment consumption in all Class I areas.

Regional haze modeling was first conducted using the default FLAG approach. Some alternative methods were also applied to account for meteorological interferences, other components of natural background (e.g., natural salt concentrations), and EPA's revised f(RH) curves used in the implementation of the Regional Haze Rule. The result of one of the alternative approaches, which included a detailed analysis of meteorological interference periods and an hourly ratio averaging approach, resulted in an insignificant modeled impact for the proposed facility. The permit application was submitted with the conclusion that the proposed project will not have an adverse impact on regional haze.

Acidic deposition results were also provided as part of the permit application. Although the results were above the deposition analysis thresholds (DATs), these thresholds incorporate a conservative factor of 25 for source clustering, and the results of the modeling showed impacts that were well below that margin.

1.3 Comments on permit application air quality analysis

A summary of comments received on the air quality modeling analysis in the 16 months since the permit application was filed is provided below. Several comments were received regarding the PSD Class I modeling, and very few regarding the Class II (local) modeling. The comments discussed below refer mostly to the Class I modeling issues, and were primarily submitted by the National Park Service.

- Minor source baseline dates need to be identified before a cumulative analysis is conducted.
- The validity of sources in the cumulative inventory is questionable. Some of the emission rates used may be too low. Also, there is a question as to whether minor sources have been accounted for.
- It is not clear whether the increment expansion sources modeled for the Class I SO_2 cumulative inventory are fully creditable.
- The visibility impact analysis resulted in a conclusion of insignificant impacts, but the alternative procedures used in that conclusion are questioned by the National Park Service, such as the way the meteorological interferences were addressed and the quantification of the natural salt particle influence on natural background.
- The meteorological data used in the analysis was not properly evaluated.
- Some of the CALPUFF model system technical options selected need more justification, such as the dispersion option.
- For regional haze, there is a concern about winter events with an easterly wind that could advect the project emissions to the Grand Canyon, have these emissions pass through (and possibly stagnate within) a cloud layer within the Canyon, accelerate formation of a sulfate cloud, and cause a visibility impairment that is under-predicted by CALPUFF. To address this problem, a meteorological wind field with a resolution of 4-12 km is needed. In addition, there is concern that CALPUFF is understating the sulfate transformation inside clouds. On the other hand, ENSR noticed that CALPUFF appears to be overstating the nitrate formation in winter due to its dominance relative to sulfate formation in cold weather, while IMPROVE observations indicated dominance of sulfates rather than nitrates.
- Since the FLAG method did not show low impacts for the proposed facility, a refined analysis must be undertaken to resolve the predicted project impacts.
- The protocol we have discussed to date has really only dealt with the Desert Rock impacts in isolation. The issue of methods for a cumulative impact assessment is not covered. We expect that a cumulative assessment will still be done.
- We want to be clear that the modeling protocol as currently presented will not satisfy two of our primary concerns. First, there is still no consideration of aqueous phase conversion of sulfates.

> Secondly, the meteorological fields proposed for use are still unlikely to capture some of the important flow phenomena that lead to impacts in the Class I areas in the region. We are attempting to generate more accurate wind fields for some specific time periods, and will make them available to you as soon as they are available. We anticipate looking at these results as well as refining previous work done at the NPS when making our recommendations. We will need copies of all of the CALPUFF input and output files to complete our evaluations.

The next two sections discuss a resolution to these comments and how the next round of modeling will be conducted.

2.0 Resolution of comments regarding the modeling analysis

This section presents each comment stated above, and then provides a discussion regarding a response to the comment.

1. Minor source baseline dates need to be identified before a cumulative analysis is conducted.

Discussion: these dates have been assembled by WESTAR and are available at http://www.westar.org/Committees/TDocs/AQCR%20maps/SO2_02Dec04.pdf. The emission inventories already supplied by each state are consistent with these dates.

2. The validity of sources in the cumulative inventory is questionable. Some of the emission rates used may be too low. Also, there is a question as to whether minor sources have been accounted for.

Discussion: The cumulative emission inventories are most likely overstating increment consumption because increment expanding sources (other than perhaps San Juan Generating Station and Four Corners Power Plant) are not included. In addition, the implementation of the on-road ultra-low diesel sulfur fuel program in 2006 and off-road diesel program in the 2007-2010 time frame. As Scott Bohning indicated in his April 29, 2005 notes for the May 3, 2005 meeting, the "states seem to agree that minor source growth does not pose a problem for SO_2 increment."

For the Electric Generation Unit (EGU) sources in the inventory that already exist, EPA Region 9 has conducted a thorough review of the emissions, and has determined that the use of the 99th percentile emission rate will be sufficiently conservative so as to estimate the maximum routine operations. The EPA analysis is further described in Section 3.

3. It is not clear whether the increment expansion sources modeled for the Class I SO_2 cumulative inventory are fully creditable.

Discussion: This issue has been resolved by EPA Region 9, and is further discussed in Section 3 and Appendix A.

4. The visibility impact analysis resulted in a conclusion of insignificant impacts, but the alternative procedures used in that conclusion are questioned by the National Park Service, such as the way the meteorological interferences were addressed and the quantification of the natural salt particle influence on natural background.

Discussion: There has been an evolution of techniques that have been proposed and discussed to deal with the issue of meteorological interferences. This is an important issue because the peak modeled visibility impacts using the default FLAG approach can often occur during high relative humidity conditions, and these conditions can often be associated with natural obscuration such as fog, snow, rain, etc. These factors are not taken into account in CALPOST. The problem with procedures that attempt to address these conditions on a case-by-case basis is that the required analysis resources are extensive and the information regarding actual obscuration is often incomplete. Therefore, significant disagreements can occur regarding how to handle individual events.

An alternative approach to a case-by-case meteorological interference analysis is to adopt the method in EPA's final BART rules for determining whether an existing source has an adverse visibility impact on any Class I area. That approach involves the following method:

a. Use Method 6 in CALPOST, which uses monthly average relative humidity values in the f(RH) calculation.

b. For each year (or over 3 years), take the 98% highest daily impact at any point in the Class I area to compare to a 0.5 deciview (or 5% extinction change) threshold for significance. For a one-year analysis, this would involve looking at the 8th highest day's impact at each receptor, while for a three-year analysis, it would involve the 22nd highest over the entire period.

5. The meteorological data used in the analysis was not properly evaluated.

Discussion: A comparison of the meteorological data at several surface airport stations was submitted with the permit application. However, some changes to the meteorological data are being proposed that will adopt publicly available data that have been independently reviewed. For 2001, we will use the 36-km data documented by McNally (2003). For 2002, we will use the recently-completed WRAP 12-km MM5 database, as documented by ENVIRON and UC Riverside (2004). For 2003, we will continue to use the 20-km RUC data, provided by Earth Tech. Three additional periods provided by the FLMs for a review of specific regional haze impacts will also be included.

6. Some of the CALPUFF model system technical options selected need more justification, such as the dispersion option. We would like to see CALPUFF run with the P-G dispersion option as our preferred choice. If the applicant uses the AERMOD-like MDISP=2 option only, the National Park Service will rerun CALPUFF with MDISP=3, thus delaying the review of the permit application.

Discussion: There has been extensive discussion of these options, and we have come to an agreement with the National Park Service. The agreed-upon options are listed in Section 3.

Additional information regarding the dispersion option is provided here. An EPA study available at http://www.epa.gov/scram001/7thconf/calpuff/tracer.pdf presents a comparison of CALPUFF predictions vs. observations for some far-field experiments and has mixed conclusions about the two dispersion options mentioned above. In the main report, the figures showing the crosswind concentration distributions predicted by CALPUFF with MDISP=2 and MDISP=3 overall show that when there are differences, the peak predictions are higher for MDISP=3, but that the MDISP=2 peak predictions generally have a better agreement with the observed peak values. This can be seen most clearly in Figure 3 and in Figure 4a (two different experiments). The Appendix A to the EPA report seems to provide a reverse conclusion for one experiment, showing overpredictions with the similarity dispersion curves and better agreement with the P-G curves. Therefore, there are mixed results reported here for the tendency of the two different options to predict higher or lower relative to each other for long-range transport, although two different experiments showed better performance with MDISP=2. In general, the choice of MDISP=2 does not appear to lead to underpredictions of the peak impact, and it is more accurate most of the time.

It is also noteworthy that the model developer, Earth Tech presents in its CALPUFF courses (Scire, 2005) the following features of the Pasquill-Gifford coefficients vs. the turbulence-based dispersion coefficients:

The P-G dispersion coefficients:

- are based on ground-level releases over short distances
- neglect variation of diffusion with height
- neglect variation of diffusion due to surface characteristics (except urban/rural distinction).

The turbulence-based dispersion coefficients:

- are continuous functions of height, surface properties, and measured or estimated values of σ_v, σ_w

- include spatial variability in dispersion rates; puffs respond to surface characteristics as they move
- respond to changes in surface roughness, soil moisture, and other surface parameters.

We do not have any further technical justification from the National Park Service regarding their choice of MDISP = 3, an option that is associated with a model (ISC) that is now being phased out by EPA. Accordingly, we will present results with MDISP = 3, but may include results as well with MDISP=2 (and MPDF=1) in some cases, especially for regional haze results, to provide more complete information for the reviewers.

7. For regional haze, there is a concern about winter events with an easterly wind that could advect the project emissions to the Grand Canyon, have these emissions pass through (and possibly stagnate within) a cloud layer within the Canyon, accelerate formation of a sulfate cloud, and cause a visibility impairment that is under-predicted by CALPUFF. Such impairment is typically seen after the clouds evaporate, and is usually limited to 24 hours or less. To address this issue, the FLMs feel that a meteorological wind field with a resolution of 4-12 km is needed. In addition, there is concern that CALPUFF is understating the sulfate transformation inside clouds. On the other hand, ENSR noticed that CALPUFF appears to be overstating the nitrate formation in winter due to its dominance relative to sulfate formation in cold weather, while IMPROVE observations indicated dominance of sulfates rather than nitrates.

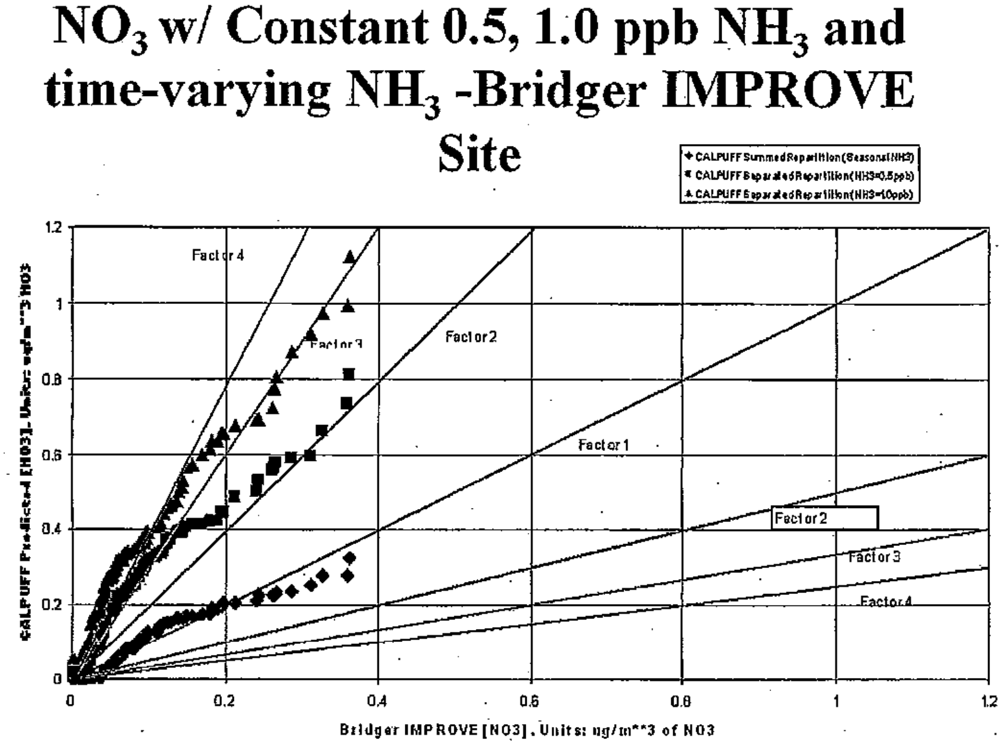
Discussion: We have had numerous discussions about this issue. At this time, it is not possible to change CALPUFF to enhance its treatment of aqueous-phase chemistry because the model developer, Earth Tech, is not currently prepared to take on that task. Joe Scire of Earth Tech also notes (2005) that an advanced algorithm for aqueous phase chemistry is highly dependent upon the concentration of hydrogen peroxide, which is not generally known. Therefore, it is not advisable to adopt a more advanced algorithm until scientists achieve a better understanding of hydrogen peroxide concentrations in the atmosphere. Any advanced treatment would directly access liquid water content input data, rather than the relative humidity surrogate values currently used.

As noted above, there is no appropriate "quick fix" to this treatment. The use of Eulerian regional models such as CAMx or CMAQ have other difficulties, such as lack of regulatory approval and insufficient validation; they could be challenged as unproven alternate models to CALPUFF and may suffer from the same dependence upon the unknown concentrations of hydrogen peroxide and other compounds. In addition, plume dispersion for individual sources is not adequately simulated in these models unless the meteorological resolution is very good (such as 4 km), which makes the effort involved too unwieldy.

To move on, we will run CALPUFF with its current algorithms for the proposed project and then provide for agency review a series of animation files of the concentration fields for further analysis for specific periods that the FLMs identify that are of interest.

The likely overprediction of nitrates in winter can be addressed by using a monthly variation of background ammonia concentrations. The default value of 1.0 ppb for arid lands as referenced in the IWAQM Phase 2 document is valid at 20 deg C, but the same document cites a strong dependence with ambient temperature, with variations of a factor of 3-4. This same dependence is seen at the CASTNET monitor at Bondville, Illinois (see page 5 at http://www.ladco.org/tech/monitoring/docs_gifs/NH3proposal-revised3.pdf). In addition, a study of light-affecting particles in SW Wyoming indicated that nitrates were overpredicted by a factor of 3 for a constant ammonia concentration of 1.0 ppb, and by a factor of 2 for an ammonia concentration of 0.5 ppb (see Figure 2-1, also provided as slide 57 at http://www.air.dnr.state.ga.us/airpermit/psd/dockets/longleaf/facilitydocs/050711_CALPUFF_eval.pdf). Since there are no large sources of ammonia due to agricultural activities near the Class I areas being analyzed, it is appropriate to introduce a monthly varying ammonia background concentration to the CALPUFF modeling. The following values are proposed (and have been agreed to by the National Park Service):

Figure 2-1 Prediction of NO_3 as a function of ammonia background concentration in SW Wyoming



- January- March: 0.2 ppb (average temperature ~ 20-40 deg F)
- April-May: 0.5 ppb (average temperature 40-50 deg F)
- June-September: 1.0 ppb (average temperature 60-70 deg F)
- October - November: 0.5 ppb (average temperature 40-50 deg F)
- December: 0.2 ppb (average temperature ~ 30 deg F).

Even the relative low wintertime estimate of 0.2 ppb could be too high for the coldest days that appear to trigger the most nitrate formation in the model, so additional sensitivity modeling may be presented for cold-weather months.

8. Since the FLAG method did not show low impacts for the proposed facility, a much more refined analysis must be undertaken to resolve the predicted project impacts.

Discussion: The FLAG method has several conservative features, most notably the inability to handle cases of peak visibility impact predictions when the natural visibility is limited due to nighttime conditions or obscuration due to precipitation and fog. Therefore, we conducted alternative analyses, which can show lower facility impacts. This was done for the May 2004 submittal. In this revised analysis, we will conduct a simpler alternative analysis along the lines of the BART approach. If such an approach shows low impacts (98% day with less than 0.5 deciview change), then we do not believe that a refined analysis is needed. The manner in which a refined analysis could be conducted is not defined, and has no precedent that the applicant is aware of.

9. The protocol we have discussed to date has really only dealt with the Desert Rock impacts in isolation. The issue of methods for a cumulative impact assessment is not covered. We expect that a cumulative assessment will still be done.

Discussion: We assume that this comment addresses the need for a cumulative impact assessment for regional haze. If so, it is first helpful to review two possible results from the modeling analysis for the proposed facility alone that determine whether a cumulative regional haze modeling analysis is needed.

One possible result is that the proposed project's impacts are shown not to cause a perceptible impact on regional haze in a Class I area. Although the application of a strict FLAG procedure once again may show impacts over a 5% extinction change from natural background, an alternative analysis may indicate no perceptible impact. Since FLAG arguably has many conservative assumptions, we will also look at the alternative analysis for concluding whether the proposed project's emissions are likely to cause a perceptible visibility impact. We will also provide a substantial amount of information to the National Park Service for their review as well. If the project shows an extinction change below 5% of natural background conditions, then a cumulative regional haze analysis is not needed.

Even if the proposed project could potentially have a perceptible visibility impact, it is clear from the language in a comment provided by the National Park Service that *sulfate is a major constituent of regional haze in the Four Corners area*. (Other components of lesser importance are NO_x and PM_{10} emissions.) The proposed facility will emit a maximum of about 3,300 tons per year of SO_2 and NO_x, and about 1,100 TPY of PM_{10}. As we noted in our presentation at the May 3, 2005 meeting in Fort Collins, the recently announced reductions of emissions from the nearby San Juan Generating Station are as follows by the year 2010, relative to emissions in 1999:

- SO_2 annual emissions reduced by nearly 7,000 TPY (vs. about 3,300 TPY Desert Rock)
- NO_x annual emissions reduced by about 7,000 TPY (vs. about 3,300 TPY Desert Rock)
- PM_{10} annual emissions reduced by nearly 2,500 TPY (vs. about 1,100 TPY Desert Rock)

In addition, recent changes in emissions at the nearby Four Corners Power Plant are also important to account for in the cumulative impact evaluation. These changes appear to be voluntary SO_2 emission reductions throughout 2004 due to increased scrubbing efficiency, and can be seen from data posted on the EPA's Acid Rain Database. Annual SO_2 emissions appear to be dropping from about 35,000 TPY to about 15,000 TPY, a reduction of some 20,000 TPY.

It is clear from the above tallies of emission reductions in the Four Corners area that a cumulative analysis, which should properly account for recent voluntary emission reductions, would clearly show that the reductions are many times the increases from the proposed project, especially for SO_2. Therefore, a cumulative regional haze analysis is clearly not necessary, because the cumulative impact will be an improvement even with the project's emissions included.

10. We want to be clear that the modeling protocol as currently presented will not satisfy two of our primary concerns. First, there is still no consideration of aqueous phase conversion of sulfates. Secondly, the meteorological fields proposed for use are still unlikely to capture some of the important flow phenomena that lead to impacts in the Class I areas in the region. We are attempting to generate more accurate wind fields for some specific time periods, and will make them available to you as soon as they are available.

We anticipate looking at these results as well as refining previous work done at the NPS when making our recommendations. We will need copies of all of the CALPUFF input and output files to complete our evaluations.

Discussion: As we have discussed extensively since the May 3 meeting, we attempted to engage the services of Joe Scire and Earth Tech to include enhancements to CALPUFF to address the concerns of the National Park Service. These attempts were unsuccessful. One reason for this is that the model developer does not feel that sufficient information about certain important compounds involved in SO_2 to sulfate transformation, such as hydrogen peroxide concentrations, is available to allow an enhanced algorithm to be practical. Basically, the unknowns associated with a more advanced algorithm make it unworkable at this time. Alternative modeling approaches might be SCICHEM for a Lagrangian model such as CALPUFF and Eulerian models such as CMAQ and CAMx; they may suffer from the same poor knowledge of certain critical compounds. None of these models have been used in a single-source PSD permitting application that we know of.

While advanced Eulerian models such as CAMx or CMAQ may better address the aqueous phase chemistry issue, the model dispersion is poorly characterized near the source and is dependent upon the grid size, as noted in the National Park Service's comments about REMSAD modeling that were provided prior to the May 3 meeting. Even if a 4-km grid size were to be developed for CAMx, the model running time might be as long as 2 weeks per simulation month, or about 50% of real time. Such a model run would be too resource-intensive for modeling a single source. In addition, a demonstration that the concentration predictions from CAMx and CMAQ are better than those of CALPUFF, which is required for use of an alternative model, is not available to our knowledge.

Therefore, we are proceeding with CALPUFF, but providing information on concentration patterns with animation files so that possible interactions of the plume with clouds can be further reviewed by the National Park Service. We will also provide concentration files so that, if warranted for a particular period, the National Park Service can add the SO_2 concentrations (multiplied by 1.5) to the SO_4 concentrations to simulate complete transformation to sulfate.

In terms of the adequacy of the meteorological data, we are using 3 years of the best available MM5 data, including the 12-km 2002 WRAP database. We are accommodating periods of 4-km MM5 as provided by the National Park Service that cover the periods identified as being of particular interest.

3.0 Procedures for final modeling of proposed project

3.1 Stack emission data

The facility layout has been revised since the May 2004 permit application, with the main stack location shifted within the plant boundaries. The new main stack location, within a meter, will be 719,690 UTM East and 4,041,760 UTM North, Zone 12, NAD 83. Exhaust characteristics of the stack have not changed. The stack emissions and the dependence of the exhaust parameters on ambient temperature are listed in Section 6.2.2 of the May 2004 PSD Permit Application document.

For purpose of regional haze modeling, the PM_{10} emissions are further speciated as specified by Sithe Global:

- Half of the emissions are assumed to be filterable, and half condensable (0.010 lb/MMBtu for each portion).
- The particle size distributions are based on the EPA's *Compilation of Air Pollutant Emission Factors, Publication AP-42,* Tables 1.1-5 (for a baghouse control technology) and 1.1-6. The size ranges considered are based on AP-42 Table 1.1-6, which provides size ranges for filterable PM. Table 1.1-5 of AP-42 indicates that condensable PM can be assumed to be < 1.0 micron in diameter. Therefore, the non-sulfate condensable emissions will be assigned to the smallest size category. Sulfate emissions are modeled separately as primary $SO_4^=$.
- Of the total filterable PM_{10} emissions, 96.3% of "fine" particulate emissions are considered "soils", and 3.7% elemental carbon (following guidance in AP-42 Table 1.1-5); all of the "coarse" particles are assumed as "soils". The elemental carbon is provided a size distribution throughout the fine particle categories in the proportion assigned to the four size categories in the sub-2.5 micron range. The condensable PM emissions will be considered to be composed of H_2SO_4 and secondary organic aerosols, all in the smallest size category.

The Class I analysis modeling will consider only the main stack only at 100 percent load. A SCREEN3 analysis, provided in Appendix D of the modeling protocol submitted in May 2004 indicates that the lowest normal operating load case (40% of capacity) can possibly lead to the highest near-field concentration predictions. Therefore, for the Class II analysis, the main stack at both 40 and 100 percent (maximum and minimum) load for both one and two units operating will be modeled (stack parameters for these cases have not changed from the May 2004 submittal). Emissions from the auxiliary boiler, the diesel generator and fire water pump, and the material-handling sources will also included in the Class II compliance analysis.

3.2 PSD Class II modeling procedures

A local modeling domain that extends approximately 125 km in the east-west direction and 190 km in the north-south direction from the proposed facility location is proposed for this near-field Class II CALPUFF modeling analysis (and the Class I analysis for Mesa Verde), as shown in Figure 3-1. The grid spacing for this analysis is 500 m.

For the Class II modeling within 50 km, plant emissions from the main stack as well as low-level combustion and fugitive sources will be included. The plant impacts will be compared with Significant Impact Levels to determine the need for cumulative modeling. Based upon previous results, cumulative modeling is likely to be required for SO_2 and PM_{10}. In a cumulative modeling assessment, the project sources, along with secondary sources (such as the BHP mine emissions) and other nearby sources will be modeled with CALPUFF to demonstrate compliance with PSD Class II increments and the NAAQS.

3.3 PSD Class I modeling procedures

For the Class I modeling (and for distant sensitive Class II areas that were previously modeled), CALPUFF will be used as described in Section 2 for the main stack emissions as described in Section 3.1. The project is likely to have a modeled significant impact for SO_2, but not for PM_{10} and NO_2. Therefore, we have had extensive discussions with EPA Region 9 regarding the sources and emission rates for the cumulative analysis for SO_2. More details regarding this inventory are provided in Appendix A.

The regional haze modeling will be conducted using the FLAG approach (with an RHMAX = 95% and EPA f(RH) curves), and alternative analyses will consider the following features:

- Using the BART approach with Method 6 and reporting the 98% day (8th highest for each year, and 22nd highest over 3 years) to determine whether the project has an impact over 0.5 deciviews (about 5% change in extinction)
- Use of a finer grid resolution for areas such as Mesa Verde, for which a grid spacing as small as 0.5 km may be run, as described above. The purpose of this exercise would be to better define the terrain features within the modeling domain, especially at the nearest Class I area.
- Use of an alternative dispersion option (similar to the AERMOD treatment) may be considered for the project emission impact because this method is consistent with EPA's recent updates for short-range model, for which ISCST3 has been replaced by AERMOD.

Files showing the isopleths of gridded concentration data will be provided for review by the FLMs. If feasible, liquid water content fields associated with the MM5 data will also be displayed.

The CALPUFF modeling will be conducted for all aspects of the analysis (PSD increment consumption, regional haze, and acidic deposition) for the period 2001-2003. The National Park Service has provided 4-km and 12-km MM5 data for the following periods (involving complete days of data):

- 2001: January 3 – January 29
- 2003: January 1 – January 16
- 2004: April 20 – May 1.

These periods will be run only for the assessment of regional haze impacts because they were provided to us due to specific concerns for that Air Quality Related Value (AQRV). Results for these periods will be directly compared to the same periods with the full year MM5 data for 2001 and 2003.

For these selected periods, 4-km MM5 data is not available at all PSD Class I areas within 300 km of the proposed project site. However the 12-km MM5 data does cover all of the Class I areas within 300 km of the project site. Therefore, the selected periods mentioned above will be run with 4-km MM5 data for:

- Canyonlands
- Capitol Reef
- Grand Canyon
- Mesa Verde
- Weminuche.

Portions of these Class I areas that are either very close to the edge or outside of the 4-km MM5 data set or are greater than 300 km from the proposed source will not be assessed with this grid. The 4-km MM5 runs will be conducted with a 3-km CALMET grid resolution (except for Mesa Verde) and the domain depicted in Figure 3-1.

The remaining Class I areas will be assessed using the 12-km MM5 for the same periods of interest. Those areas are as follows:

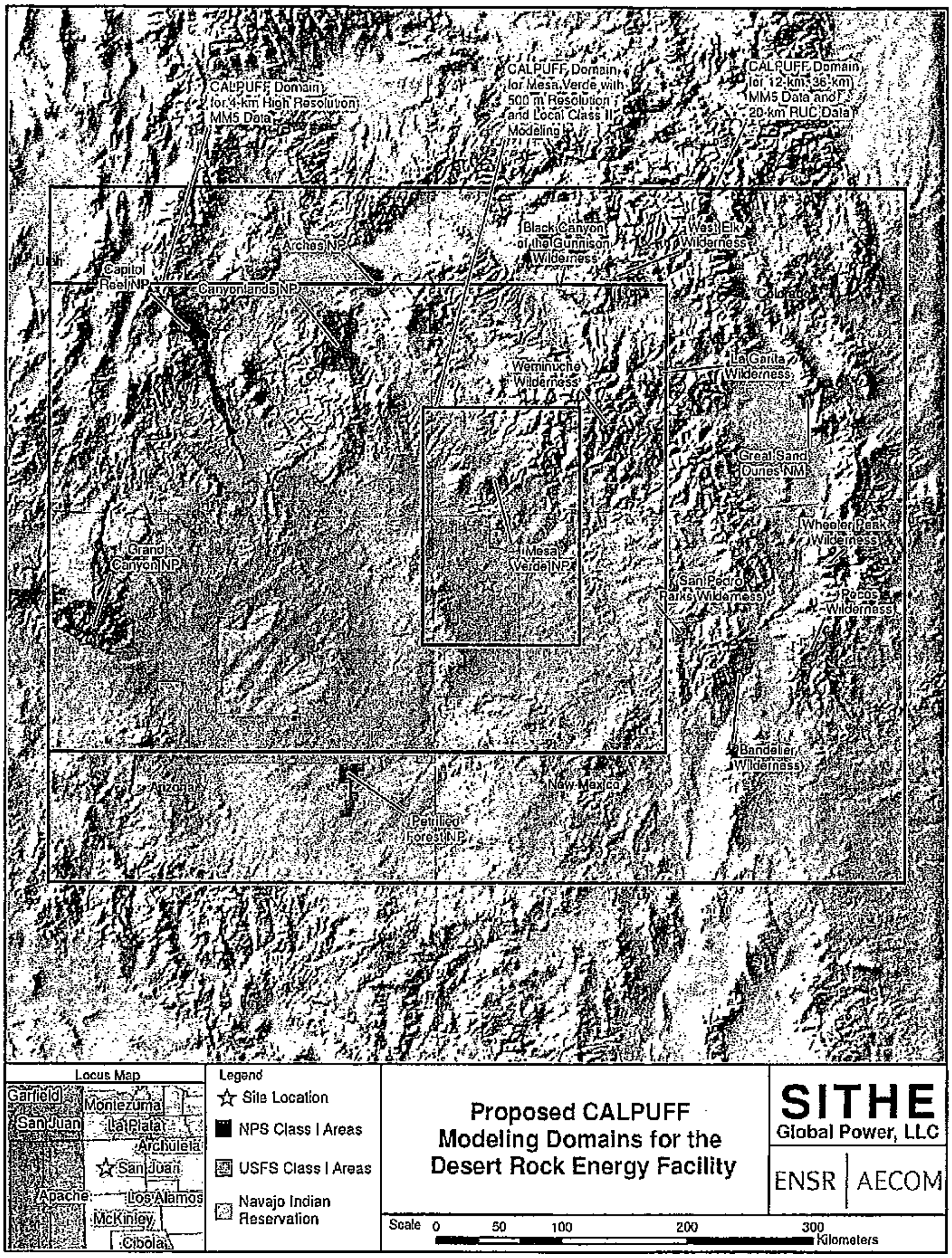
- Arches
- Black Canyon of the Gunnison
- Bandelier
- Great Sand Dunes
- La Garita
- Pecos
- Petrified Forest
- San Pedro Park
- West Elk
- Wheeler Peak

The 12-km MM5 runs will be conducted with 4-km CALMET grid resolution and the original domain designed for this project as depicted in Figure 3-1.

The following technical options and settings have been agreed upon by EPA Region IX, the NPS, and ENSR.

- The monthly background ammonia values listed in Section 2 will be used.
- Puff splitting will not be activated. Sensitivity runs with this option produced small changes in the modeling results, but with large effects upon model runtime.
- MDISP = 3 (P-G dispersion coefficients) will be used for the CALPUFF modeling. In some sensitive areas such as regional haze impacts of the proposed project or SO_2 increment consumption analyses, an alternative modeling assessment using MDISP=2 and MPDF=1 may be provided.
- For certain CALMET settings, the following guidance applies:
  - 4-km MM5 (for certain Class I Areas from periods in 2001, 2003, and 2004):
    - TERRAD = 10 km
    - R1 = 2 km
    - R2 = 20 km
    - RMAX1 = 6 km
    - RMAX2 = 30 km
  - 12-km MM5 (all of 2002 and for certain Class I Areas from periods in 2001, 2003, and 2004):
    - TERRAD = 10 km
    - R1 = 6 km
    - R2 = 20 km
    - RMAX1 = 12 km
    - RMAX2 = 30 km

Figure 3-1 Depiction of CALMET/CALPUFF modeling domains



- 20-km RUC (all of 2003):
  - TERRAD = 10 km
  - R1 = 10 km
  - R2 = 20 km
  - RMAX1 = 20 km
  - RMAX2 = 30 km

- 36-km MM5 (all of 2001):
  - TERRAD = 10 km
  - R1 =18 km
  - R2 = 20 km
  - RMAX1 = 30 km
  - RMAX2 = 100 km

ENSR has already provided meteorological evaluations of the MM5 data used in the May 2004 submittal. Of these MM5 data sets, the 2001 and 2002 data sets are being replaced by publicly available data used in several regional modeling exercises. Reports describing the meteorological evaluations for the 2001 and 2002 MM5 databases are available (McNally, 2003 and ENVIRON and UC Riverside, 2004). Independent evaluations of the 4-km MM5 databases supplied directly from the National Park Service will not be conducted.

The National Park Service may conduct their own analysis of possible periods for which significant aqueous phase chemistry transformation of SO_2 to sulfates should be predicted to occur.

4.0 References

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Appendix A
Cumulative SO_2 PSD Inventory

Appendix A: Cumulative SO_2 PSD inventory

Key issues with regard to the appropriate entries in the cumulative SO_2 PSD increment inventory for this project are:

1. What is the appropriate emission rate that reflects "maximum actual" emissions, especially if facility-wide emissions could reflect periods with some units lower than peak production or even off-line?

Discussion: EPA Region 9 talked to other EPA regions on this question. There seems to be agreement that one should use the maximum actual hourly rate, though some regions felt there was some justification for using, e.g., 90th percentile as indicative of "normal" source operation, as opposed to the 100th percentile, which would include anomalous spikes, as it does for at least some of the Four Corners Power Plant (FCPP) units. In Region 8's own modeling for North Dakota SO_2 increment, 90th percentile was used because it is very unlikely that all sources would simultaneously operate at their maximum; and further, the sum of the 90th percentiles was close to the maximum emissions that actually occurred. In this case, the sources are not as clustered as they are for the North Dakota situation, so a percentile value closer to 100% would be conservative. Due to the fact that the 100th percentile case does include hours that involve upset conditions, and because the shortest regulatory averaging time is 3 hours for SO_2, a 99th percentile selection based upon hourly values for emitting unit should be quite conservative. For more conservatism, the 99th percentile is taken only from the nonzero emission hours for each EGU unit for years 2003 and 2004, and averaged to provide the emission value for input to the model.

2. For the Four Corners Power Plant and the San Juan Generating Station, what are the appropriate baseline emissions that reflect the same "maximum actual" treatment as current emissions?

Discussion: There were Federal Register notices in 1981 that addressed appropriate emission limits for the FCPP and San Juan Generating Station (SJGS) units. Language from 46 FR 30653-30654, June 10, 1981 states: "The revised emission limits provide for an average of 60 percent control for Four Corners units 1, 2 and 3 and no control on units 4 and 5 by the end of 1982, and an average of 72 percent control for the entire Four Corners plant (5 units total) by the end of 1984." "Plant-wide average SO_2 emissions will be 0.47 lb/MMBtu for The Four Corners plant and 0.65 lb/MMBtu for the San Juan plant after 1984."

In summary, for FCPP, the 1981 SO_2 limit requirement for 1984 is 0.47 lb/MMBtu for FCPP; 72% control. For SJGS, the 1981 limit requirement for 1984 is 0.65 lb/MMBtu. These values are long-term averages. To obtain maximum short-term peaks for the baseline period, a ratio of peak to mean will be established for each relevant unit at FCPP and SJGS for 2003 and 2004, and then applied to this mean baseline emissions given above to represent the peak short-term baseline emissions for each unit.

The resulting SO_2 PSD increment inventory is provided in Table A-1. The modeling archive will include spreadsheets that support the values provided in the table.

Table A-1 SO_2 PSD increment inventory

Facility Name	Lat (deg)	Long (deg)	Base El. (m)	2003-2004 99%tile Emissions (g/s)	Stack Height (m)	Stack Temp (K)	Exit Velocity (m/s)	Stack Diameter (m)
PSD Increment Consuming Sources								
Desert Rock	36.50	-108.55	1645.8	102.810	279.50	323.15	24.99	11.21
Cholla Unit 2	34.93	-110.30	1529.0	89.089	167.64	348.71	34.14	4.48
Springerville GS	34.32	-109.17	2128.0	1064.432	152.40	339.00	21.30	6.10
Abitibi Consolidated	34.50	-110.33	1844.0	43.650	65.23	380.37	18.35	3.66
AE Staley MFG	37.58	-106.09	2322.6	2.451	5.18	1273.00	20.80	0.10
Nixon Unit 1	38.63	-104.71	1676.4	220.322	140.21	422.59	19.62	5.33
Kinder Morgan	37.47	-108.79	2017.8	1.008	6.10	644.26	2.54	0.61
Cameo Station (current)	39.15	-108.32	1463.0	82.566	45.72	399.81	7.77	2.67
Nucla Station	38.24	-108.51	1694.7	69.466	65.53	408.15	23.34	3.66
Holcim-Florence	38.38	-105.02	1536.2	109.000	110.00	376.00	14.52	6.00
Holcim-Florence	38.38	-105.02	1536.2	44.900	110.00	356.00	13.99	1.70
Hunter Unit 2	39.17	-111.03	1723.6	103.210	182.88	329.26	17.82	7.32
Hunter Unit 3	39.17	-111.03	1723.6	92.767	182.88	322.04	16.63	7.32
Lisbon Flare	38.16	-109.28	1828.8	1.155	12.20	613.15	83.58	0.46
Lisbon Incinerator	38.16	-109.27	1828.8	38.800	64.98	736.76	7.35	1.83
Consolidated Constr.	36.71	-108.24	1638.3	4.299	12.80	427.59	19.60	1.036
San Juan GS Unit 3	36.80	-108.44	1614.9	264.835	121.92	322.04	15.85	8.534
San Juan GS Unit 4	36.80	-108.44	1614.9	299.264	121.92	322.04	15.85	8.534
Bloomfield Refinery	36.70	-107.97	1673.3	5.383	24.38	1273.15	20.12	0.305
Peabody Mustang	35.66	-107.91	2112.3	43.474	147.28	343.09	18.29	5.505
Tri-State Escalante	35.41	-108.08	2103.8	47.110	138.07	324.26	15.24	6.096
PSD Increment Expanding Sources*								
Cameo Station (baseline)	39.15	-108.32	1463.0	-79.254	12.65	416.5	2.29	45.72
San Juan Unit 1	36.80	-108.44	1614.9	-373.839	121.92	317.59	18.29	6.096
San Juan Unit 2	36.80	-108.44	1614.9	-348.371	121.92	317.59	18.29	6.096
Four Corners Unit 1	36.69	-108.48	1615.0	-79.627	76.20	327.59	18.29	5.36
Four Corners Unit 2	36.69	-108.48	1615.0	-67.202	76.20	327.59	18.29	5.36
Four Corners Unit 3	36.69	-108.48	1615.0	-62.855	76.20	327.59	31.63	4.36
Four Corners Unit 4	36.69	-108.48	1615.0	-162.148	115.82	333.15	23.89	8.69
Four Corners Unit 5	36.69	-108.48	1615.0	-109.897	115.82	333.15	18.29	8.69
*Baseline peak emissions listed								

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NY, Syracuse Air Lab
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Colorado Department of Public Health and Environment – CALMET/CALPUFF Modeling Protocol dated October 24, 2005 (Ammonia Sensitivity Tests)

CALMET/CALPUFF BART Protocol for Class I Federal Area Individual Source Attribution Visibility Impairment Modeling Analysis

October 24, 2005

Colorado Department of Public Health and Environment
Air Pollution Control Division
Technical Services Program
4300 Cherry Creek Drive South
Denver, Colorado 80246

Table of Contents

1. Introduction

Federal law requires Best Available Retrofit Technology (BART) for any BART-eligible source that ''emits any air pollutant which may reasonably be anticipated to cause or contribute to any impairment of visibility" in any mandatory Class I federal area. Pursuant to federal regulations, states have the option of exempting a BART-eligible source from the BART requirements based on dispersion modeling demonstrating that the source cannot reasonably be anticipated to cause or contribute to visibility impairment in a Class I area.

Federal regulations implementing the BART requirement afford states some latitude in the criteria in determining whether a BART-eligible source is subject to BART. The Division has proposed state regulations establishing criteria and procedures for determining which Colorado sources will be subject to the BART requirement. The Division's proposal is scheduled for a December 15, 2005 hearing before the Air Quality Control Commission. In advance of the hearing, and in preparation for the submittal of a state implementation plan for regional haze, the Division will perform air quality modeling with the CALPUFF modeling system to assess which BART-eligible sources in Colorado are likely to be subject to BART based on the proposed state regulation.

According to 40 CFR Part 51, Appendix Y (BART guideline), a BART-eligible source is considered to "contribute" to visibility impairment in a Class I area if the modeled 98th percentile change in deciviews is equal to or greater than the "contribution threshold." Any BART-eligible source determined to cause or contribute to visibility impairment in any Class I area is subject to BART. The Division has proposed a state regulation establishing a "contribution threshold" of 0.5 deciviews.

The Division will apply CALPUFF with at least three years of meteorological data to determine if the 98th percentile 24-hour change in visibility (delta-deciview) from a BART-eligible source is equal to or greater than a contribution threshold of 0.5 deciviews at any Class I area. The initial phase of the BART modeling process is referred to as the "subject-to-BART" analysis. The modeling includes SO2, NOx, and direct PM10 emissions from all BART-eligible units at a given facility.

The Division will use this protocol for the initial subject-to-BART modeling. However, additional modeling performed by the Division or source operator may supersede the results. Subsequent modeling should use modeling techniques consistent with the recommendations in this protocol and the BART guideline. The Division may approve deviations from this protocol for a specific source if the changes are acceptable to U.S. EPA and improve model performance while retaining consistency with the BART guideline. All modeling will be subject to Division review and approval.

The contribution threshold and other criteria used for this modeling demonstration have not been finalized and may change in the final rule adopted by the Commission. Therefore, the results of modeling performed with this protocol are not a final agency action. Any source that the Division determines is subject to BART will receive a separate notice of the agency's final determination. Such separate notice will occur after the Commission acts on the proposed regulations establishing criteria and procedures for determining which sources will be subject to the BART requirement.

Relevant language from the BART guideline is included, below, to show the modeling recommendations in context. Other sections of this protocol explain how the Division proposes to implement the recommendations. The BART guidelines set out 40 CFR Part 51, Appendix Y, provide in part:

> ***III. HOW TO IDENTIFY SOURCES "SUBJECT TO BART"***
> *Once you have compiled your list of BART-eligible sources, you need to determine whether (1) to make BART determinations for all of them or (2) to consider exempting some of them from BART because they may not reasonably be anticipated to cause or contribute to any visibility impairment in a Class I area. If you decide to make BART determinations for all the BART-eligible sources on your list, you should work with your regional planning organization (RPO) to show that, collectively, they cause or contribute to visibility impairment in at least one Class I area. You should then make individual BART determinations by applying the five statutory factors discussed in Section IV below.*
>
> *On the other hand, you also may choose to perform an initial examination to determine whether a particular BART-eligible source or group of sources causes or contributes to visibility impairment in nearby Class I areas. If your analysis, or information submitted by the source, shows that an individual source or group of sources (or certain pollutants from those sources) is not reasonably anticipated to cause or contribute to any visibility impairment in a Class I area, then you do not need to make BART determinations for that source or group of sources (or for certain pollutants from those sources). In such a case, the source is not "subject to BART" and you do not need to apply the five statutory factors to make a BART determination. This section of the Guideline discusses several approaches that you can use to exempt sources from the BART determination process.*
>
> ***A. What Steps Do I Follow to Determine Whether A Source or Group of Sources Cause or Contribute to Visibility Impairment for Purposes of BART?***
> ***1. How Do I Establish a Threshold?***
> *One of the first steps in determining whether sources cause or contribute to visibility impairment for purposes of BART is to establish a threshold (measured in deciviews) against which to measure the visibility impact of one or more sources. A single source that is responsible for a 1.0 deciview change or more should be considered to "cause" visibility impairment; a source that causes less than a 1.0 deciview change may still contribute to visibility impairment and thus be subject to BART.*
>
> *Because of varying circumstances affecting different Class I areas, the appropriate threshold for determining whether a source "contributes to any visibility impairment" for the purposes of BART may reasonably differ across States. As a general matter, any threshold that you use for determining whether a source "contributes" to visibility impairment should not be higher than 0.5 deciviews.*

In setting a threshold for "contribution," you should consider the number of emissions sources affecting the Class I areas at issue and the magnitude of the individual sources' impacts.[5] In general, a larger number of sources causing impacts in a Class I area may warrant a lower contribution threshold. States remain free to use a threshold lower than 0.5 deciviews if they conclude that the location of a large number of BART eligible sources within the State and in proximity to a Class I area justify this approach.[6]

2. What Pollutants Do I Need to Consider?

You must look at SO2, NOx, and direct particulate matter (PM) emissions in determining whether sources cause or contribute to visibility impairment, including both PM10 and PM2.5. Consistent with the approach for identifying your BART-eligible sources, you do not need to consider less than de minimis emissions of these pollutants from a source.

As explained in section II, you must use your best judgement to determine whether VOC or ammonia emissions are likely to have an impact on visibility in an area. In addition, although as explained in Section II, you may use PM10 an indicator for particulate matter in determining whether a source is BART eligible, in determining whether a source contributes to visibility impairment, you should distinguish between the fine and coarse particle components of direct particulate emissions. Although both fine and coarse particulate matter contribute to visibility impairment, the long-range transport of fine particles is of particular concern in the formation of regional haze. Air quality modeling results used in the BART determination will provide a more accurate prediction of a source's impact on visibility if the inputs into the model account for the relative particle size of any directly emitted particulate matter (i.e. PM_{10} vs. $PM_{2.5}$).

3. What Kind of Modeling Should I Use to Determine Which Sources and Pollutants Need Not Be Subject to BART?

This section presents several options for determining that certain sources need not be subject to BART. These options rely on different modeling and/or emissions analysis approaches. They are provided for your guidance. You may also use other reasonable approaches for analyzing the visibility impacts of an individual source or group of sources.

Option 1: Individual Source Attribution Approach (Dispersion Modeling)

You can use dispersion modeling to determine that an individual source cannot reasonably be anticipated to cause or contribute to visibility impairment in a Class I area and thus is not subject to BART. Under this option, you can analyze an individual source's impact on visibility as a result of its emissions of SO_2, NO_x and direct PM emissions. Dispersion modeling cannot currently be used to estimate the predicted impacts on visibility from an individual source's emissions of VOC or ammonia. You may use a more qualitative

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[5] *We expect that regional planning organizations will have modeling information that identifies sources affecting visibility in individual class I areas.*

[6] *Note that the contribution threshold should be used to determine whether an individual source is reasonably anticipated to contribute to visibility impairment. You should not aggregate the visibility effects of multiple sources and compare their collective effects against your contribution threshold because this would inappropriately create a "contribute to contribution" test.*

assessment to determine on a case-by-case basis which sources of VOC or ammonia emissions may be likely to impair visibility and should therefore be subject to BART review, as explained in section II.A.3. above.

You can use CALPUFF[7] *or other appropriate model to predict the visibility impacts from a single source at a Class I area. CALPUFF is the best regulatory modeling application currently available for predicting a single source's contribution to visibility impairment and is currently the only EPA-approved model for use in estimating single source pollutant concentrations resulting from the long range transport of primary pollutants.*[8] *It can also be used for some other purposes, such as the visibility assessments addressed in today's rule, to account for the chemical transformation of* SO_2 *and* NO_x*.*

There are several steps for making an individual source attribution using a dispersion model:

1. Develop a modeling protocol.

Some critical items to include in the protocol are the meteorological and terrain data that will be used, as well as the source-specific information (stack height, temperature, exit velocity, elevation, and emission rates of applicable pollutants) and receptor data from appropriate Class I areas. We recommend following EPA's Interagency Workgroup on Air Quality Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long Range Transport Impacts[9] *for parameter settings and meteorological data inputs. You may use other settings from those in IWAQM, but you should identify these settings and explain your selection of these settings.*

One important element of the protocol is in establishing the receptors that will be used in the model. The receptors that you use should be located in the nearest Class I area with sufficient density to identify the likely visibility effects of the source. For other Class I areas in relatively close proximity to a BART-eligible source, you may model a few strategic receptors to determine whether effects at those areas may be greater than at the nearest Class I area. For example, you might chose to locate receptors at these areas at the closest point to the source, at the highest and lowest elevation in the Class I area, at the IMPROVE monitor, and at the approximate expected plume release height. If the highest modeled effects are observed at the nearest Class I area, you may choose not to analyze the other Class I areas any further as additional analyses might be unwarranted.

You should bear in mind that some receptors within the relevant Class I area may be less than 50 km from the source while other receptors within that same Class I area may be

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[7] *The model code and its documentation are available at no cost for download from* http://www.epa.gov/scram001/tt22.htm#calpuff.

[8] *The Guideline on Air Quality Models, 40 CFR part 51, appendix W, addresses the regulatory application of air quality models for assessing criteria pollutants under the CAA, and describes further the procedures for using the CALPUFF model, as well as for obtaining approval for the use of other, nonguideline models.*

[9] *Interagency Workgroup on Air Quality Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long Range Transport Impacts*, U.S. Environmental Protection Agency, EPA-454/R-98-019, December 1998.

greater than 50 km from the same source. As indicated by the Guideline on Air Quality Models, 40 CFR part 51, appendix W, this situation may call for the use of two different modeling approaches for the same Class I area and source, depending upon the State's chosen method for modeling sources less than 50 km. In situations where you are assessing visibility impacts for source-receptor distances less than 50 km, you should use expert modeling judgment in determining visibility impacts, giving consideration to both CALPUFF and other appropriate methods.

In developing your modeling protocol, you may want to consult with EPA and your regional planning organization (RPO). Up-front consultation will ensure that key technical issues are addressed before you conduct your modeling.

2. [Run model in accordance] with the accepted protocol and compare the predicted visibility impacts with your threshold for "contribution."

You should calculate daily visibility values for each receptor as the change in deciviews compared against natural visibility conditions. You can use EPA's "Guidance for Estimating Natural Visibility Conditions Under the Regional Haze Rule,"'EPA-454/B-03-005 (September 2003) in making this calculation. To determine whether a source may reasonably be anticipated to cause or contribute to visibility impairment at Class I area, you then compare the impacts predicted by the model against the threshold that you have selected.

The emissions estimates used in the models are intended to reflect steady-state operating conditions during periods of high capacity utilization. We do not generally recommend that emissions reflecting periods of start-up, shutdown, and malfunction be used, as such emission rates could produce higher than normal effects than would be typical of most facilities. We recommend that States use the 24 hour average actual emission rate from the highest emitting day of the meteorological period modeled, unless this rate reflects periods start-up, shutdown, or malfunction. In addition, the monthly average relative humidity is used, rather than the daily average humidity -- an approach that effectively lowers the peak values in daily model averages.

For these reasons, if you use the modeling approach we recommend, you should compare your "contribution" threshold against the 98th percentile of values. If the 98th percentile value from your modeling is less than your contribution threshold, then you may conclude that the source does not contribute to visibility impairment and is not subject to BART.

1.1. Visibility Calculations

The general theory for performing visibility calculations with the CALPUFF modeling system is described in several documents, including:

- "Interagency Workgroup on Air Quality Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long Range Transport Impacts" (IWAQM, 1998)
- "Federal Land Manager's Air Quality Related Values Workgroup (FLAG): Phase I Report" (FLAG, 2000)
- "A User's Guide for the CALPUFF Dispersion Model" (Scire, 2000)

In general, visibility is characterized either by visual range (the greatest distance that a large object can be seen) or by the light extinction coefficient, which is a measure of the light attenuation per unit distance due to scattering and absorption by gases and particles.

Visibility is impaired when light is scattered in and out of the line of sight and by light absorbed along the line of sight. The light extinction coefficient (b_{ext}) considers light extinction by scattering (b_{scat}) and light extinction by absorption (b_{abs}):

$$b_{ext} = b_{scat} + b_{abs}$$

The scattering components of extinction can be represented by these components:

- light scattering due to air molecules = Rayleigh scattering = $b_{rayleigh}$
- light scattering due to particles = b_{sp}

The absorption components of extinction can be represented by these components:

- light absorption due to gaseous absorption = b_{ag}
- light absorption due to particle absorption = b_{ap}

Particle scattering, b_{sp}, can be expressed by its components:

$$b_{sp} = b_{SO4} + b_{NO3} + b_{OC} + b_{SOIL} + b_{Coarse}$$

where:

- b_{SO4} = scattering coefficient due to sulfates = $3[(NH_4)_2SO_4]f(RH)$
- b_{NO3} = scattering coefficient due to nitrates = $3[NH_4NO_3]f(RH)$
- b_{OC} = scattering coefficient due to organic aerosols = 4[OC]
- b_{SOIL}= scattering coefficient due to fine particles = 1[Soil]
- b_{Coarse}= scattering coefficient due to coarse particles = 0.6[Coarse Mass]

Particle absorption from soot is defined as:

- b_{ap} = absorption due to elemental carbon (soot) = 10[EC]

The concentration values (in brackets) are expressed in micrograms per cubic meter. The numeric coefficient at the beginning of each equation is the dry scattering or absorption efficiency in meters-squared per gram. The f(RH) term is the relative humidity adjustment factor.

The total atmospheric extinction can be expressed as:

$$b_{ext} = b_{SO4} + b_{NO3} + b_{OC} + b_{SOIL} + b_{Coarse} + b_{ap} + b_{rayleigh}$$

In this equation, the sulfate (SO4) and nitrate (NO3) components are referred to as hygroscopic components because the extinction coefficient depends upon relative humidity. The other components are non-hygroscopic.

The variation of the effect of relative humidity on the extinction coefficients for SO4 and NO3 can be determined in several ways. According to the BART guideline, monthly f(RH) values should be used.

The CALPUFF modeling techniques in this protocol will provide ground level concentrations of visibility impairing pollutants. The concentration estimates from CALPUFF are used with the previously shown equations to calculate the extinction coefficient.

As described in the IWAQM Phase 2 Report, the change in visibility is compared against background conditions. The delta-deciview, Δdv, value is calculated from the source's contribution to extinction, b_{source}, and background extinction, $b_{background}$, as follows:

$$\Delta dv = 10\ ln((b_{background} + b_{source}) / b_{background})$$

2. Emission Estimates

According to the BART guideline, "*The emissions estimates used in the models are intended to reflect steady-state operating conditions during periods of high capacity utilization. We do not generally recommend that emissions reflecting periods of start-up, shutdown, and malfunction be used, as such emission rates could produce higher than normal effects than would be typical of most facilities. We recommend that States use the 24 hour average actual emission rate from the highest emitting day of the meteorological period modeled, unless this rate reflects periods start-up, shutdown, or malfunction.*"

Short-term emission rates (≤24-hours) should be modeled since visibility impacts are calculated for a 24-hour averaging period. SO_2, NOx, and PM10 (including condensible and filterable direct PM10[1]) should be modeled from all BART-eligible units at the facility. The Division will initially use allowable emission rates or federally enforceable emission limits. If 24-hour emissions limits do not exist, limits of a different averaging period may be used. Specifically, if limits do not exist, maximum hourly emissions based on emission factors and design capacity may be used.

If the source operator elects to develop emission rates for subject-to-BART modeling, case-by-case procedures should be developed in consultation with the Division. In general, the following emission rates are acceptable:

- Short-term (≤24-hours) allowable emission rates (e.g., emission rates calculated using the maximum rated capacity of the source).
- Federally enforceable short-term limits (≤24-hours).
- Peak 24-hour actual emission rates (or calculated emission rates) from the most recent 3 to 5 years of operation that account for "high capacity utilization" during normal operating conditions and fuel/material flexibility allowed under the source's permit. In situations where a unit is allowed to use more than one fuel, the fuel resulting in the highest emission rates should be used for the modeling, even if that fuel has not been used in the last 3 to 5 years.

If short-term rates are not available, emissions rates based on averaging periods longer than 24-hours are acceptable only in cases where the modeling shows that the source has impacts equal to or greater than the contribution threshold.

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[1] Common speciated PM species for CALPUFF include fine particulate matter (PMF), coarse particulate matter (PMC), soot or elemental carbon (EC), organic aerosols (SOA), and sulfate (SO4). H_2SO_4, for example, is a PM10 species emitted from coal-fired units that is typically modeled as SO4 in CALPUFF.

3. CALMET/CALPUFF Modeling Methodology

For the subject-to-BART modeling, the Division will use the January 2005 CALMET/CALPUFF parameter settings and input files generated by CH2M HILL for the Public Service Company Comanche Unit 3 PSD permit application because it underwent extensive review by the Division and by Federal Land Managers as part of the PSD permitting process. The Division has modified the CALPUFF input files to include three additional Class I areas. It has also been modified as necessary to account for PM10 speciation. An additional post-processing step with POSTUTIL has been added to implement ammonia limiting. The CALPOST model setup is different from the setup for PSD permit modeling and should be consistent with the U.S. EPA's BART guideline. In addition, the Division has reviewed available data to determine appropriate ammonia background values for various parts of Colorado. The Division has performed sensitivity tests to understand the response of the model to changes in ammonia background concentration levels. Since the current regulatory version of CALPOST does not generate 98th percentile results, the Division has modified CALPOST to generate a file with a full distribution of daily delta-deciview values for each receptor. In addition, the Division developed a FORTRAN processor to generate 98th percentile results.

The Division will use this protocol for the initial subject-to-BART modeling. However, the Division's initial modeling may be superseded by additional modeling performed by the Division or source operator. Subsequent modeling should use modeling techniques consistent with the recommendations in this protocol and the BART guideline. All modeling will be subject to Division review and approval. The Division may approve deviations from this protocol for a specific source if the changes are acceptable to U.S. EPA and improve model performance while retaining consistency with the BART guideline. For example, if the source operator wants to use 2-kilometer CALMET grid cells instead of 4-kilometer cells and wants to include additional meteorological observations in a way that improves the performance of the CALMET meteorological fields, the Division would probably approve the analysis.

This protocol is intended to provide sufficient technical documentation to support the application of CALPUFF at distances up to 300 kilometers. While CALPUFF will be used at source-to-receptor distances less than 50 kilometers for some receptors, there is a Class I area within the 50 to 300 km range from every BART-eligible source in Colorado. Impacts at Class I areas greater than 300 km may be used, but it should be recognized that the use of puff splitting in CALPUFF would provide more accurate results for Class I areas beyond 300km.

According to "*Interagency Workgroup on Air Quality Modeling (IWAQM) Phase 2 Summary Report and Recommendations for Modeling Long Range Transport Impacts*" (IWAQM Phase 2 Report):

> *In the context of the Phase 2 recommendation, the focus of the visibility analysis is on haze. These techniques are applicable in the range of thirty to fifty kilometers and beyond from a*

source. At source-receptor distances less than thirty to fifty kilometers, the techniques for analyzing visual plumes (sometimes referred to as 'plume blight') should be applied.

For the few cases where BART-eligible source-to-receptors distances are less than 50 kilometers, both the topography and the meteorological fields are complex and the use of CALPUFF appears to be appropriate based on the possibility of recirculation, stagnation, and complex flows. The shortest source-to-receptor distance modeled will be about 25 kilometers, but it involves an elevation change of about 3000 ft. In addition, in each case, only a portion of the Class I area is less than 50 km from the source. If there were issues regarding the 50 km distance, PLUVUEII would be an appropriate model to consider for source-to-receptor distances less than 50 kilometers. If a PLUVUEII is used, a protocol should be developed.

3.1. CALMET/CALPUFF Model Selection

The following model versions will be used:

- CALPUFF: July 2004 beta version 5.711a, level 040716
- CALMET: July 2004 beta version 5.53a, level 040716
- POSTUTIL: May 2003 version 1.31, level 030528
- CALPOST: July 2003 version 5.51, level 030709
  - Modified by Division for this analysis:
    - CALPOST_BART98_v3.EXE (version 5.51_CO_v3, level 030709)
    - BART98_v3.EXE

The use of CALPUFF is recommended in 40 CFR 51 Appendix Y (BART guideline). The primary niche for CALPUFF is as a long-range transport model. It is a multi-layer, non-steady-state puff dispersion model that can simulate the effects of time- and space-varying meteorological conditions on pollutant transport, chemical transformations, vertical wind shear, and deposition (Scire, 2000).

3.1.1. CALMET

The MM5/CALMET meteorological fields have been generated for 1996, 2001, and 2002. CALMET is based on the Diagnostic Wind Model (Douglas, S. and R. Kessler, 1988). It has been significantly enhanced by Earth Tech, Inc (Scire, 2000). For this particular study, the model uses a Lambert Conformal Projection coordinate system to account for the Earth's curvature.

CALMET uses a two-step approach to calculate wind fields. In the first step, an initial-guess wind field is adjusted for slope flows and terrain blocking effects, for example, to produce a Step 1 wind field. In the second step, an objective analysis is performed to introduce observational data into the Step 1 wind field.

In this application, the initial guess wind fields are based on 36-kilometer MM5[2] meteorological fields for 1996, 2001, and 2002 (i.e., IPROG=14). The MM5 files were provided to the Division by CH2M HILL as part of the Public Service Company (PSCo) Comanche Unit 3 PSD permit application. Alpine Geophysics extracted the MM5 data into

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[2] Fifth-Generation NCAR/Penn State Mesoscale Model.

a CALMET MM5.DAT format for 1996, 2001, and 2002. Both the 1996 and 2001 MM5 data were generated by the U.S. EPA. The 2002 MM5 data was originally developed for the Visibility Improvement State and Tribal Association of the Southeast (VISTAS). While the VISTAS data was considered to be acceptable for the PSCo Comanche PSD permit and for this analysis based on data availability issues, the Western Regional Air Partnership (WRAP) 36km and 12 km 2002 data should be considered as a replacement for the 2002 VISTAS data if additional CALPUFF modeling is performed beyond this initial effort. In addition, the Midwest Regional Planning Organization (MRPO) 36 km 2003 and 2004 MM5 data should be considered as additional years of data. Finally, if other better resolution and more representative meteorological fields become available, they may be considered for any future modeling. However, before accepting data from other meteorological models, the Division may require submission of a meteorological model performance evaluation to demonstrate that the proposed meteorological fields perform better than the MM5 fields proposed in this protocol.

The BART guideline does not specify the exact number of years of mesoscale meteorological data for use in CALPUFF, but according to 40 CFR 51 Appendix W, at least three years of meteorological data should be used. Five years of meteorological data is preferable. At the time of this analysis, five years of agency-approved mesoscale meteorological data were not readily available at reasonable grid resolutions for Colorado. While the Division has the national 80km 1990 MM4 and 80km 1992 MM5 data sets, use of the coarse resolution 1990 and 1992 data sets would not improve the accuracy of the modeling results in Colorado.

3.1.1.1. CALMET Modeling Domain

The modeling domain is shown in Figure 1. It is based on a Lambert Conformal Conic projection. As determined by CH2M HILL, the Standard Parallels within the domain are 1/6th and 5/6th of the north-to-south extent instead of the 30-degree and 60-degree lines that are listed as defaults in CALMET. This was done to minimize distortion. See Figure 7 for specific parameter settings.

The domain includes all Class I areas in Colorado with the exception of Mesa Verde NP. Mesa Verde was excluded because it is more than 300 km from all of the BART-eligible sources in Colorado and because the BART-eligible sources in Colorado would have higher impacts at other Class I areas. That is, preliminary modeling indicates that impacts at Mesa Verde will not be the controlling 98th percentile values for this analysis. The domain does not include Class I areas in any nearby states because the 98th percentile impacts from Colorado's BART-eligible sources are expected to be highest at Class I areas in Colorado. This assumption is based on source-to-receptor distances and professional judgment regarding prevailing air pollutant transport regimes. The CALMET domain includes almost the entire state of Colorado. It is about 480 km x 480 km in the longitudinal and meridonal directions, respectively, with 4-kilometer CALMET grid cells.

Any modeling beyond this initial analysis should consider a larger domain that extends south of Albuquerque, New Mexico and west of the Canyonlands NP Class I area in Utah so that all Class I areas within 300 kilometers of every BART-eligible source in Colorado are included in the domain.

If a source operator elects to perform additional subject-to-BART modeling beyond the Division's initial modeling using a different CALMET/CALPUFF setup, the Division may approve a smaller modeling domain on a case-by-case basis. For example, if the Division's initial modeling shows that a source has impacts above the contribution threshold at only two Class I federal areas, the Division may approve a smaller modeling domain if the reduction in size is necessary to implement 2 km CALMET grid spacing.

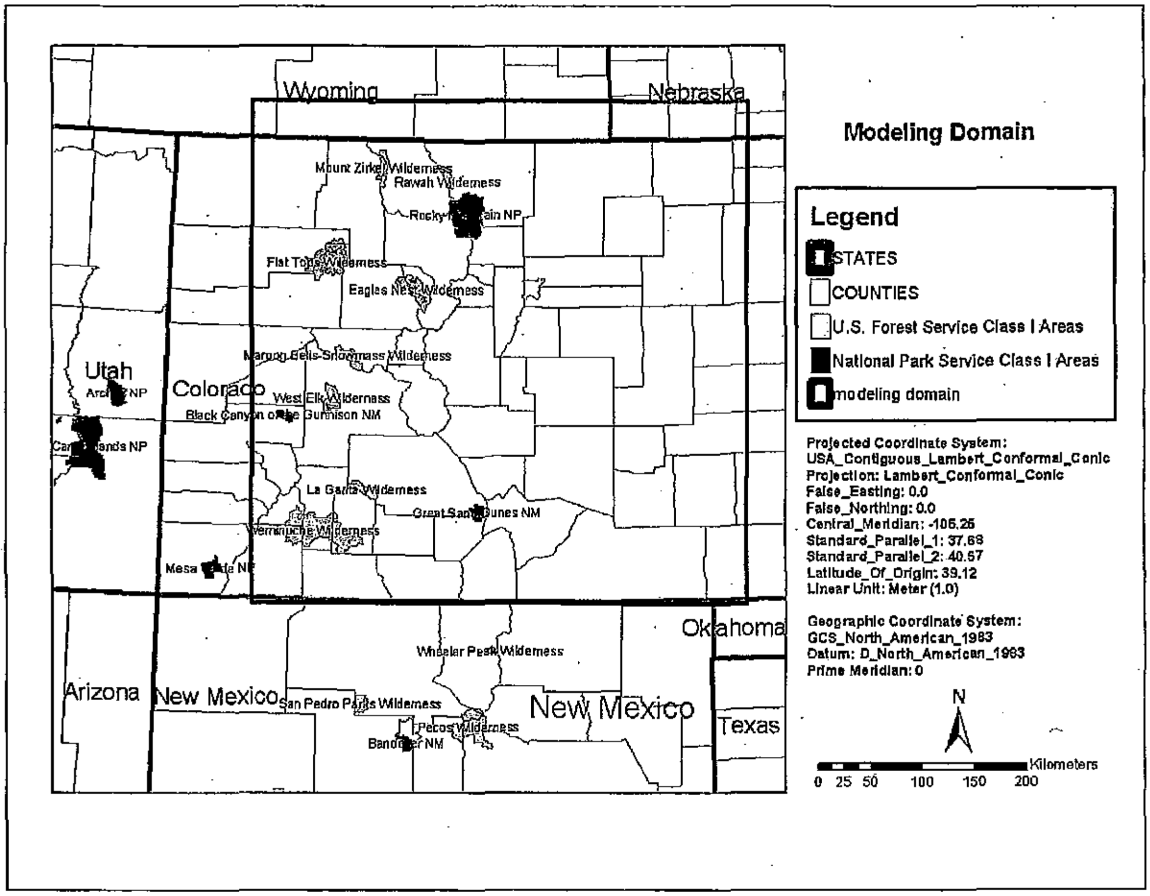


Figure 1. CALMET/CALPUFF modeling domain.

3.1.1.2. CALMET Performance Evaluation

The meteorological fields developed by the MM5/CALMET modeling system were evaluated by CH2M HILL for Xcel Energy as part of the PSCo Comanche Unit 3

PSD permit. Specifically, "CH2M HILL examined vector plots of selected periods within the CALMET output for validation of the wind fields with the CalDESK (Environmodeling Ltda.) program (CH2M HILL, 2005)." The Division replicated the CALMET modeling and performed additional review of the meteorological fields with the Lakes Environmental CALPUFF View software package. In general, the meteorological fields were found to be reasonable given the 36km MM5 resolution, although model performance could be improved with better resolution MM5/CALMET fields and the inclusion of more observations in CALMET.

If the meteorological fields described in this protocol are not used and new CALMET fields are generated, the meteorological fields should be evaluated by a meteorologist.

3.1.1.3. Terrain

Gridded terrain elevations for the modeling domain are derived from 3 arc-second digital elevation models (DEMs) produced by the United States Geological Survey (USGS). The files cover 1-degree by 1-degree blocks of latitude and longitude. USGS 1:250,000 scale DEMs were used. The elevations are in meters relative to mean sea level and have a resolution of about 90 meters, shown in Figure 2.

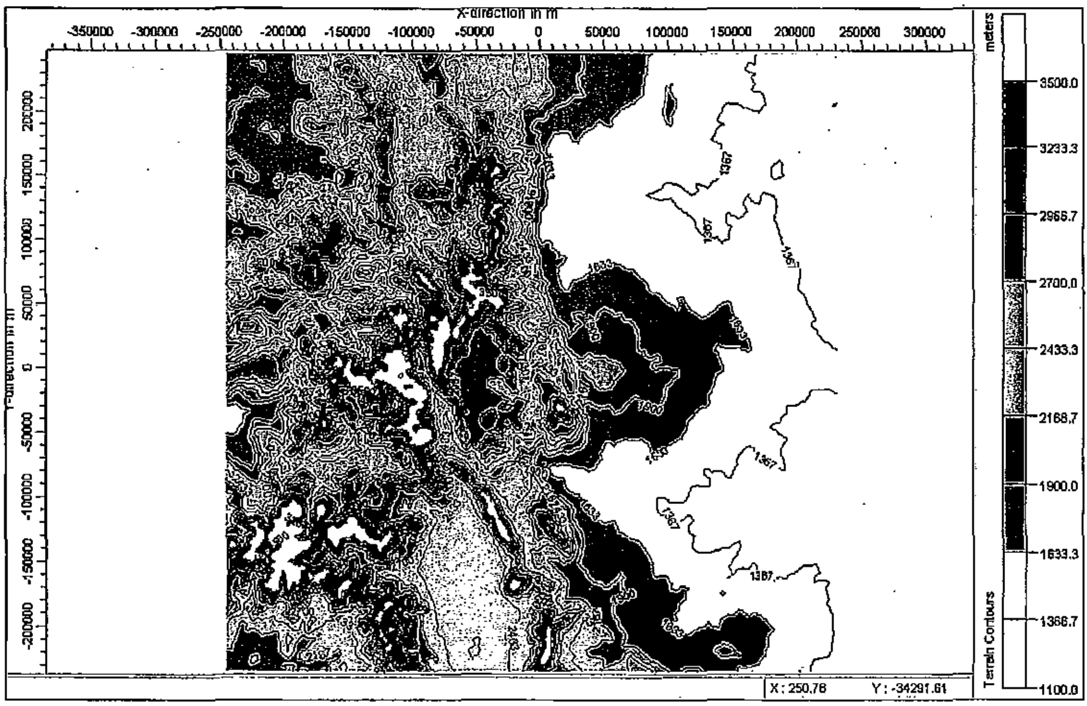


Figure 2. CALMET Terrain.

3.1.1.4. Land Use

The land use data is based on the Composite Theme Grid format (CTG) using Level I USGS land use categories were "mapped into the 14 primary CALMET land use categories (CH2M HILL, 2005)," shown in Figure 3. The land use categories are described in Figure 4.

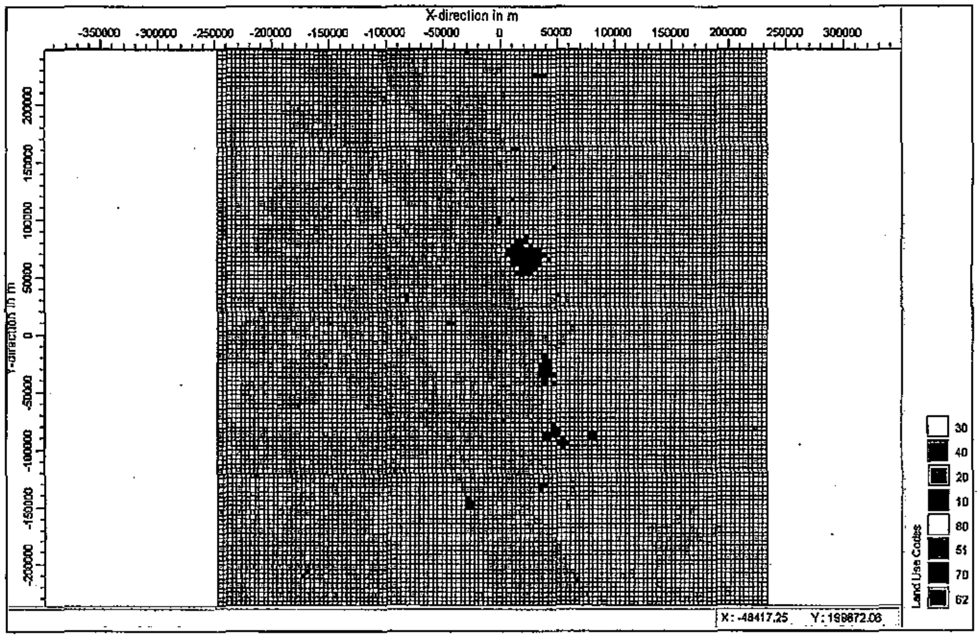


Figure 3. CALMET land use categories.

Default CALMET Land Use Categories and Associated Geophysical Parameters
Based on the U.S. Geological Survey Land Use Classification System
(14-Category System)

Land Use Type	Description	Surface Roughness (m)	Albedo	Bowen Ratio	Soil Heat Flux Parameter	Anthropogenic Heat Flux (W/m²)	Leaf Area Index
10	Urban or Built-up Land	1.0	0.18	1.5	.25	0.0	0.2
20	Agricultural Land - Unirrigated	0.25	0.15	1.0	.15	0.0	3.0
-20*	Agricultural Land - Irrigated	0.25	0.15	0.5	.15	0.0	3.0
30	Rangeland	0.05	0.25	1.0	.15	0.0	0.5
40	Forest Land	1.0	0.10	1.0	.15	0.0	7.0
51	Small Water Body	0.001	0.10	0.0	1.0	0.0	0.0
54	Bays and Estuaries	0.001	0.10	0.0	1.0	0.0	0.0
55	Large Water Body	0.001	0.10	0.0	1.0	0.0	0.0
60	Wetland	1.0	0.10	0.5	.25	0.0	2.0
61	Forested Wetland	1.0	0.1	0.5	0.25	0.0	2.0
62	Nonforested Wetland	0.2	0.1	0.1	0.25	0.0	1.0
70	Barren Land	0.05	0.30	1.0	.15	0.0	0.05
80	Tundra	.20	0.30	0.5	.15	0.0	0.0
90	Perennial Snow or Ice	.20	0.70	0.5	.15	0.0	0.0

* Negative values indicate "irrigated" land use

Figure 4. Land use categories table from CALMET User's Guide.

3.1.1.5. CALMET ZFACE and ZIMAX Settings

Eleven vertical layers have been used with vertical cell face (ZFACE) heights at: 0, 20, 100, 200, 350, 500, 750, 1000, 2000, 3000, 4000, and 5000 meters.

ZIMAX was set to 4500 meters based on analyses of soundings for summer ozone events. The analysis suggests mixing heights in Denver are often well above the CALMET default value of 3000 meters during the summer. For example, on some summer days, ozone levels are elevated all the way to 6000 meters MSL or beyond during some meteorological regimes, including some regimes associated with high ozone episodes. A sounding from the evening of July, 1 2002 (see Figure 5), which is a day the 8-hour ozone standard was exceeded at Rocky Mountain National Park, suggests the mixing height was probably around 6000 meters MSL. The mixing height estimate is based on the relative uniformity of the water vapor mixing ratio below 6000 meters, the temperature profile, the inverted "V" in the sounding, and data from a NOAA ozonesonde from Boulder that shows relatively constant ozone levels with height. Although low mixing heights can occur during the summer, maximum summertime daytime mixing heights in the Denver area often range from about 12,000 feet (3700 m) to 20,000 feet (6000 m) MSL. Since the CALMET ZIMAX setting is above ground level (AGL), not above mean sea level (MSL), the maximum summer daytime mixing height range over the plains would be about 15000 feet (4500 m) AGL. Thus, a ZIMAX setting of 4500 m is used.

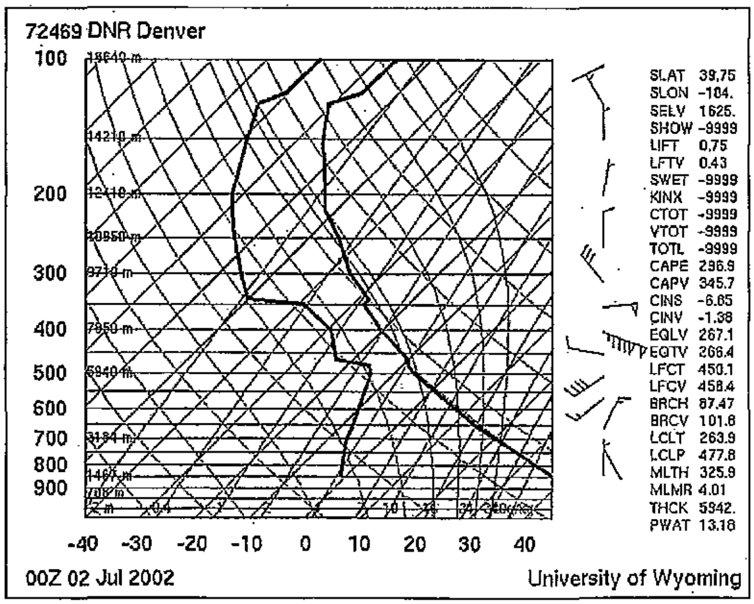


Figure 5. Example Denver summertime sounding.

3.1.1.6. CALMET BIAS Setting

The BIAS settings for each vertical cell determine the relative weight given to the vertically extrapolated surface meteorological observations and upper air soundings. The initial guess field is computed with an inverse distance weighting of the surface and upper air data. It can be modified by the layer-dependent bias factor (BIAS). The values for BIAS can range from –1.0 to 1.0. For example, if BIAS is set to +0.25, the weight of the surface wind observation is reduced by 25%. If BIAS is set to –0.25, the weight of the upper air wind observation is reduced by 25%. If BIAS is set to zero, there is no change in the weighting from the normal inverse distance squared weighting. As recommended by the NPS, the default values of 0.0 have been used for all 11 vertical layers in this analysis.

3.1.1.7. CALMET RMIN2 and IXTERP Settings

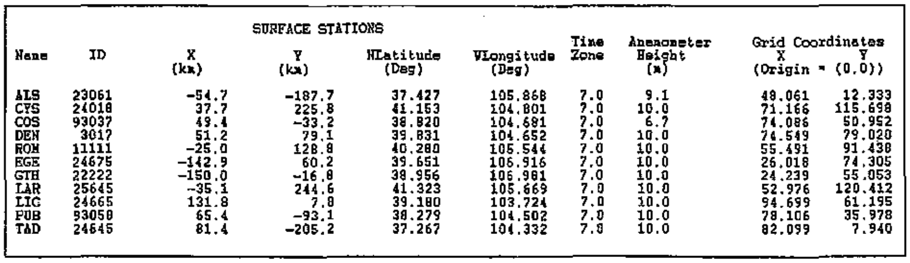
Vertical extrapolation of data from a surface station is skipped if the surface station is close to the upper air station. The variable RMIN2 sets the distance between an upper air station and a surface station that must exceeded in order for the extrapolation to take place. RMIN2 has been set to the default value of 4, as recommended by the NPS. The default value of –4 for IEXTRP is used. By setting IEXTRP to –4 (as opposed to +4), layer 1 data at upper air stations is ignored. When IEXTRP=±4, the van Ulden and Holtslag wind extrapolation method is used. The method uses similarity theory and observed data to extend the influence of the surface wind speed and direction aloft.

3.1.1.8. CALMET Settings: R1, R2, RMAX1, RMAX2, RMAX3

An inverse-distance method is used to determine the influence of observations in the Step 1 wind field. R1 controls weighting of the surface layer and R2 controls weighting of the layers aloft. For example, R1 is the distance from an observational station at which the observation and first guess field are equally weighted. In addition, RMAX1, RMAX2, and RMAX3 determine the radius of influence over land in the surface layer, over land in layers aloft, and over water, respectively. That is, an observation is excluded if the distance from the observational site to a given grid point exceeds the maximum radius of influence. As recommended by the NPS, R1 and RMAX1 have been set to 30 km so that the initial guess field does not overwhelm the surface observations. R2 is set to 50 km and RMAX2 is set to 100 km. RMAX3 is not much of a factor in Colorado given the lack of large water bodies. RMAX3 is set to 500 km.

3.1.1.9. CALMET Surface Stations

Eleven surface stations shown in Figure 6 were used, including Alamosa (ALS), Colorado Springs (CYS), Denver (DEN), Eagle (EGE), Limon (LIC), Pueblo (PUB), Trinidad (TAD), Cheyenne (CYS), Laramie (LAR), Rocky Mountain NP (ROM), and Gothic (GTH). Any future modeling analyses should consider additional surface stations.



```
                                  SURFACE STATIONS
                                                                      Time   Anemometer       Grid Coordinates
Name    ID          X            Y         NLatitude      WLongitude  Zone     Height          X          Y
                   (km)         (km)         (Deg)          (Deg)               (m)        (Origin = (0.0))

ALS    23061       -54.7       -187.7       37.427        105.868     7.0       9.1         48.061     12.333
CYS    24018        37.7        225.8       41.153        104.801     7.0      10.0         71.166    115.698
COS    93037        49.4        -33.2       38.820        104.681     7.0       6.7         74.086     50.952
DEN     3017        51.2         79.1       39.831        104.652     7.0      10.0         74.549     79.020
ROM    11111       -25.0        128.8       40.280        105.544     7.0      10.0         55.491     91.438
EGE    24675      -142.9         60.2       39.651        106.916     7.0      10.0         26.018     74.305
GTH    22222      -150.0        -16.8       38.956        106.981     7.0      10.0         24.239     55.053
LAR    25645       -35.1        244.6       41.323        105.669     7.0      10.0         52.976    120.412
LIC    24665       131.8          7.8       39.180        103.724     7.0      10.0         94.699     61.195
PUB    93058        65.4        -93.1       38.279        104.502     7.0      10.0         78.106     35.978
TAD    24645        81.4       -205.2       37.267        104.332     7.0      10.0         82.099      7.940
```

Figure 6. Surface meteorological stations.

3.1.1.10. CALMET Upper Air Stations

Two upper air stations were included: Grand Junction and Denver.

3.1.1.11. CALMET Precipitation Stations

CH2M HILL obtained precipitation data from the National Climatic Data Center (NCDC). All available data in fixed-length, TD-3240 format were ordered for the modeling domain. CH2M HILL processed the data with the PXTRACT and PMERGE processors. Stations with incomplete or poor quality data for a given year were excluded. The number of stations used for each year is as follows (CH2M HILL, 2005):

- 1996 - 84 stations
- 2001 - 82 stations
- 2002 - 86 stations

3.1.1.12. CALMET Sample Input File

Figure 7 summarizes some of the key CALMET parameters.

3.1.1.13. CALMET Parameter Summary

Figure 7 summarizes some of the key CALMET settings.

```
Map projection                                         Default: UTM     ! PMAP = LCC !
Latitude and Longitude (decimal degrees) of projection origin           ! RLAT0 = 39.12N !
                                                                        ! RLON0 = 105.25W !
Matching parallel(s) of latitude (decimal degrees) for projection       ! XLAT1 = 37.68N !
                                                                        ! XLAT2 = 40.57N !
 (DATUM)                                              Default: WGS-G    ! DATUM = NAS-C  !
No. X grid cells (NX)                                 No default        ! NX =   120  !
No. Y grid cells (NY)                                 No default        ! NY =   121  !
Grid spacing (DGRIDKM)                                No default        ! DGRIDKM = 4. !
Reference grid coordinate of SW corner of grid cell (1,1)               ! XORIGKM = -246.984 !
                                                                        ! YORIGKM = -237.000 !
No. of vertical layers (NZ)                           No default        ! NZ =  11  !
Cell face heights in arbitrary vertical grid (ZFACE(NZ+1)):
   ! ZFACE = 0.,20.,100.,200.,350.,500.,750.,1000.,2000.,3000.,4000.,5000.!
NO OBSERVATION MODE                          (NOOBS)  Default: 0        ! NOOBS = 0. !
Number of surface stations                   (NSSTA)  No default        ! NSSTA =  11  !
Number of precipitation stations             (NPSTA)  No default        ! NPSTA =  86  !
Griddid cloud fields:                       (ICLOUD)  Default: 0        ! ICLOUD =  0  !
Model selection variable (IWFCOD)                     Default: 1        ! IWFCOD =  1  !
Compute Froude number adjustment effects ? (IFRADJ)   Default: 1        ! IFRADJ =  1  !
Compute kinematic effects ?                  (IKINE)  Default: 0        ! IKINE  =  0  !
Use O'Brien procedure?                                Default: 0        ! IOBR =  0  !
Compute slope flow effects ?                (ISLOPE)  Default: 1        ! ISLOPE  =  1  !
Extrapolate surface wind obs to upper layers?         Default: -4       ! IEXTRP =  -4  !
Extrapolate surface winds even if calm? (ICALM)       Default: 0        ! ICALM  =  0  !
Layer-dependent biases. Default: NZ*0         ! BIAS =  0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0  !
                                                      Default: 4.       ! RMIN2 = 4 !
Use gridded prognostic wind field model output fields as input to the diagnostic
  wind field model (IPROG)                            Default: 0        ! IPROG =  14  !
Maximum radius of influence over land in the surface layer              ! RMAX1 = 30. !
Maximum radius of influence over land aloft (RMAX2)                     ! RMAX2 = 100. !
Maximum radius of influence over water                                  ! RMAX3 = 500. !
Minimum radius of influence used in the wind field interpolation (RMIN)
                                                      Default: 0.1      ! RMIN = 0.1 !
Radius of influence of terrain features (TERRAD)      No default        ! TERRAD = 40. !
Relative weighting of the first guess field and observations in the SURFACE layer
                                                      No default        ! R1 = 30. !
Relative weighting of the first guess field and observations in the layers ALOFT
                                                      No default        ! R2 = 50. !
Minimum overland mixing height                        Default:  50.     ! ZIMIN = 50. !
Maximum overland mixing height                        Default: 3000.    ! ZIMAX = 4500. !
Interpolation type (1 = 1/R ; 2 = 1/R**2)             Default:1         ! IRAD =  1  !
Radius of influence for temperature interpolation     Default: 500.     ! TRADKM = 500. !
```

Figure 7. CALMET parameter summary.

3.1.2. CALPUFF

The default technical options in CALPUFF should be used, unless specified otherwise in this protocol. If non-default options or values are used, the reason should be explained and justified in the modeling report.

3.1.2.1. Receptor Network and Class I Federal Areas

The modeling domain should contain all Class I federal areas in Colorado within 300 kilometers of the BART-eligible source. Class I areas outside Colorado within 300 kilometers should be included if an expanded domain is used. The setup recommended by the Division includes eleven Class I federal areas in Colorado:

- Flat Tops Wilderness Area
- Rawah Wilderness Area
- Mt Zirkel Wilderness Area
- Weminuche Wilderness Area
- Rocky Mountain National Park
- Maroon Bells-Snowmass Wilderness Area
- La Garita Wilderness Area
- Great Sand Dunes National Park
- West Elk Wilderness Area
- Eagles Nest Wilderness Area
- Black Canyon of the Gunnison National Park

The discrete receptors for eight of the Class I federal areas were generated by the National Park Service (NPS) for CH2M HILL using the *NPS Convert Class I Areas* (NCC) computer program. For the remaining three areas not included in the CH2M HILL modeling, receptors were generated by the Division with the NCC program. Receptor elevations provided by the NPS conversion program have been used. The receptors for each Class I area are shown in Figure 8

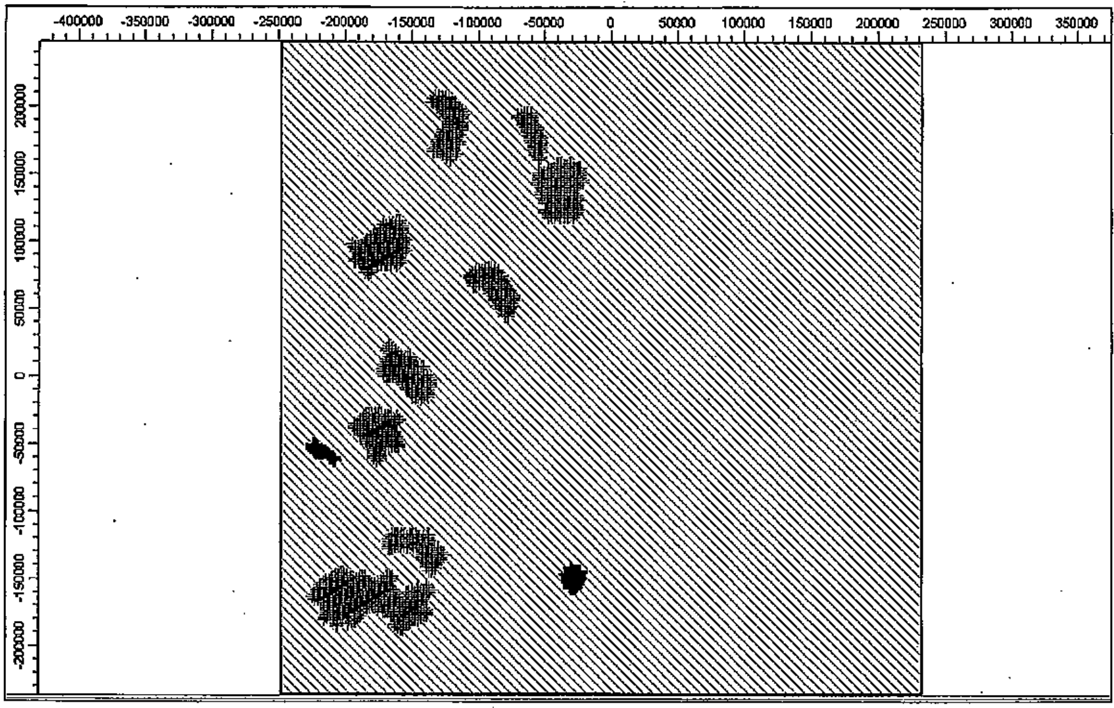
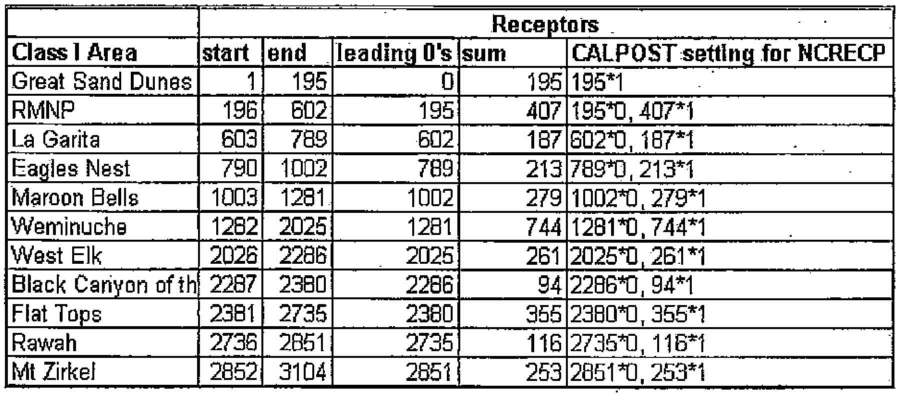


Figure 8. Class I federal area receptors.

All receptors should be included in a single CALPUFF simulation. To calculate the visibility impacts in CALPOST for each Class I area, the NCRECP parameter can be used. It specifies the receptor range to be processed in CALPOST. The range of receptors in the Division's recommended setup is shown in Figure 9.



	Receptors				
Class I Area	**start**	**end**	**leading 0's**	**sum**	**CALPOST setting for NCRECP**
Great Sand Dunes	1	195	0	195	195*1
RMNP	196	602	195	407	195*0, 407*1
La Garita	603	789	602	187	602*0, 187*1
Eagles Nest	790	1002	789	213	789*0, 213*1
Maroon Bells	1003	1281	1002	279	1002*0, 279*1
Weminuche	1282	2025	1281	744	1281*0, 744*1
West Elk	2026	2286	2025	261	2025*0, 261*1
Black Canyon of th	2287	2380	2286	94	2286*0, 94*1
Flat Tops	2381	2735	2380	355	2380*0, 355*1
Rawah	2736	2851	2735	116	2735*0, 116*1
Mt Zirkel	2852	3104	2851	253	2851*0, 253*1

Figure 9. Receptor numbers for specific Class I areas.

3.1.2.2. CALPUFF Meteorology

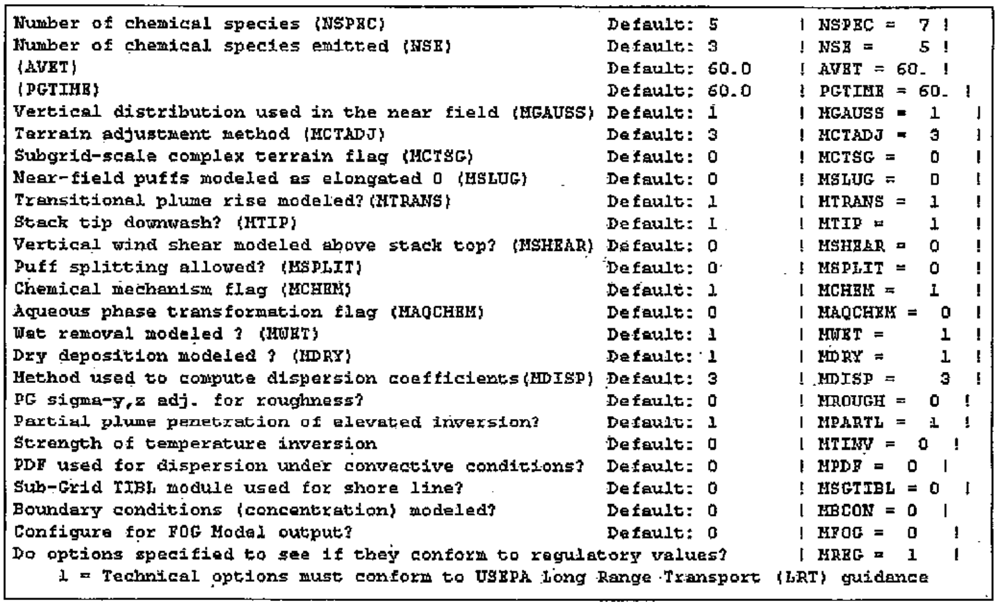
Refer to the CALMET section of the report for details.

3.1.2.3. CALPUFF Modeling Domain

The CALPUFF modeling domain is identical to the CALMET modeling domain.

3.1.2.4. CALPUFF Parameter Summary

Figure 10 summarizes some of the key CALPUFF settings.



```
Number of chemical species (NSPEC)                    Default: 5        ! NSPEC =  7 !
Number of chemical species emitted (NSE)              Default: 3        ! NSE =    5 !
(AVET)                                                Default: 60.0     ! AVET = 60. !
(PGTIME)                                              Default: 60.0     ! PGTIME = 60. !
Vertical distribution used in the near field (MGAUSS) Default: 1        ! MGAUSS =  1   !
Terrain adjustment method (MCTADJ)                    Default: 3        ! MCTADJ =  3   !
Subgrid-scale complex terrain flag (MCTSG)            Default: 0        ! MCTSG =   0   !
Near-field puffs modeled as elongated 0 (MSLUG)       Default: 0        ! MSLUG =   0   !
Transitional plume rise modeled?(MTRANS)              Default: 1        ! MTRANS =  1   !
Stack tip downwash? (MTIP)                            Default: 1        ! MTIP =    1   !
Vertical wind shear modeled above stack top? (MSHEAR) Default: 0        ! MSHEAR =  0   !
Puff splitting allowed? (MSPLIT)                      Default: 0        ! MSPLIT =  0   !
Chemical mechanism flag (MCHEM)                       Default: 1        ! MCHEM =   1   !
Aqueous phase transformation flag (MAQCHEM)           Default: 0        ! MAQCHEM =  0  !
Wet removal modeled ? (MWET)                          Default: 1        ! MWET =     1  !
Dry deposition modeled ? (MDRY)                       Default: 1        ! MDRY =     1  !
Method used to compute dispersion coefficients(MDISP) Default: 3        ! MDISP =    3  !
PG sigma-y,z adj. for roughness?                      Default: 0        ! MROUGH =  0  !
Partial plume penetration of elevated inversion?      Default: 1        ! MPARTL =  1  !
Strength of temperature inversion                     Default: 0        ! MTINV =  0  !
PDF used for dispersion under convective conditions?  Default: 0        ! MPDF =  0  !
Sub-Grid TIBL module used for shore line?             Default: 0        ! MSGTIBL = 0  !
Boundary conditions (concentration) modeled?          Default: 0        ! MBCON = 0  !
Configure for FOG Model output?                       Default: 0        ! MFOG =  0   !
Do options specified to see if they conform to regulatory values?       ! MREG =  1   !
    1 = Technical options must conform to USEPA Long Range Transport (LRT) guidance
```

Figure 10. CALPUFF parameter summary.

3.1.2.5. Chemical Mechanism

The MESOPUFF II pseudo-first-order chemical reaction mechanism (MCHEM=1) is used for the conversion of SO_2 to sulfate (SO4) and NOx to nitrate (NO3). Refer to the CALPUFF User's Guide for a description of the mechanism (Scire, 2000).

In the MESOPUFF II mechanism, the ammonia background concentration affects the equilibrium between nitric acid, ammonia, and ammonium nitrate. The equilibrium constant for the reaction is a non-linear function of temperature and relative humidity (Scire, 2000). Unlike sulfate, the calculated nitrate concentration is limited by the amount of available ammonia, which is preferentially scavenged by sulfate (Scire, 2000). In particular, the amount of ammonia available for the nitric acid, ammonium nitrate, and ammonia reactions is determined by subtracting sulfate from total ammonia.

While the chemical mechanism simulates both the gas phase and aqueous phase conversion of SO_2 to sulfate, the aqueous phase method, which is important when the plume interacts with clouds and fog, can significantly underestimate sulfate formation. In this report, as recommended by the IWAQM Phase 2 report, the "nighttime SO_2 loss rate (RNITE1)" is set to 0.2 percent per hour. The "nighttime NOx loss rate (RNITE2)" is set to 2.0 percent per hour and the "nighttime HNO_3 formation rate (RNITE3)" is set to 2.0 percent per hour.

According to the 1996 "Mt. Zirkel Wilderness Area Reasonable Attribution Study of Visibility Impairment. Volume II: Results of Data Analysis and Modeling - Final Report,"

> *The CALPUFF chemical module is formulated around linear transformation rates for SO_2 to sulfate and NO_X to total nitrate. There are two options for specifying these transformation rates:*
>
> *Option 1: An internal calculation of rates based on local values for several controlling variables (e.g., solar radiation, background ozone, relative humidity, and plume NO_X) as used in MESOPUFF-II. The parametric transformation rate relationships employed were derived from box model calculations using the mechanism of Atkinson et al. (1982).*
>
> *Option 2: A user-specified input file of diurnally varying but spatially uniform conversion rates.*
>
> *Morris et al. (1987) reviewed the MESOPUFF-II mechanism as part of the U.S. EPA Rocky Mountain Acid Deposition Model Assessment study. They found that it provided physically plausible responses to many of the controlling environmental parameters. However, the mechanism had no temperature dependence, which is an important factor in the Rocky Mountain region where there are wide variations in temperature. Furthermore, the MESOPUFF-II transformation scheme was based on box model simulations for conditions more representative of the Eastern U.S. than of the Rocky Mountains.*
>
> *The largest deficiency in the MESOPUFF-II chemical transformation algorithm is the lack of explicit treatment for in-cloud (aqueous-phase) enhanced oxidation of SO_2 to sulfate. The MESOPUFF-II chemical transformation algorithm includes a surrogate reaction rate to account for aqueous-phase oxidation of SO2 to sulfate as follows:*
>
> $$K_{aq} = 3 \times 10^{-8} \times RH^4 \ (\%/hr) \qquad (B.2\text{-}1)$$
>
> *Thus, at 100% relative humidity (RH), the MESOPUFF-II aqueous-phase surrogate SO_2 oxidation rate will be 3% per hour. Measurements in generating station plumes suggest spatially- and temporally-integrated SO_2 oxidation rates due to oxidants in clouds to be 10 times this value.*

Another issue is the amount of ammonia available for nitrate chemistry. According to a paper by EarthTech (Escoffier-Czaja and Scire, 2002),

> *"In the CALPUFF model, total nitrate (TNO3 = HNO3 + NO3) is partitioned into each species according to the equilibrium relationship between HNO3 and NO3. This equilibrium varies as a function of time and space, in response to both the*

> *ambient temperature and relative humidity. In addition, the formation of nitrate is subject to the availability of NH3 to form ammonium nitrate (NH4NO3), the assumed form of nitrate in the model. In CALPUFF, a continuous plume is simulated as a series of puffs, or discrete plume elements. The total concentration at any point in the model is the sum of the contribution of all nearby puffs from each source. Because CALPUFF allows the full amount of the specified background concentration of ammonia to be available to each puff for forming nitrate, the same ammonia may be used multiple times in forming nitrate, resulting in an overestimate of nitrate formation. In order to properly account for ammonia consumption, a program called POSTUTIL was introduced into the CALPUFF modeling system in 1999. POSTUTIL allows total nitrate to be repartitioned in a post-processing step to account for the total amount of sulfate scavenging ammonia from all sources (both project and background sources) and the total amount of TNO3 competing for the remaining ammonia. In POSTUTIL, ammonia availability is computed based on receptor concentrations of total sulfate and TNO3, not on a puff-by-puff basis."*

Ammonia-limiting methods will be used repartitioning nitric acid and nitrate on a receptor-by-receptor and hour-by-hour basis to account for over prediction due to overlapping puffs in CALPUFF. Specifically, the use of the MNIRATE=1 option in POSTUTIL is acceptable. At this time, other ammonia-limiting methods, including iterative techniques that use observational data to resolve backward the thermodynamic equilibrium equation between NO3/HNO_3 for each hour to minimize available ammonia, are not acceptable. Generally, for regulatory CALPUFF modeling in Colorado, techniques that assume the atmosphere is always ammonia poor are not acceptable, particularly in eastern Colorado.

3.1.2.6. Chemical Mechanism – Ammonia Sensitivity Tests

To better understand the response of the modeling system to background ammonia when a single point source with significant emissions of SO_2 and NOx is modeled, the Division performed sensitivity tests for a source in northeast Colorado and a source in northwest Colorado using the 2002 MM5/CALMET meteorology. In the test case, SO_2, NOx, and filterable PM10 emissions were modeled. The ammonia background value was varied from 0 to 100 ppb. In the northeast Colorado test case, the SO_2 emission rate is about 3 times higher than the NOx emission rate. In the northwest Colorado test case, the modeled NOx emission rate is about 4.4 times higher than the SO_2 rate.

In both cases, when the background ammonia concentration is zero, the model produces no nitrate, as expected; however, it produces sulfate.

For the northeast Colorado sensitivity test (see Figure 11), where the modeled SO_2 emission rate is significantly higher than the NOx emission rate, the change in visibility (delta-deciview) is not very sensitive to the background ammonia concentration across the range from 1.0 ppb to 100.0 ppb because of the high SO_2 emission rates relative to NOx and the way sulfate is produced in the MESOPUFF II chemical mechanism. Visibility impacts drop significantly when the ammonia background is less than 1.0 ppb, but even at 0.0 ppb of ammonia, sulfate impacts remain relative high.

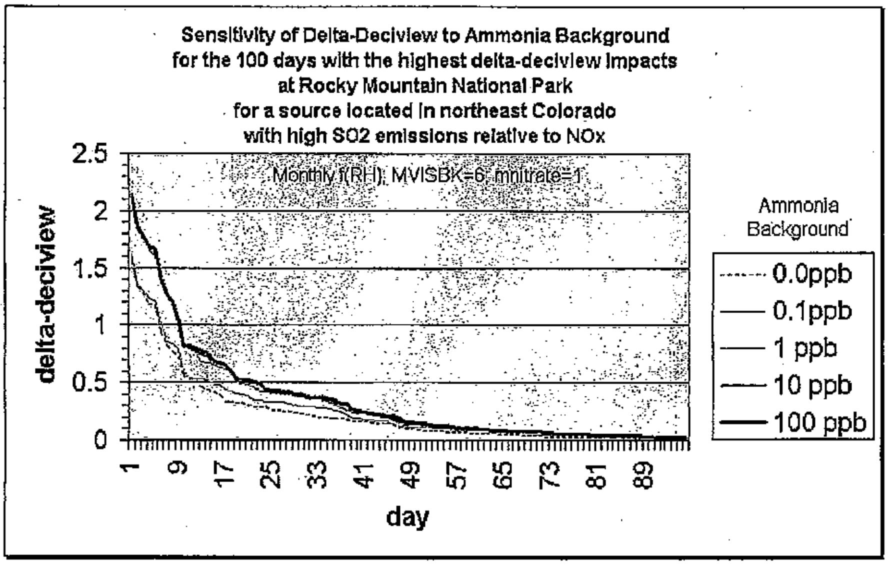


Figure 11. Sensitivity of CALPUFF visibility impacts (delta-deciview) to ammonia backgrounds from 0 ppb to 100 ppb from a source with high SO_2 emissions relative to NOx.

For the northeast Colorado case, on days with the highest visibility impacts, the relative contribution of nitrate and sulfate vary (see Figure 12 and Figure 13), but most of the modeled visibility impairment is due to sulfate. When comparing these figures, be aware the relative rank for some days is different. For example, day 85 is the 2nd worst day for the 0.1 ppb ammonia case, but it's the 3rd worst day for the 100 ppb case. On the day with the highest impact (day 84), the contribution from sulfate is 98.8% for the 0.1 ppb ammonia case and 72.7% for the 100 ppb ammonia case. For the 8th high delta-deciview value, the contribution from sulfate is 86.3% for the 0.1 ppb case and 67.9% for the 100 ppb case.

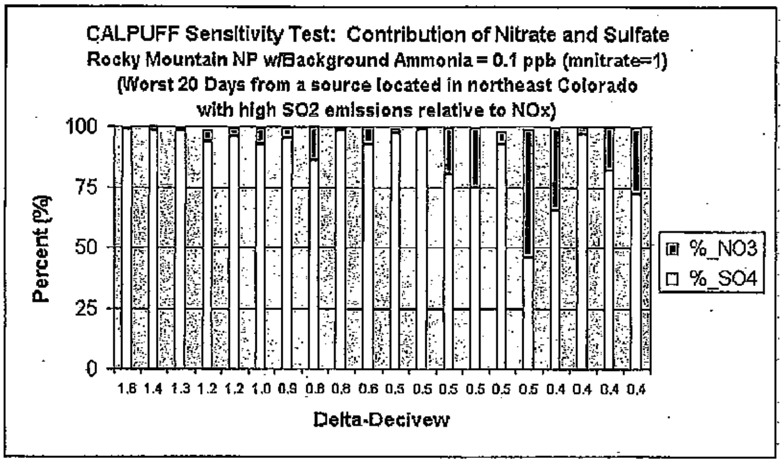


Figure 12. Contribution of sulfate and nitrate to the modeled change in deciviews, assuming a background ammonia of 0.1 ppb in CALPUFF.

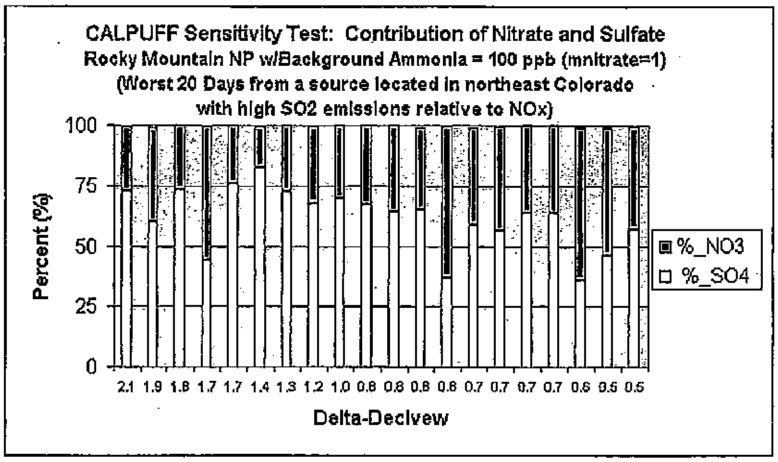


Figure 13. Contribution of sulfate and nitrate to the modeled change in deciviews, assuming a background ammonia of 100 ppb.

For the northwest Colorado sensitivity test (see Figure 14), where the modeled NOx emission rate is significantly higher than the SO_2 emission rate, the change in visibility (delta-deciview) is not sensitive to the background ammonia concentration across the range from 10 ppb to 100 ppb. While there is a moderate drop in impacts when ammonia is dropped from 10 ppb to 1.0 ppb, the model is very sensitive to ammonia when the background ammonia level is less than 1.0 ppb.

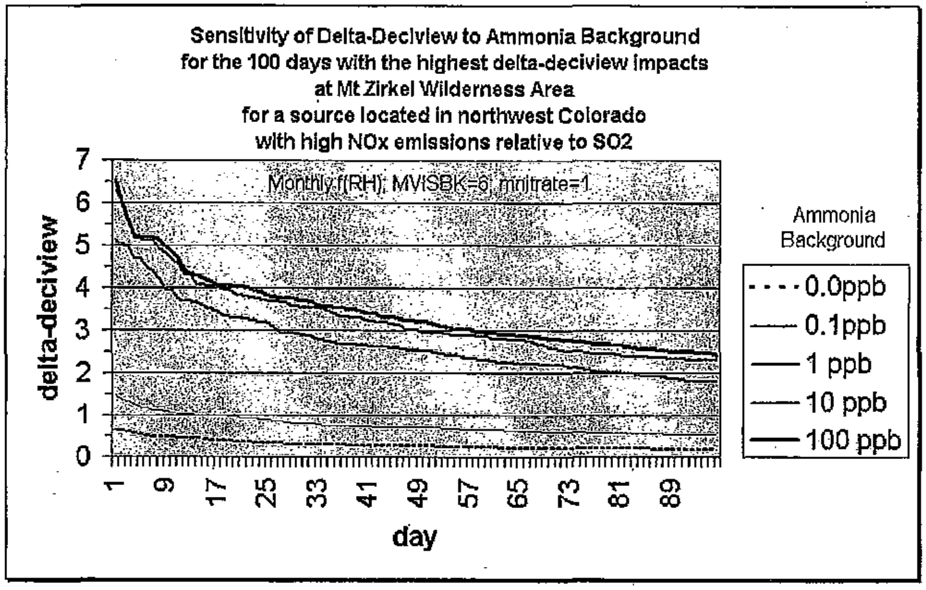


Figure 14. Sensitivity of CALPUFF visibility impacts (delta-deciview) to ammonia backgrounds from 0 ppb to 100 ppb from a source with high NOx emissions relative to SO_2.

For the northwest Colorado test case, according to CALPUFF as implemented here, impairment is primarily due to nitrate (see Figure 15 and Figure 16), but the contribution due to nitrate varies significantly depending on the assumed ammonia background level. For the 100 ppb background case, the nitrate contribution is greater than 90% for the top 20 days. However, for the 0.1 ppb case, the nitrate contribution varies from 43% to 81% for the top 20 days.

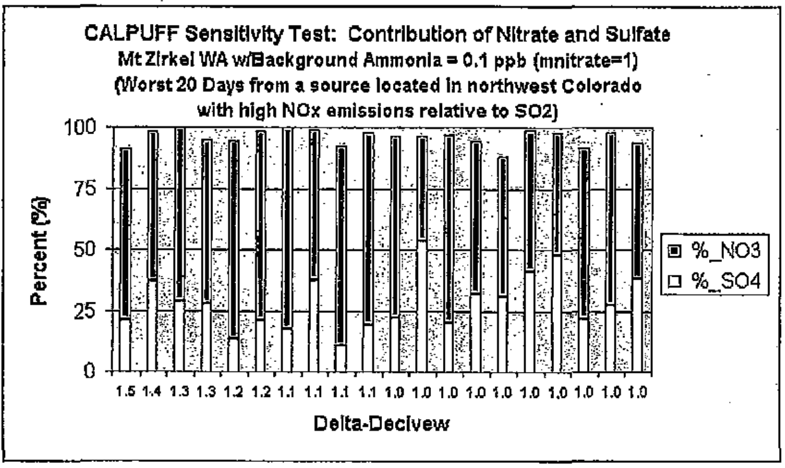


Figure 15. Contribution of sulfate and nitrate to the modeled change in deciviews, assuming a background ammonia of 0.1 ppb in CALPUFF.

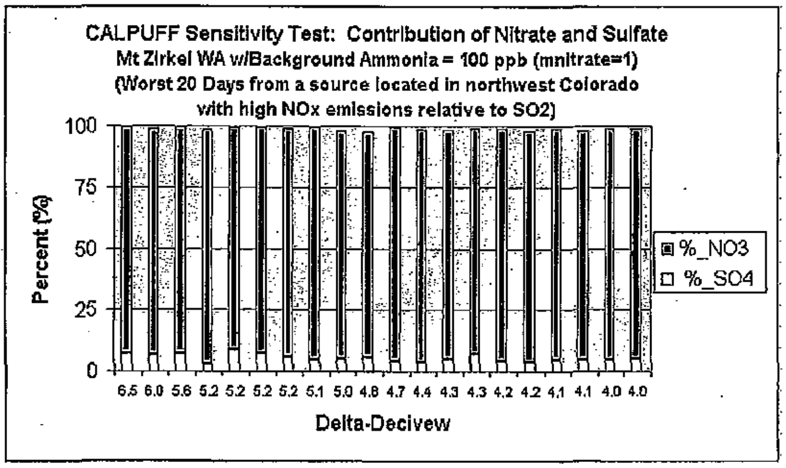


Figure 16. Contribution of sulfate and nitrate to the modeled change in deciviews, assuming a background ammonia of 100 ppb in CALPUFF.

Caution should be used when extrapolating the results of these tests to other CALPUFF applications.

Since the MESOPUFF II chemical mechanism used in this analysis depends on several parameters, including ozone and ammonia background concentrations, the methods for determining the background ozone and ammonia concentration fields are discussed in more detail in the next two sections.

3.1.2.7. Ammonia Assumptions - Discussion

In CALPUFF, as used in this application, the background ammonia concentration is temporally and spatially uniform. It is likely that some portions of the modeling domain are ammonia poor and some are ammonia rich. Thus, setting a domain-wide background is problematic. As discussed in the previous section, when modeling a single large source with high SO_2 emission rates relative to NOx, the assumed background ammonia concentration is not a critical parameter for determining visibility impacts.

According to the IWAQM Phase 2 Report,

> *A further complication is that the formation of particulate nitrate is dependent on the ambient concentration of ammonia, which preferentially reacts with sulfate. The ambient ammonia concentration is an input to the model. Accurate specification of this parameter is critical to the accurate estimation of particulate nitrate concentrations. Based on a review of available data, Langford et al. (1992) suggest that typical (within a factor of 2) background values of ammonia are: 10 ppb for grasslands, 0.5 ppb for forest, and 1 ppb for arid lands at 20 C. Langford et al. (1992) provide strong evidence that background levels of ammonia show strong dependence with ambient temperature (variations of a factor of 3 or 4) and a strong dependence on the soil pH. However, given all the uncertainties in ammonia data, IWAQM recommends use of the background levels provided above, unless specific data are available for the modeling domain that would discredit the values cited. It should be noted, however, that in areas where there are high ambient levels of sulfate, values such as 10 ppb might overestimate the formation of particulate nitrate from a given source, for these polluted conditions. Furthermore, areas in the vicinity of strong point sources of ammonia, such as feedlots or other agricultural areas, may experience locally high levels of background ammonia.*

The Northern Front Range is assumed to be ammonia rich. "Sulfate along the Northern Front Range is completely neutralized by available ammonium and is present in the form of ammonium sulfate.... The Northern Front Range is ammonia rich. There was sufficient ammonia, on most days during winter, to completely neutralize available nitric acid (NFRAQS, 1998)."

For northeast Colorado, a background ammonia concentration of 30.4 $\mu g/m^3$ (about 44 ppb) or less appears to be reasonable based on measurements for this modeling study. According to monitoring conducted for NFRAQS,

- *"With respect to gaseous measurements, only ammonia was acquired at all nine sites with the denuder difference method at the Brighton and Welby sites and with the filter-pack method (i.e., impregnated cellulose-fiber filters behind Teflon-membrane filters) at the other sites. Average ammonia concentrations* *were 30.4 ± 53.4 μg/m3 at the core sites and 10.3 ±12.6 μg/m3 at the satellite sites. The large standard deviation is mainly due to elevated ammonia concentrations found at the Evans site. Maximum 24-hour ammonia concentrations were 187.0 ± 5.4 μg/m3 at the Evans core site on 01/17/97 and 66.7 ± 3.5 μg/m3 at the Masters site on 01/20/97. Figure 6.3-5 shows that during the mid-January episode, 24-hour ammonia concentrations varied by orders of magnitude at the nine NFRAQS sites."*

- *"For the 6- and 12-hour samples, Figure 6.4-3*[not included in this report] *ammonia concentrations were rather consistent throughout the day, with apparent site -to-site and season-to-season variation. Average ammonia concentrations at the Brighton site were double those at the Welby site during Winter 97. Summertime ammonia concentrations were ~1 to 2 μg/m3 higher than the wintertime at the Welby site. Since ammonia concentrations closely reflect the vicinity of the sampling area, site-to-site variations were more pronounced than seasonal or diurnal variations. This is evidenced by the graph in Figure 6.4-4*[not included in this report], *which shows ammonia concentrations were factors of 10 to 20 higher at the Evans site than at most of the other sites during Winter 97. Elevated concentrations exceeded 50 μg/m3 on 20% of the days at the Evans site. Twenty-four hour ammonia concentrations at the Masters and Longmont sites were also factors of 5 to 10 higher than at the other sites."*

For other areas like northwest Colorado, an annual background ammonia concentration of about 1 ppb or less is probably more reasonable, based on ammonia measurements from the Mt. Zirkel Visibility Study.

In the Aerosol Evolution Model (AEM) simulations done for the Mt Zirkel Study for a specific period, "*base case background air concentrations for ammonia were assumed to be 0.5 μg/m^3 and 30 ppb$_v$ for ozone, consistent with measured values at the Hayden VOR site.*" An ammonia concentration of 0.5μg/m^3 is about 0.7 ppb.

In the CALPUFF modeling section of the Mt Zirkel Study report,

> *"The CALPUFF default value for background ammonia concentrations of 10 ppb was also considered far too high as a representative area-average. Measurements from the Buffalo Pass and Gilpin Creek sites were used to adjust ammonia concentration to episode and site-mean values."*

Based on a review of CALUFF files used for the Mt. Zirkel Study, for the August simulations, the assumed ammonia background (BCKNH3) was 1.6 ppb; for the October simulation, the assumed background was 0.5 ppb; and for the September simulation, the assumed background was 0.8 ppb.

3.1.2.8. Ammonia Assumptions

Based on information in the previous section, for sources located in northeast Colorado and along the South Platte River, a domain-wide ammonia background value of 44 ppb is used. For sources located in northwest Colorado, a background ammonia concentration of 1.0 ppb is used. For sources located in southeastern Colorado and for source located along the Arkansas River, a background value of 10 ppb is used.

3.1.2.9. Ozone Assumptions

According to the IWAQM Phase 2 Report,

> *CALPUFF provides two options for providing the ozone background data: (1) a single, typical background value appropriate for the modeling region, or (2) hourly ozone data from one or more ozone monitoring stations. The second and preferred option requires the creation of the OZONE.DAT file containing the necessary data. For the Demonstration Assessment, the domain was large (700 km by 1000 km) such that the second option was necessary. The IWAQM does not anticipate such large domains as being the typical application. Rather, it is anticipated that the more typical application will involve domains of order 400 km by 400 km or smaller. But even for smaller domains, the ability to provide at least monthly background values of ozone is deemed desirable. The problem in developing time (and perhaps spatial) varying background ozone values is having access to representative background ozone data. Ozone data are available from EPA's Aerometric Information Retrieval System (AIRS); however, AIRS data must be used with caution. Many ozone sites are located in urban and suburban centers and are not representative of oxidant levels experienced by plumes undergoing long range transport.*

In this study, "*CH2M HILL obtained hourly ozone data from the following stations located within the modeling domain for some or all of the years 1996, 2001, and 2002:*

- *Gothic (Gunnison County, Colorado)*
- *Rocky Mountain National Park*

Additional, hourly data for 1996, 2001, and 2002 were provided to CH2M HILL by the APCD for the following stations along the Front Range:

- *Greeley*
- *Highlands Ranch*
- *Colorado Springs*

Data recovery for the years 2001 and 2002 for the Greeley station was very low, and therefore data from the nearby Fort Collins station were used instead. Any data missing from the hourly records were replaced with a domain-wide default concentration of 60 parts per billion (ppb), as determined by the APCD/NPS (CH2M HILL, 2005)."

3.1.3. CALPOST Settings and Visibility Post-Processing

The CALPUFF results will be post-processed with a modified version of CALPOST (version 5.51_CO_v3, level: 030709), POSTUTIL (version 1.31, level 030528), and BART98_v3. The CALPOST modifications were performed by the Division and do not affect any of the calculations in CALPOST for the deciview values used in this report; however, some simple calculations were done within CALPOST in order to output delta-deciview values (instead of percent change values) for the individual species that contribute to the overall delta-deciview value, but these values are not used for the subject-to-BART modeling. Otherwise, the CALPOST code modification consists of a "write" statement and supporting code. It outputs all daily delta-deciview values for every receptor to a file called "deciview24.dat." The 98th percentile values are computed from "deciview24.dat" by a separate FORTRAN processor (BART98_v3) written by the Division specifically for this analysis. The Division's processors are available upon request.

For the initial modeling analysis, all PM10 may be assumed to have a scattering efficiency of 1.0 since the contribution of direct PM10 emissions is expected to be relatively small compared to visibility impairment caused by SO_2 and NOx emissions. However, if modeled impacts are below the contribution threshold, condensible and filterable PM10 emissions should be quantified and speciated. Alternatively, a sensitivity test could be performed to determine if speciation would change the outcome of the subject-to-BART demonstration. For example, if all PM10 is modeled as PMF in CALPOST, the scattering efficiency for PMF could be changed from 1.0 to 10.0 to simulate a worst-case speciation scenario. If this type of sensitivity test or another analysis suggests that PM10 speciation could change the outcome of the analysis, then speciation should be performed. If speciated PM10 emissions are modeled, the following species should be considered: fine particulates (PMF), coarse particulates (PMC), elemental carbon (EC), organic carbon (SOA), and sulfate (SO4).

To calculate background light extinction, MVISBK should be set to 6. That is, monthly RH adjustment factors are applied directly to the background and modeled sulfate and nitrate concentrations, as recommended by the BART guideline. The RHMAX parameter, which is the maximum relative humidity factor used in the particle growth equation for visibility processing, is not used when method 6 is selected. Similarly, the relative humidity adjustment factor (f(RH)) curves in CALPOST (e.g., IWAQM growth curve and the 1996 IMPROVE curve) are not used when MVISBK is equal to 6.

The natural background is based on the 20 percent best visibility days, as recommended by the BART guideline preamble:

> *Finally, these BART guidelines use the natural visibility baseline for the 20 percent best visibility days for comparison to the "cause or contribute" applicability thresholds. We believe this estimated baseline is likely to be reasonably conservative and consistent with the goal of natural conditions* (70 FR 39125).

The method for estimating natural background is presented in section 3.1.3.1. Specifically, for hygroscopic components, BKSO4 in CALPOST should be set to 0.0893 for all months. For non-hygroscopic components, BKSOIL should be set to 1.620 for all months. The

BKSO4 and BKSOIL values have been computed specifically for the Colorado Class I areas in the modeling domain.

The extinction due to Rayleigh scattering (i.e., the scattering of light by natural particles much smaller than the wavelength of the light) should be set to 10 Mm^{-1} (BEXTRAY = 10.0).

3.1.3.1. Natural Conditions - Determining Hygroscopic And Non-Hygroscopic Values For the Best 20% Visibility Days

3.1.3.1.1. Natural Background - Objective

The spreadsheet shown in Figure 17 was created to determine the hygroscopic (3[BKSO4]) and non-hygroscopic (equivalent to [BKSOIL]) portions of natural background for the best 20% visibility days (Best Days) at all Class I areas in Colorado's BART modeling. These concentrations, [BKSO4] and [BKSOIL], are used in CALPOST with monthly relative humidity adjustment factors (f(RH)) to determine monthly natural background visibility that would, on average, represent the average natural background visibility for the best 20% days in EPA's "Guidance for Estimating Natural Visibility Conditions Under the Regional Haze Program" (EPA, 2003).

3.1.3.1.2. Natural Background - Discussion

"Guidance for Estimating Natural Visibility Conditions Under the Regional Haze Program" (EPA, 2003), section 2.4, describes the calculation of the annual average background extinction (in 1/Mm) for a Class I area using the area's annual f(RH) and average natural concentrations based on the area's geographic location (east versus west). Annual average background extinction values (in 1/Mm) are converted to annual average Haze Index (HI) values (in deciview or dv). Then, the average HI value for the 20% best visibility days (Best Days (dv)) is estimated from 10th percentile of the annual average HI value for a Class I area assuming normal distribution. Thus, no average natural concentrations are provided for determining extinction for the 20% best visibility days.

For background extinction computation methods 2, 3, and 6 in CALPOST, background extinction is calculated with user-supplied monthly concentrations of SO4, NO3, PM coarse, organic carbon, soil, and elemental carbon species. In practice, concentrations for only 2 species, SO4 ([BKSO4]) and soil ([BKSOIL]), are supplied in the CALPOST input file to represent hygroscopic and non-hygroscopic portions of background extinction, respectively.

To determine background extinction for the BART analysis with CALPOST, average natural concentrations that represent average natural background visibility for the best 20% days need to be determined.

3.1.3.1.3. Natural Background - Method

Following EPA's approach of using regional average natural concentrations and the concept of using simplified inputs in CALPOST, the same hygroscopic ($3[BKSO4]_{best20}$) and non-hygroscopic ($[BKSOIL]_{best20}$) values would be used in CALPOST for all Class I areas in Colorado's BART modeling.

The spreadsheet calculates an average background (dv) based on monthly background extinction (1/Mm) for each Class I area in Colorado's BART modeling using the following equations:

1. Monthly background extinction in 1/Mm ($bext_{month}$) = $3[BKSO4]_{best20}f(RH) + [BKSOIL]_{best20}$ + Rayleigh
2. Annual average background extinction in 1/Mm ($bext_{annual\_ave}$) = ($bext_{Jan} + bext_{Feb} + \ldots + bext_{Dec})/12$
3. Calculated Best Days in dv = $10\ln(bext_{annual\_ave}/10)$

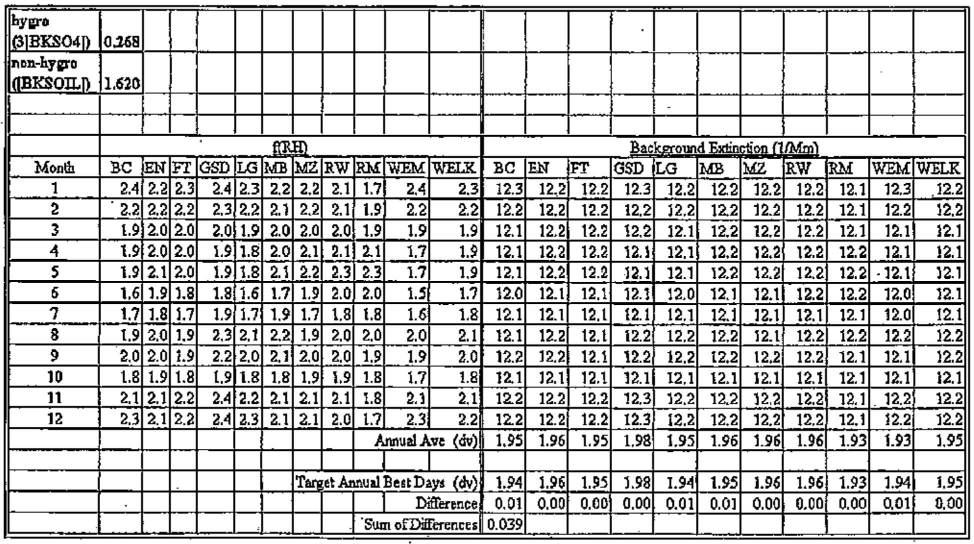
EPA guidance provides f(RH) values based on the centroid of the Class I area (see Appendix B – Monthly f(RH) Values) and a Best Days (dv) value for each of the Class I areas (see Appendix A – Natural Background Values).

The hygroscopic (3[BKSO4]) and non-hygroscopic ([BKSOIL]) values determined yielded the lowest sum of the absolute differences between the published Best Days (dv) and calculated Best Days (dv) for all Class I areas in the analysis:

$$\text{Minimize} \sum_{n=1}^{11} \left| (\text{published Best Days})_n - (\text{calculated Best Days})_n \right|$$

where: n = number of Class I areas in analysis

The "hygro (3[BKSO4])" and "non-hygro ([BKSOIL])" values of 0.268 and 1.620 were calculated in Microsoft Excel using the "solver add-in" tool for optimization and equation solving (Figure 17). As can be seen from the "difference" values in Figure 17, the annual 20% best visibility days background concentrations for each Class I area calculated with this method are within 0.01 deciviews or less of the annual 20% best visibility days background values recommended by EPA. For CALPOST, the hygroscopic component of extinction is divided by 3 (the extinction coefficient of sulfate and nitrate) and input as BKSO4 (i.e., BKSO4 = 0.268/3 = 0.0893). The non-hygroscopic component is used directly (i.e., BKSOIL = 1.620).

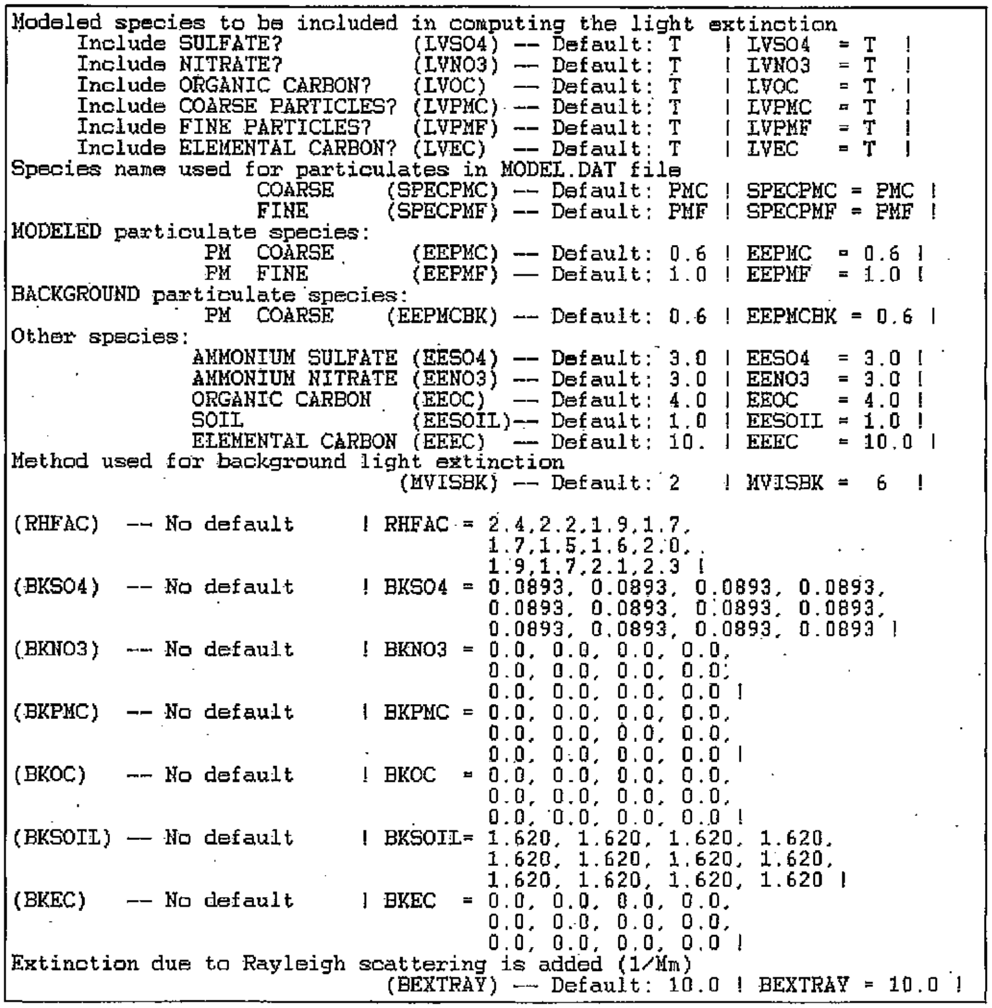


hygro (3[BKSO4])	0.268																					
non-hygro ([BKSOIL])	1.620																					
	f(RH)											Background Extinction (1/Mm)										
Month	BC	EN	FT	GSD	LG	MB	MZ	RW	RM	WEM	WELK	BC	EN	FT	GSD	LG	MB	MZ	RW	RM	WEM	WELK
1	2.4	2.2	2.3	2.4	2.3	2.2	2.2	2.1	1.7	2.4	2.3	12.3	12.2	12.2	12.3	12.2	12.2	12.2	12.2	12.1	12.3	12.2
2	2.2	2.2	2.2	2.3	2.2	2.1	2.2	2.1	1.9	2.2	2.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.1	12.2	12.2
3	1.9	2.0	2.0	2.0	1.9	2.0	2.0	2.0	1.9	1.9	1.9	12.1	12.2	12.2	12.2	12.1	12.2	12.2	12.2	12.1	12.1	12.1
4	1.9	2.0	2.0	1.9	1.8	2.0	2.1	2.1	2.1	1.7	1.9	12.1	12.2	12.2	12.1	12.1	12.2	12.2	12.2	12.2	12.1	12.1
5	1.9	2.1	2.0	1.9	1.8	2.1	2.2	2.3	2.3	1.7	1.9	12.1	12.2	12.2	12.1	12.1	12.2	12.2	12.2	12.2	12.1	12.1
6	1.6	1.9	1.8	1.8	1.6	1.7	1.9	2.0	2.0	1.5	1.7	12.0	12.1	12.1	12.1	12.0	12.1	12.1	12.2	12.2	12.0	12.1
7	1.7	1.8	1.7	1.9	1.7	1.9	1.7	1.8	1.8	1.6	1.8	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.0	12.1
8	1.9	2.0	1.9	2.3	2.1	2.2	1.9	2.0	2.0	2.0	2.1	12.1	12.2	12.1	12.2	12.2	12.2	12.1	12.2	12.2	12.2	12.2
9	2.0	2.0	1.9	2.2	2.0	2.1	2.0	2.0	1.9	1.9	2.0	12.2	12.2	12.1	12.2	12.2	12.2	12.2	12.2	12.1	12.1	12.2
10	1.8	1.9	1.8	1.9	1.8	1.8	1.9	1.9	1.8	1.7	1.8	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
11	2.1	2.1	2.2	2.4	2.2	2.1	2.1	2.1	1.8	2.1	2.1	12.2	12.2	12.2	12.3	12.2	12.2	12.2	12.2	12.1	12.2	12.2
12	2.3	2.1	2.2	2.4	2.3	2.1	2.1	2.0	1.7	2.3	2.2	12.2	12.2	12.2	12.3	12.2	12.2	12.2	12.2	12.1	12.2	12.2
											Annual Ave (dv)	1.95	1.96	1.95	1.98	1.95	1.96	1.96	1.96	1.93	1.93	1.95
											Target Annual Best Days (dv)	1.94	1.96	1.95	1.98	1.94	1.95	1.96	1.96	1.93	1.94	1.95
											Difference	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00
											Sum of Differences	0.039										

Figure 17. Spreadsheet showing the "hygro (3[BKSO4])" (0.268)and "non-hygro ([BKSOIL])" (1.620) values calculated in Microsoft Excel using the "solver add-in" tool for optimization and equation solving.

3.1.3.2. CALPOST and POSTUTIL Parameters

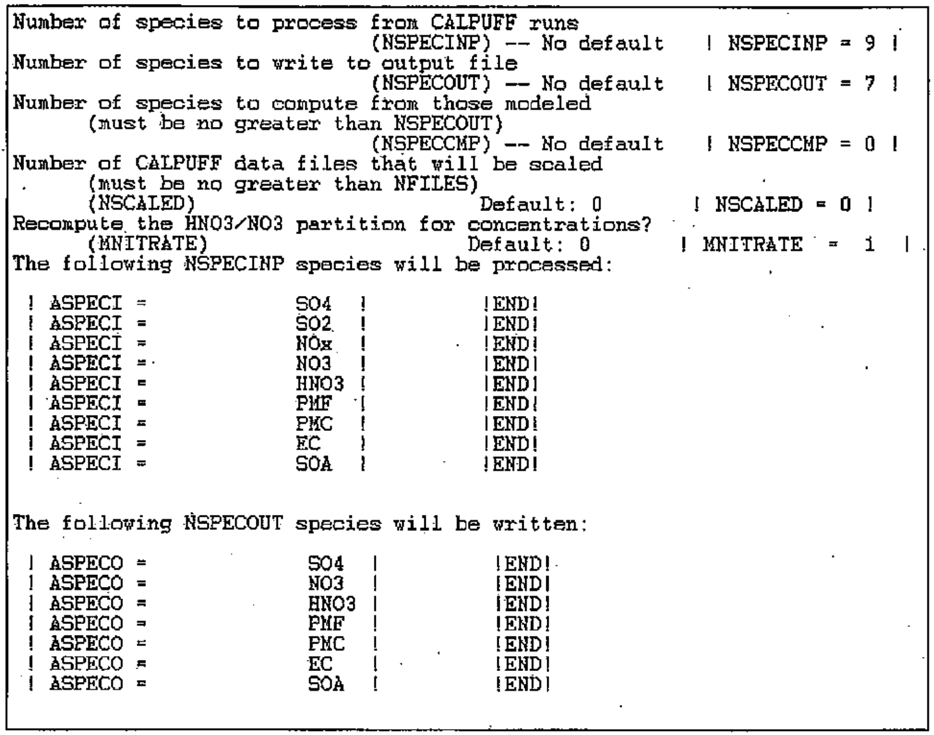
Two post-processing examples are provided. In example #1, fine particulate emissions are speciated into PMF, PMC, EC, SOA, and SO4 and explicitly included as species in CALPUFF. Emission rates for each species are included in CALPUFF. Figure 18 summarizes some of the key CALPOST settings. The monthly f(RH) values (RHFAC), which are different for each Class I area, are from Appendix B – Monthly f(RH) Values.



```
Modeled species to be included in computing the light extinction
     Include SULFATE?           (LVSO4) -- Default: T   ! LVSO4   = T  !
     Include NITRATE?           (LVNO3) -- Default: T   ! LVNO3   = T  !
     Include ORGANIC CARBON?    (LVOC)  -- Default: T   ! LVOC    = T  !
     Include COARSE PARTICLES?  (LVPMC) -- Default: T   ! LVPMC   = T  !
     Include FINE PARTICLES?    (LVPMF) -- Default: T   ! LVPMF   = T  !
     Include ELEMENTAL CARBON?  (LVEC)  -- Default: T   ! LVEC    = T  !
Species name used for particulates in MODEL.DAT file
                  COARSE     (SPECPMC) -- Default: PMC ! SPECPMC = PMC !
                  FINE       (SPECPMF) -- Default: PMF ! SPECPMF = PMF !
MODELED particulate species:
              PM  COARSE       (EEPMC) -- Default: 0.6 ! EEPMC   = 0.6 !
              PM  FINE         (EEPMF) -- Default: 1.0 ! EEPMF   = 1.0 !
BACKGROUND particulate species:
              PM  COARSE     (EEPMCBK) -- Default: 0.6 ! EEPMCBK = 0.6 !
Other species:
             AMMONIUM SULFATE (EESO4) -- Default: 3.0 ! EESO4   = 3.0 !
             AMMONIUM NITRATE (EENO3) -- Default: 3.0 ! EENO3   = 3.0 !
             ORGANIC CARBON   (EEOC)  -- Default: 4.0 ! EEOC    = 4.0 !
             SOIL             (EESOIL)-- Default: 1.0 ! EESOIL  = 1.0 !
             ELEMENTAL CARBON (EEEC)  -- Default: 10. ! EEEC    = 10.0 !
Method used for background light extinction
                              (MVISBK) -- Default: 2   ! MVISBK =  6  !

(RHFAC)  -- No default     ! RHFAC = 2.4,2.2,1.9,1.7,
                                     1.7,1.5,1.6,2.0,
                                     1.9,1.7,2.1,2.3 !
(BKSO4)  -- No default     ! BKSO4 = 0.0893, 0.0893, 0.0893, 0.0893,
                                     0.0893, 0.0893, 0.0893, 0.0893,
                                     0.0893, 0.0893, 0.0893, 0.0893 !
(BKNO3)  -- No default     ! BKNO3 = 0.0, 0.0, 0.0, 0.0,
                                     0.0, 0.0, 0.0, 0.0,
                                     0.0, 0.0, 0.0, 0.0 !
(BKPMC)  -- No default     ! BKPMC = 0.0, 0.0, 0.0, 0.0,
                                     0.0, 0.0, 0.0, 0.0,
                                     0.0, 0.0, 0.0, 0.0 !
(BKOC)   -- No default     ! BKOC  = 0.0, 0.0, 0.0, 0.0,
                                     0.0, 0.0, 0.0, 0.0,
                                     0.0, 0.0, 0.0, 0.0 !
(BKSOIL) -- No default     ! BKSOIL= 1.620, 1.620, 1.620, 1.620,
                                     1.620, 1.620, 1.620, 1.620,
                                     1.620, 1.620, 1.620, 1.620 !
(BKEC)   -- No default     ! BKEC  = 0.0, 0.0, 0.0, 0.0,
                                     0.0, 0.0, 0.0, 0.0,
                                     0.0, 0.0, 0.0, 0.0 !
Extinction due to Rayleigh scattering is added (1/Mm)
                             (BEXTRAY) -- Default: 10.0 ! BEXTRAY = 10.0 !
```

Figure 18. CALPOST - key parameters (example #1 setup).

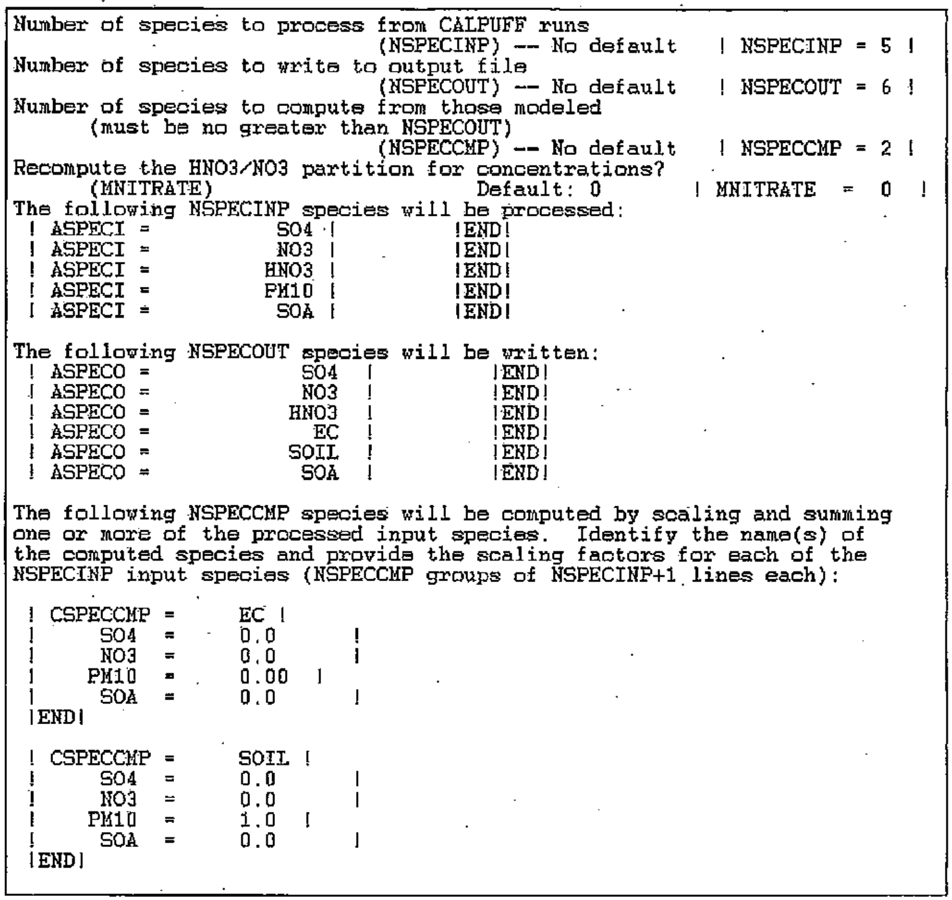
In example #1, POSTUTIL is used to compute the partition for the total concentration fields with MNITRATE=1 and the appropriate ammonia background concentration. The ammonia background concentration, BCKNH3, in POSTUTIL is the same as the background value presented in section 3.1.2.8. In POSTUIL, the input species include SO2, SO4, NOX, HNO3, NO3, SOA, PMF, PMC, and EC and the output species include SO4, HNO3, NO3, SOA, PMF, PMC, and EC. Key POSTUTIL parameters are shown in Figure 19.



```
Number of species to process from CALPUFF runs
                              (NSPECINP) -- No default     ! NSPECINP = 9 !
Number of species to write to output file
                              (NSPECOUT) -- No default     ! NSPECOUT = 7 !
Number of species to compute from those modeled
      (must be no greater than NSPECOUT)
                              (NSPECCMP) -- No default     ! NSPECCMP = 0 !
Number of CALPUFF data files that will be scaled
      (must be no greater than NFILES)
      (NSCALED)                        Default: 0        ! NSCALED = 0 !
Recompute the HNO3/NO3 partition for concentrations?
      (MNITRATE)                       Default: 0        ! MNITRATE  =  1  !
The following NSPECINP species will be processed:

 ! ASPECI =            SO4  !          !END!
 ! ASPECI =            SO2  !          !END!
 ! ASPECI =            NOx  !          !END!
 ! ASPECI =            NO3  !          !END!
 ! ASPECI =            HNO3 !          !END!
 ! ASPECI =            PMF  !          !END!
 ! ASPECI =            PMC  !          !END!
 ! ASPECI =            EC   !          !END!
 ! ASPECI =            SOA  !          !END!


The following NSPECOUT species will be written:

 ! ASPECO =             SO4  !          !END!
 ! ASPECO =             NO3  !          !END!
 ! ASPECO =             HNO3 !          !END!
 ! ASPECO =             PMF  !          !END!
 ! ASPECO =             PMC  !          !END!
 ! ASPECO =             EC   !          !END!
 ! ASPECO =             SOA  !          !END!
```

Figure 19. POSTUTIL - key parameters for cases with nitrate partitioning and speciated PM10 concentrations (example #1 setup).

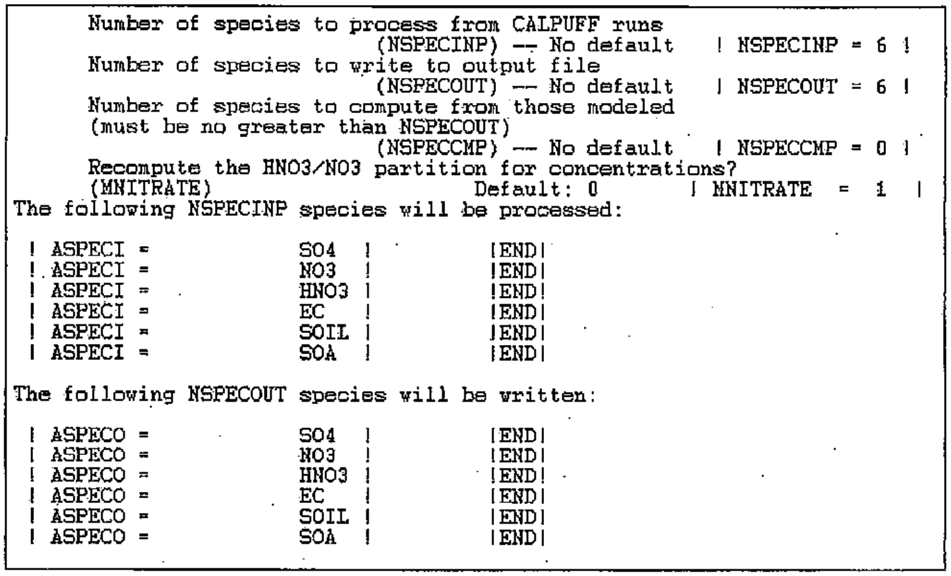
In example #2, PM10 is included as a species in CALPUFF and ammonia limiting is performed with POSTUTIL. The example #2 CALPOST setup is the same as shown in example #1 (see Figure 18) except LVPMC=F, since there are is no coarse PM, and SPECPMF=SOIL because the PM10 emissions from CALPUFF are reallocated to the species SOIL and EC in the first of two POSTUTIL runs. The first POSTUTIL setup for example #2 (see Figure 20) is intended to provide a post-processing opportunity to divide the PM10 concentrations into SOIL and EC components; however, in the setup example shown in Figure 20, all of the PM10 is allocated to SOIL and none is allocated to EC.



```
Number of species to process from CALPUFF runs
                             (NSPECINP) -- No default    ! NSPECINP = 5 !
Number of species to write to output file
                             (NSPECOUT) -- No default    ! NSPECOUT = 6 !
Number of species to compute from those modeled
      (must be no greater than NSPECOUT)
                             (NSPECCMP) -- No default    ! NSPECCMP = 2 !
Recompute the HNO3/NO3 partition for concentrations?
      (MNITRATE)                      Default: 0       ! MNITRATE  =  0  !
The following NSPECINP species will be processed:
 ! ASPECI =          SO4 !          !END!
 ! ASPECI =          NO3 !          !END!
 ! ASPECI =         HNO3 !          !END!
 ! ASPECI =         PM10 !          !END!
 ! ASPECI =          SOA !          !END!

The following NSPECOUT species will be written:
 ! ASPECO =              SO4   !          !END!
 ! ASPECO =              NO3   !          !END!
 ! ASPECO =             HNO3   !          !END!
 ! ASPECO =               EC   !          !END!
 ! ASPECO =             SOIL   !          !END!
 ! ASPECO =              SOA   !          !END!

The following NSPECCMP species will be computed by scaling and summing
one or more of the processed input species.  Identify the name(s) of
the computed species and provide the scaling factors for each of the
NSPECINP input species (NSPECCMP groups of NSPECINP+1 lines each):

 ! CSPECCMP =     EC !
 !      SO4  =    0.0        !
 !      NO3  =    0.0        !
 !     PM10  =    0.00   !
 !      SOA  =    0.0        !
 !END!

 ! CSPECCMP =     SOIL !
 !      SO4  =    0.0        !
 !      NO3  =    0.0        !
 !     PM10  =    1.0    !
 !      SOA  =    0.0        !
 !END!
```

Figure 20. POSTUTIL setup for simulations where PM10 is divided into SOIL and EC species (example #2 setup).

In the second POSTUTIL setup for example #2, POSTUTIL is used to compute the partition for the total concentration fields with MNITRATE=1 and the appropriate ammonia background concentration. The ammonia background concentration, BCKNH3, in POSTUTIL is the same as the background value presented in section 3.1.2.8. In this POSTUIL setup, the input species include SO4, NO3, HNO3, EC, SOIL, and SOA and the output species include SO4, NO3, HNO3, EC, SOIL, and SOA. Key POSTUTIL parameters are shown in Figure 19.



```
      Number of species to process from CALPUFF runs
                             (NSPECINP) -- No default     ! NSPECINP = 6 !
      Number of species to write to output file
                             (NSPECOUT) -- No default     ! NSPECOUT = 6 !
      Number of species to compute from those modeled
      (must be no greater than NSPECOUT)
                             (NSPECCMP) -- No default     ! NSPECCMP = 0 !
      Recompute the HNO3/NO3 partition for concentrations?
      (MNITRATE)                       Default: 0      ! MNITRATE  =  1  !
The following NSPECINP species will be processed:

 ! ASPECI =              SO4  !          !END!
 ! ASPECI =              NO3  !          !END!
 ! ASPECI =              HNO3 !          !END!
 ! ASPECI =              EC   !          !END!
 ! ASPECI =              SOIL !          !END!
 ! ASPECI =              SOA  !          !END!

The following NSPECOUT species will be written:

 ! ASPECO =              SO4  !          !END!
 ! ASPECO =              NO3  !          !END!
 ! ASPECO =              HNO3 !          !END!
 ! ASPECO =              EC   !          !END!
 ! ASPECO =              SOIL !          !END!
 ! ASPECO =              SOA  !          !END!
```

Figure 21. POSTUTIL setup for simulations where ammonia limiting is performed using the output file generated from the POSTUTIL setup in Figure 20 (example #2 setup).

3.1.3.3. 98th Percentile Methods

According the BART guideline:

...you should compare your "contribution" threshold against the 98th percentile of values. If the 98th percentile value from your modeling is less than your contribution threshold, then you may conclude that the source does not contribute to visibility impairment and is not subject to BART. (70 FR 39162)

The BART guideline does not contain a specific method for calculating the "98th percentile value" and CALPOST version 5.51 does not generate a 98th percentile delta-deciview value. Consequently, the Division developed a FORTRAN program (BART98_v3) to compute 98th percentile results. The program implements several methods because, at the time the code was written, U.S. EPA had not yet specified an explicit method for determining the 98th percentile value.

The U.S.EPA recommends using the 98th percentile value from the distribution of values containing the highest modeled delta-deciview value for each day of the simulation from all modeled receptors at a given Class I area. The 98th percentile delta-deciview value should be determined in several ways:

- The 8th highest value for each year modeled
- The 3-year average of the annual 8th high values
- The 22nd highest value for the 3-year modeling period

The highest value from all of the above methods should be compared to the contribution threshold. The contribution threshold has an implied level of precision equal to the level of precision reported from CALPOST. Specifically, the 98th percentile results should be reported to three decimal places.

The Division's processor BART98_v3 calculates the 98th percentile value with the method recommended by U.S. EPA. The Division refers to the method as the "day-specific method" or "method 1." The first step in the method is to find the highest modeled delta-deciview value for each day of the simulation from all modeled receptors for the selected time period. While this set of delta-deciview values is generated by CALPOST in an unranked format, the Division's processor BART98_v3 outputs all daily delta-deciview values for each receptor from CALPOST and finds the highest impact for each day. Next, the processor ranks the daily delta-deciview maxima in descending order for the number of days processed in CALPOST. Then, the processor determines the 98th percentile value from the distribution of ranked modeled daily maximum values, irrespective of receptor location. For example, for a 365-day simulation, the 98th percentile value would be the 8th highest modeled delta-deciview value from the list of ranked delta-deciview values. That is, the top 7 days are ignored, even though the values being ignored may be at different receptors. Similarly, for a 3-year period, the 98th percentile would be the 22nd highest modeled delta-deciview value.

The processor BART98_v3 also generates 98th percentile values using the "receptor-specific method" or "method 2." This method, which calculates 98th percentile values on a receptor-by-receptor basis, is not used for the subject-to-BART modeling in Colorado.

In order to make the processor more general and to handle missing data, the "8th high" (for one year) and "22nd high" (for 3 years) values recommended by U.S. EPA are not hardwired into the processor; rather, the processor contains an algorithm that calculates the appropriate "nth high" value from the distribution of data. The 8th high and 22nd high values recommended by U.S. EPA are consistent with the values that would be generated from the equations in 40 CFR 50 Appendix N - "Interpretation of the National Ambient Air Quality Standards for PM2.5" – for determining 98th percentile values for PM2.5 monitoring. Thus, the Appendix N method is used in the processor. For the exact algorithm, see Appendix N, the BART98_v3 source code, or the BART98_v3 "readme" file.

4. Results

The CALPUFF modeling results will include eleven of the twelve Class I federal areas in Colorado. Mesa Verde was excluded because it is more than 300 km from all of the BART-eligible sources in Colorado. In addition, the BART-eligible sources in Colorado would have higher impacts at other Class I areas. That is, impacts at Mesa Verde would not be the controlling 98th percentile values for this analysis.

The results for source-to-receptor distances beyond 300 kilometers may be used, but they may overestimate impacts because puff splitting has not been used. The model setup used here should provide reasonable estimates for source-to-receptor distances up to 300 kilometers. The modeling report should include a figure such as Figure 22 that shows the 50km and 300 km radius circles around the BART-eligible source.

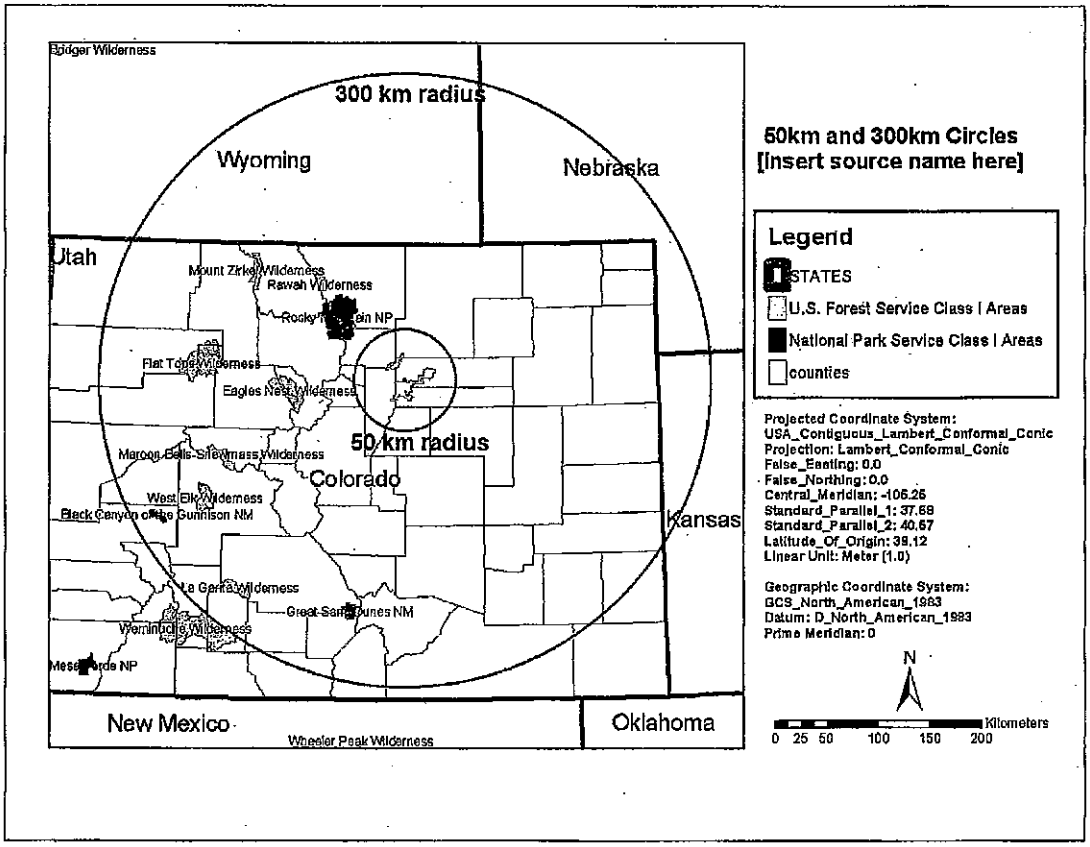


Figure 22. Example figure showing Class I areas within 50 and 300 kilometers of the BART-eligible source.

The results section of the report should include a table like Table 1 and a figure like Figure 23 that show the 98th percentile daily delta-deciview values for each Class I area in the modeling domain.

The 98th percentile delta-deciview value should be determined several ways:

- The 8th highest value for each year modeled
- The 3-year average of the annual 8th high values
- The 22nd highest value for the 3-year modeling period

The highest value from the three methods above should be compared to the contribution threshold. The contribution threshold has an implied level of precision equal to the level of precision reported from CALPOST. Specifically, the 98th percentile results should be reported to three decimal places.

Table 1. Example table showing maximum 98th percentile value, 98th percentile values calculated with several methods, and the number of days the impact is equal to or greater than 0.5 deciviews for the entire period modeled.

CALPUFF Individual Source Attribution Analysis BART-eligible source name:			Maximum 98th Percentile Value =			0.000
	98th Percentile Daily Change in Visibility from BART-Eligible Source Compared Against Natural Background Conditions					
	8th High Delta-Deciview Value				**22nd High Delta-Deciview Value from 3-year Modeling Period**	**Number of Days Impact >0.5dv (1996, 2001, 2002)**
Class I federal area	**1996**	**2001**	**2002**	**3-year Average**		
Flat Tops WA						
Rawah WA						
Mt Zirkel WA						
Weminuche WA						
Rocky Mountain NP						
Maroon Bells-Snowmass WA						
La Garita WA						
Great Sand Dunes NP						
West Elk WA						
Eagles Nest WA						
Black Canyon of the Gunnison NP						

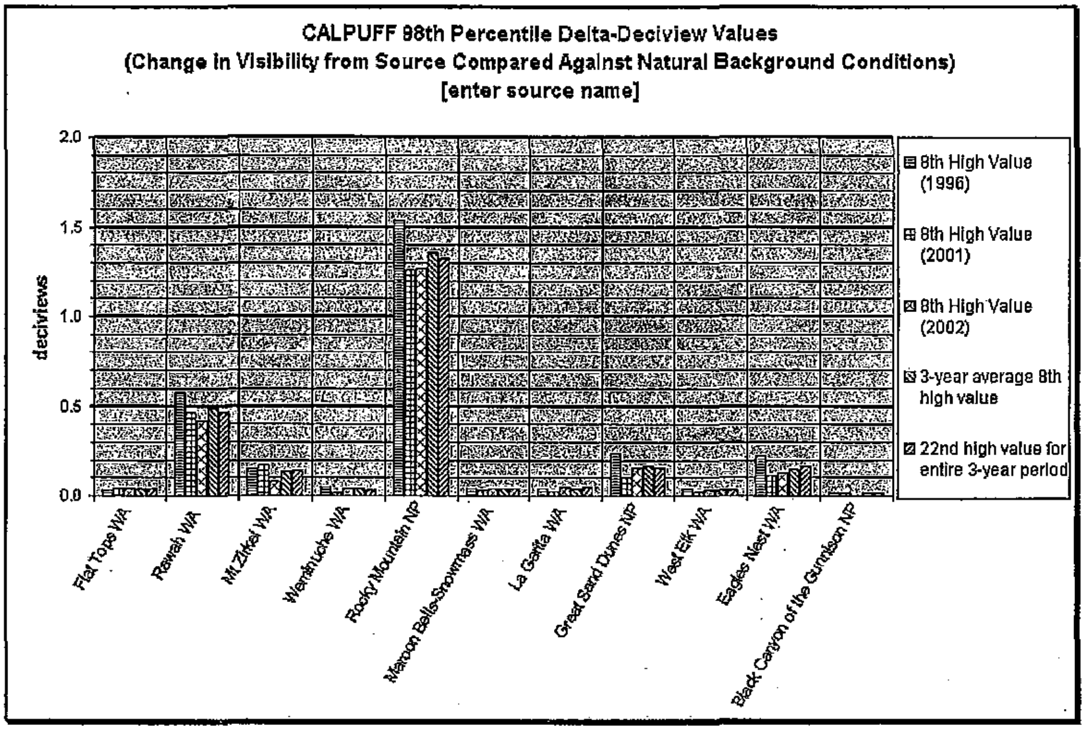


Figure 23. Example graph comparing 98th percentile daily change in visibility values (delta-deciviews). The highest value should be compared to the contribution threshold of 0.5 deciviews.

5. References

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Appendix A – Natural Background Values

Appendix B
Default Natural b_{ext}, *dv*, and 10th and 90th Percentile *dv* Values at All Mandatory Federal Class I Areas

Mandatory Federal Class I Area	State	Lat.	Lon.	bext (Mm-1)	Ann. Avg. (dv)	Best Days (dv) $^{(a)}$	Worst Days (dv) $^{(b)}$
Acadia NP	ME	44.35	-68.24	21.40	7.61	3.77	11.45
Agua Tibia Wilderness	CA	33.42	-116.99	15.86	4.61	2.05	7.17
Alpine Lake Wilderness	WA	47.55	-121.16	16.99	5.30	2.74	7.86
Anaconda-Pintler Wilderness	MT	45.95	-113.5	16.03	4.72	2.16	7.28
Arches NP	UT	38.73	-109.58	15.58	4.43	1.87	6.99
Badlands NP	SD	43.81	-102.36	16.06	4.74	2.18	7.30
Bandelier NM	NM	35.79	-106.34	15.62	4.46	1.90	7.02
Bering Sea	AK	60.46	-172.75				
Big Bend NP	TX	29.33	-103.31	15.48	4.37	1.81	6.93
Black Canyon of the Gunnison NM	CO	38.57	-107.75	15.68	4.50	1.94	7.06
Bob Marshall Wilderness	MT	47.68	-113.23	16.17	4.80	2.24	7.36
Bosque del Apache	NM	33.79	-106.85	15.54	4.41	1.85	6.97
Boundary Waters Canoe Area	MN	48.06	-91.43	20.89	7.37	3.53	11.21
Breton	LA	29.87	-88.82	21.57	7.69	3.85	11.53
Bridger Wilderness	WY	42.99	-109.49	15.71	4.52	1.96	7.06
Brigantine	NJ	39.49	-74.39	21.05	7.44	3.60	11.28
Bryce Canyon NP	UT	37.57	-112.17	15.58	4.43	1.87	6.99
Cabinet Mountains Wilderness	MT	48.18	-115.68	16.27	4.87	2.31	7.43
Caney Creek Wilderness	AR	34.41	-94.08	21.14	7.49	3.65	11.33
Canyonlands NP	UT	38.23	-109.91	15.60	4.45	1.89	7.01
Cape Romain	SC	32.99	-79.49	21.22	7.52	3.68	11.36
Capitol Reef NP	UT	38.06	-111.15	15.63	4.47	1.91	7.03
Caribou Wilderness	CA	40.49	-121.21	16.05	4.73	2.17	7.29
Carlsbad Caverns NP	NM	32.12	-104.59	15.61	4.46	1.90	7.02
Chassahowitzka	FL	28.69	-82.66	21.46	7.63	3.79	11.47
Chiricahua NM	AZ	32.01	-109.34	15.47	4.36	1.80	6.92
Chiricahua Wilderness	AZ	31.86	-109.28	15.45	4.35	1.79	6.91
Cohutta Wilderness	GA	34.93	-84.57	21.39	7.60	3.76	11.44
Crater Lake NP	OR	42.92	-122.13	16.74	5.15	2.59	7.71
Craters of the Moon NM	ID	43.39	-113.54	15.80	4.57	2.01	7.13
Cucamonga Wilderness	CA	34.24	-117.59	15.85	4.61	2.05	7.17
Denali Preserve NP	AK	63.31	-151.19	16.27	4.86	2.30	7.42
Desolation Wilderness	CA	38.9	-120.17	15.80	4.57	2.01	7.13
Diamond Peak Wilderness	OR	43.53	-122.1	16.84	5.21	2.65	7.77
Dolly Sods Wilderness	WV	39	-79.37	21.13	7.48	3.64	11.32
Dome Land Wilderness	CA	35.84	-118.23	15.70	4.51	1.95	7.07
Eagle Cap Wilderness	OR	45.22	-117.37	16.12	4.78	2.22	7.34

Appendix B

Default Natural b_{ext}, *dv*, and 10th and 90th Percentile *dv* Values at All Mandatory Federal Class I Areas

Mandatory Federal Class I Area	State	Lat.	Lon.	bext (Mm-1)	Ann. Avg. (dv)	Best Days (dv) (a)	Worst Days (dv) (b)
Acadia NP	ME	44.35	-68.24	21.40	7.61	3.77	11.45
Agua Tibia Wilderness	CA	33.42	-116.99	15.86	4.61	2.05	7.17
Alpine Lake Wilderness	WA	47.55	-121.16	16.99	5.30	2.74	7.86
Anaconda-Pintler Wilderness	MT	45.95	-113.5	16.03	4.72	2.16	7.28
Arches NP	UT	38.73	-109.58	15.58	4.43	1.87	6.99
Badlands NP	SD	43.81	-102.36	16.06	4.74	2.18	7.30
Bandelier NM	NM	35.79	-106.34	15.62	4.46	1.90	7.02
Bering Sea	AK	60.46	-172.75				
Big Bend NP	TX	29.33	-103.31	15.48	4.37	1.81	6.93
Black Canyon of the Gunnison NM	CO	38.57	-107.75	15.68	4.50	1.94	7.06
Bob Marshall Wilderness	MT	47.68	-113.23	16.17	4.80	2.24	7.36
Bosque del Apache	NM	33.79	-106.85	15.54	4.41	1.85	6.97
Boundary Waters Canoe Area	MN	48.06	-91.43	20.89	7.37	3.53	11.21
Breton	LA	29.87	-88.82	21.57	7.69	3.85	11.53
Bridger Wilderness	WY	42.99	-109.49	15.71	4.52	1.96	7.08
Brigantine	NJ	39.49	-74.39	21.05	7.44	3.60	11.28
Bryce Canyon NP	UT	37.57	-112.17	15.58	4.43	1.87	6.98
Cabinet Mountains Wilderness	MT	48.18	-115.68	16.27	4.87	2.31	7.43
Caney Creek Wilderness	AR	34.41	-94.08	21.14	7.49	3.65	11.33
Canyonlands NP	UT	38.23	-109.91	15.60	4.45	1.89	7.01
Cape Romain	SC	32.99	-79.49	21.22	7.52	3.68	11.36
Capitol Reef NP	UT	38.05	-111.15	15.63	4.47	1.91	7.03
Caribou Wilderness	CA	40.49	-121.21	16.05	4.73	2.17	7.29
Carlsbad Caverns NP	NM	32.12	-104.59	15.61	4.46	1.90	7.02
Chassahowitzka	FL	28.69	-82.66	21.46	7.63	3.79	11.47
Chiricahua NM	AZ	32.01	-109.34	15.47	4.36	1.80	6.92
Chiricahua Wilderness	AZ	31.86	-109.28	15.45	4.35	1.79	6.91
Cohutta Wilderness	GA	34.93	-84.57	21.39	7.60	3.76	11.44
Crater Lake NP	OR	42.92	-122.13	16.74	5.15	2.59	7.71
Craters of the Moon NM	ID	43.39	-113.54	15.80	4.57	2.01	7.13
Cucamonga Wilderness	CA	34.24	-117.59	15.85	4.61	2.05	7.17
Denali Preserve NP	AK	63.31	-151.19	16.27	4.86	2.30	7.42
Desolation Wilderness	CA	38.9	-120.17	15.80	4.57	2.01	7.13
Diamond Peak Wilderness	OR	43.53	-122.1	16.84	5.21	2.65	7.77
Dolly Sods Wilderness	WV	39	-79.37	21.13	7.48	3.64	11.32
Dome Land Wilderness	CA	35.84	-118.23	15.70	4.51	1.95	7.07
Eagle Cap Wilderness	OR	45.22	-117.37	16.12	4.78	2.22	7.34

Appendix B
Default Natural b_{ext}, dv, and 10th and 90th Percentile dv Values at All Mandatory Federal Class I Areas

Mandatory Federal Class I Area	State	Lat.	Lon.	bext (Mm-1)	Ann. Avg. (dv)	Best Days (dv) (a)	Worst Days (dv) (a)
Eagles Nest Wilderness	CO	39.67	-106.29	15.72	4.52	1.96	7.08
Emigrant Wilderness	CA	38.18	-119.77	15.81	4.58	2.02	7.14
Everglades NP	FL	25.35	-80.98	20.77	7.31	3.47	11.15
Fitzpatrick Wilderness	WY	43.24	-109.6	15.73	4.53	1.97	7.09
Flat Tops Wilderness	CO	39.95	-107.3	15.70	4.51	1.95	7.07
Galiuro Wilderness	AZ	32.6	-110.39	15.40	4.32	1.76	6.88
Gates of the Mountains Wilderness	MT	46.86	-111.82	15.93	4.66	2.10	7.22
Gearhart Mountain Wilderness	OR	42.51	-120.86	16.33	4.90	2.34	7.46
Gila Wilderness	NM	33.21	-108.47	15.51	4.39	1.83	6.95
Glacier NP	MT	48.64	-113.84	16.48	5.00	2.44	7.56
Glacier Peak Wilderness	WA	48.21	-121	16.88	5.24	2.66	7.80
Goat Rocks Wilderness	WA	46.52	-121.47	16.93	5.26	2.70	7.82
Grand Canyon NP	AZ	36.3	-112.79	15.51	4.39	1.83	6.95
Grand Teton NP	WY	43.82	-110.71	15.74	4.53	1.97	7.09
Great Gulf Wilderness	NH	44.3	-71.28	21.10	7.47	3.63	11.31
Great Sand Dunes NM	CO	37.77	-105.57	15.74	4.54	1.98	7.10
Great Smoky Mountains NP	TN	35.6	-83.52	21.39	7.60	3.76	11.44
Guadalupe Mountains NP	TX	31.91	-104.85	15.64	4.47	1.91	7.03
Haleakala NP	HI	20.71	-156.16	16.02	4.71	2.15	7.27
Hawaii Volcanoes NP	HI	19.41	-155.34	16.33	4.91	2.35	7.47
Hells Canyon Wilderness	OR	45.54	-116.59	16.09	4.76	2.20	7.32
Hercules-Glades Wilderness	MO	36.68	-92.9	21.03	7.43	3.59	11.27
Hoover Wilderness	CA	38.11	-119.37	15.78	4.56	2.00	7.12
Isle Royale NP	MI	48.01	-88.83	20.91	7.38	3.54	11.22
James River Face Wilderness	VA	37.59	-79.44	20.96	7.40	3.56	11.24
Jarbidge Wilderness	NV	41.77	-115.35	15.75	4.54	1.98	7.10
John Muir Wilderness	CA	36.97	-118.88	15.80	4.58	2.02	7.14
Joshua Tree NM	CA	33.92	-115.88	15.72	4.52	1.96	7.08
Joyce-Kilmer-Slickrock Wilderness	TN	35.44	-83.99	21.40	7.61	3.77	11.45
Kaiser Wilderness	CA	37.28	-119.17	15.80	4.57	2.01	7.13
Kalmiopsis Wilderness	OR	42.26	-123.92	16.74	5.15	2.59	7.71
Kings Canyon NP	CA	36.92	-118.61	15.79	4.57	2.01	7.13
La Garita Wilderness	CO	37.95	-106.83	15.69	4.50	1.94	7.06
Lassen Volcanic NP	CA	40.49	-121.41	16.08	4.75	2.19	7.31
Lava Beds NM	CA	41.76	-121.52	16.37	4.93	2.37	7.49
Linville Gorge Wilderness	NC	35.88	-81.9	21.36	7.59	3.75	11.43
Lostwood	ND	48.59	-102.46	16.11	4.77	2.21	7.33

Appendix B
Default Natural b_{ext} *dv*, and 10th and 90th Percentile *dv* Values at All Mandatory Federal Class I Areas

Mandatory Federal Class I Area	State	Lat.	Lon.	bext (Mm-1)	Ann. Avg. (dv)	Best Days (dv) [a]	Worst Days (dv) [a]
Lye Brook Wilderness	VT	43.13	-73.02	20.99	7.41	3.57	11.25
Mammoth Cave NP	KY	37.2	-86.15	21.58	7.69	3.85	11.53
Marble Mountain Wilderness	CA	41.51	-123.21	16.85	5.10	2.54	7.66
Maroon Bells-Snowmass Wilderness	CO	39.1	-107.02	15.70	4.51	1.95	7.07
Mazatzal Wilderness	AZ	34.13	-111.56	15.44	4.35	1.79	6.91
Medicine Lake	MT	48.49	-104.35	16.07	4.74	2.18	7.30
Mesa Verde NP	CO	37.25	-108.45	15.73	4.53	1.97	7.09
Minarets Wilderness	CA	37.74	-119.19	15.78	4.56	2.00	7.12
Mingo	MO	37	-90.19	21.03	7.43	3.59	11.27
Mission Mountains Wilderness	MT	47.48	-113.87	16.21	4.83	2.27	7.39
Mokelumne Wilderness	CA	38.57	-120.06	15.80	4.58	2.02	7.14
Moosehorn	ME	45.09	-67.29	21.22	7.52	3.68	11.36
Mount Adams Wilderness	WA	46.2	-121.49	16.88	5.22	2.68	7.78
Mount Baldy Wilderness	AZ	33.95	-109.54	15.51	4.39	1.83	6.95
Mount Hood Wilderness	OR	45.37	-121.73	16.83	5.21	2.65	7.77
Mount Jefferson Wilderness	OR	44.61	-121.84	16.91	5.25	2.69	7.81
Mount Rainier NP	WA	46.86	-121.72	17.05	5.34	2.78	7.90
Mount Washington Wilderness	OR	44.3	-121.88	17.03	5.33	2.77	7.89
Mount Zirkel Wilderness	CO	40.75	-106.68	15.71	4.52	1.96	7.08
Mountain Lakes Wilderness	OR	42.33	-122.11	16.50	5.01	2.45	7.57
North Absaroka Wilderness	WY	44.74	-109.8	15.74	4.53	1.97	7.09
North Cascades NP	WA	48.83	-121.35	16.86	5.22	2.66	7.78
Okefenokee	GA	30.82	-82.33	21.41	7.61	3.77	11.45
Olympic NP	WA	47.77	-123.74	17.02	5.32	2.76	7.88
Otter Creek Wilderness	WV	38.99	-79.65	21.14	7.49	3.65	11.33
Pasayten Wilderness	WA	48.89	-120.44	16.84	5.21	2.65	7.77
Pecos Wilderness	NM	35.9	-105.62	15.65	4.48	1.92	7.04
Petrified Forest NP	AZ	34.99	-109.79	15.54	4.41	1.85	6.97
Pine Mountain Wilderness	AZ	34.31	-111.8	15.47	4.36	1.80	6.92
Pinnacles NM	CA	36.48	-121.19	16.12	4.78	2.22	7.34
Point Reyes NS	CA	38.06	-122.9	16.20	4.83	2.27	7.39
Presidential Range-Dry River Wilderness	NH	44.2	-71.34	21.15	7.49	3.65	11.33
Rainbow Lake Wilderness	WI	46.42	-91.31	20.99	7.42	3.58	11.26
Rawah Wilderness	CO	40.69	-105.95	15.72	4.52	1.96	7.08
Red Rock Lakes	MT	44.64	-111.78	15.81	4.58	2.02	7.14
Redwood NP	CA	41.44	-124.03	16.90	5.25	2.69	7.81
Rocky Mountain NP	CO	40.35	-105.7	15.67	4.49	1.93	7.05

Appendix B
Default Natural b_{ext}, dv, and 10th and 90th Percentile dv Values at All Mandatory Federal Class I Areas

Mandatory Federal Class I Area	State	Lat.	Lon.	bext (Mm-1)	Ann. Avg. (dv)	Best Days (dv) [a]	Worst Days (dv) [a]
Roosevelt Campobello International Park	ME	44.85	-66.94	21.22	7.52	3.68	11.36
Saguaro NM	AZ	32.17	-110.61	15.35	4.28	1.72	6.84
Salt Creek	NM	33.6	-104.41	15.58	4.43	1.67	6.99
San Gabriel Wilderness	CA	34.27	-117.94	15.86	4.61	2.05	7.17
San Gorgonio Wilderness	CA	34.12	-116.84	15.74	4.54	1.98	7.10
San Jacinto Wilderness	CA	33.75	-116.64	15.78	4.56	2.00	7.12
San Pedro Parks Wilderness	NM	36.11	-106.81	15.63	4.47	1.91	7.03
San Rafael Wilderness	CA	34.76	-119.81	16.03	4.72	2.16	7.28
Sawtooth Wilderness	ID	43.99	-115.06	15.82	4.59	2.03	7.15
Scapegoat Wilderness	MT	47.16	-112.74	16.05	4.73	2.17	7.29
Selway-Bitterroot Wilderness	ID	46.12	-114.86	16.09	4.76	2.20	7.32
Seney	MI	46.25	-86.09	21.23	7.53	3.69	11.37
Sequoia NP	CA	36.51	-118.56	15.79	4.57	2.01	7.13
Shenandoah NP	VA	38.47	-78.49	20.98	7.41	3.57	11.25
Shining Rock Wilderness	NC	35.38	-82.85	21.40	7.61	3.77	11.45
Sierra Ancha Wilderness	AZ	33.85	-110.9	15.46	4.36	1.80	6.92
Simeonof	AK	54.91	-159.28	17.21	5.43	2.87	7.99
Sipsey Wilderness	AL	34.32	-87.44	21.28	7.55	3.71	11.39
South Warner Wilderness	CA	41.31	-120.2	16.09	4.76	2.20	7.32
St. Marks	FL	30.11	-84.15	21.54	7.67	3.83	11.51
Strawberry Mountain Wilderness	OR	44.29	-118.74	16.37	4.93	2.37	7.49
Superstition Wilderness	AZ	33.5	-111.27	15.40	4.32	1.76	6.88
Swanquarter	NC	35.39	-76.39	20.91	7.38	3.54	11.22
Sycamore Canyon Wilderness	AZ	35.01	-112.09	15.53	4.40	1.84	6.96
Teton Wilderness	WY	44.04	-110.17	15.74	4.53	1.97	7.09
Theodore Roosevelt NP	ND	46.96	-103.46	16.08	4.75	2.19	7.31
Thousand Lakes Wilderness	CA	40.7	-121.58	16.10	4.76	2.20	7.32
Three Sisters Wilderness	OR	44.04	-121.91	17.01	5.31	2.75	7.87
Tuxedni	AK	60.14	-152.61	16.58	5.06	2.50	7.62
UL Bend	MT	47.54	-107.89	15.87	4.62	2.06	7.18
Upper Buffalo Wilderness	AR	36.17	-92.41	21.04	7.44	3.60	11.28
Ventana Wilderness	CA	36.21	-121.6	16.09	4.76	2.20	7.32
Virgin Islands NP (b)	VI	18.35	-64.74				
Voyageurs NP	MN	48.47	-92.8	20.64	7.25	3.41	11.09
Washakie Wilderness	WY	44.1	-109.57	15.73	4.53	1.97	7.09
Weminuche Wilderness	CO	37.61	-107.25	15.68	4.50	1.94	7.06
West Elk Wilderness	CO	38.75	-107.21	15.71	4.51	1.95	7.07

Appendix B
Default Natural b_{ext}, dv, and 10th and 90th Percentile dv Values at All Mandatory Federal Class I Areas

Mandatory Federal Class I Area	State	Lat.	Lon.	bext (Mm-1)	Ann. Avg. (dv)	Best Days (dv) [a]	Worst Days (dv) [a]
Wheeler Peak Wilderness	NM	36.57	-105.4	15.70	4.51	1.95	7.07
White Mountain Wilderness	NM	33.48	-105.85	15.56	4.42	1.86	6.98
Wichita Mountains	OK	34.75	-98.65	20.60	7.23	3.39	11.07
Wind Cave NP	SD	43.58	-103.47	15.97	4.88	2.12	7.24
Wolf Island	GA	31.33	-81.3	21.33	7.58	3.74	11.42
Yellowstone NP	WY	44.63	-110.51	15.77	4.56	2.00	7.12
Yolla Bolly Middle Eel Wilderness	CA	40.09	-122.96	16.25	4.85	2.29	7.41
Yosemite NP	CA	37.85	-119.54	15.81	4.56	2.02	7.14
Zion NP	UT	37.32	-113.04	15.56	4.42	1.86	6.98

(a) Values for the best and worst days are estimated from a statistical approach described in Section 2.6 of this document.
(b) *f(RH)* values for Virgin Islands National Park were not calculated because of the limited RH data available. As such no estimates for Natural Visibility Conditions are presented at this time.

Appendix B – Monthly f(RH) Values

Table A-3 Monthly Site-Specific f(RH) Values for Each Mandatory Federal Class I Area, Based on the Centroid of the Area (Supplemental Information)

Class I Area	Site Name	Map ID	Code	Site St	LAT	LONG	Jan f(RH)	Feb f(RH)	Mar f(RH)	Apr f(RH)	May f(RH)	Jun f(RH)	Jul f(RH)	Aug f(RH)	Sep f(RH)	Oct f(RH)	Nov f(RH)	Dec f(RH)
Acadia	Acadia	1	ACAD1	ME	44.37	68.26	3.3	2.9	2.8	3.4	3.1	3.0	3.4	3.6	4.0	3.8	3.6	3.5
Agua Tibia	Agua Tibia	100	AGTI1	CA	33.41	116.58	2.4	2.4	2.4	2.2	2.2	2.2	2.3	2.3	2.3	2.3	2.1	2.2
Alpine Lakes	Snoqualmie Pass	80	SNPA1	WA	47.42	121.42	4.9	3.8	3.5	3.9	2.9	3.2	2.9	3.1	3.3	3.9	4.5	4.5
Anaconda - Pintler	Sula	71	SULA1	MT	45.98	113.42	3.3	2.9	2.6	2.4	2.4	2.3	2.0	1.9	2.1	2.5	3.2	3.3
Ansel Adams	Kaiser	110	KAIS1	CA	37.65	119.20	3.0	2.7	2.4	2.1	1.9	1.7	1.6	1.6	1.6	1.8	2.3	2.7
Arches	Canyonlands	50	CANY1	UT	38.64	109.58	2.6	2.3	1.8	1.6	1.6	1.3	1.4	1.5	1.5	1.8	2.0	2.3
Badlands	Badlands	59	BADL1	SD	43.74	101.94	2.8	2.7	2.6	2.4	2.8	2.7	2.5	2.4	2.2	2.3	2.7	2.7
Bandelier	Bandelier	33	BAND1	NM	35.70	106.27	2.2	2.1	1.8	1.5	1.6	1.4	1.7	2.1	1.9	1.7	2.0	2.2
Bering Sea (n)					60.45	172.70												
Big Bend	Big Bend	31	BIBE1	TX	29.31	103.18	2.0	1.9	1.6	1.5	1.6	1.6	1.7	2.0	2.1	1.9	1.9	1.9
Black Canyon of the Gunnison	Weminuche	55	WEMI1	CO	38.58	107.70	2.4	2.2	1.9	1.9	1.5	1.8	1.7	1.9	2.0	1.8	2.1	2.3
Bob Marshall	Monture	73	MONT1	MT	47.75	113.30	3.6	3.1	2.9	2.6	2.7	2.7	2.3	2.2	2.6	2.9	3.5	3.5
Bosque del Apache	Bosque del Apache	38	BOAP1	NM	33.78	106.83	2.1	1.9	1.6	1.4	1.4	1.3	1.8	2.0	1.9	1.6	1.8	2.2
Boundary Waters Canoe Area	Boundary Waters	23	BOWA1	MN	47.95	91.50	3.0	2.8	2.7	2.4	2.3	2.9	3.1	3.4	3.5	2.8	3.2	3.2
Breton	Breton	20	BRET1	LA	29.73	88.88	3.7	3.5	3.7	3.6	3.8	4.0	4.3	4.3	4.2	3.7	3.7	3.7
Bridger	Bridger	65	BRID1	WY	42.98	109.76	2.5	2.4	2.3	2.2	2.1	1.8	1.5	1.5	1.7	2.0	2.4	2.4
Brigantine	Brigantine	3	BRIG1	NJ	39.46	74.45	2.8	2.6	2.7	2.6	3.0	3.2	3.4	3.7	3.8	3.3	2.9	2.8
Bryce Canyon	Bryce Canyon	49	BRCA1	UT	37.62	112.17	2.6	2.4	1.9	1.6	1.5	1.3	1.3	1.5	1.5	1.6	2.0	2.4
Cabinet Mountains	Cabinet Mountains	75	CABI1	MT	48.21	115.71	3.8	3.3	2.9	2.5	2.7	2.7	2.3	2.2	2.6	3.0	3.7	3.9
Caney Creek	Caney Creek	28	CACR1	AR	34.41	94.00	3.4	3.1	2.9	3.0	3.6	3.6	3.4	3.4	3.6	3.5	3.4	3.5
Canyonlands	Canyonlands	60	CANY1	UT	38.46	109.82	2.6	2.3	1.7	1.6	1.5	1.2	1.3	1.5	1.6	1.8	2.0	2.3
Cape Romain	Cape Romain	15	ROMA1	SC	32.94	79.66	3.3	3.6	2.9	3.0	3.7	3.7	3.6	4.3	4.0	3.7	3.4	3.2
Capitol Reef	Capitol Reef	62	CAPI1	UT	38.36	111.05	2.7	2.4	2.0	1.7	1.6	1.4	1.4	1.6	1.6	1.7	2.3	2.5
Caribou	Lassen Volcanic	90	LAVO1	CA	40.50	121.10	3.7	3.1	2.8	2.5	2.4	2.2	2.1	2.1	2.2	2.4	3.0	3.4
Carlsbad Caverns	Guadalupe Mountains	32	GUMO1	TX	32.14	104.48	2.1	2.0	1.6	1.5	1.6	1.5	1.8	2.1	2.2	1.8	1.9	2.1
Chassahowitzka	Chassahowitzka	16	CHAS1	FL	28.75	82.55	3.8	3.5	3.4	3.2	3.3	3.9	3.9	4.2	4.1	3.9	3.7	3.9
Chiricahua NM	Chiricahua	39	CHIR1	AZ	32.01	109.39	2.0	2.0	1.6	1.3	1.3	1.1	1.6	2.1	1.8	1.5	1.6	2.2
Chiricahua W	Chiricahua	39	CHIR1	AZ	31.84	109.27	2.0	1.9	1.8	1.2	1.3	1.1	1.8	2.1	1.8	1.5	1.6	2.2
Cohutta	Cohutta	12	COHU1	GA	34.92	84.56	3.3	3.1	3.0	2.8	3.4	3.8	4.0	4.2	4.2	3.8	3.4	3.5
Crater Lake	Crater Lake	86	CRLA1	OR	42.90	122.13	4.8	3.9	3.7	3.4	3.7	3.0	2.8	2.8	3.1	3.6	4.6	4.6
Craters of the Moon	Craters of the Moon	69	CRMO1	ID	43.47	113.55	3.1	2.7	2.3	2.0	2.0	1.8	1.4	1.4	1.6	2.0	2.8	3.0
Cucamonga	San Gabriel	93	SAGA1	CA	34.25	117.57	2.5	2.4	2.4	2.2	2.1	2.1	2.1	2.2	2.2	2.2	2.1	2.2
Denali	Denali	102	DENA1	AK	63.72	148.97	2.6	2.3	2.1	1.9	1.9	2.2	2.6	3.0	2.8	2.8	3.0	3.1
Desolation	Bliss	95	BLIS1	CA	38.98	120.12	3.2	2.8	2.4	2.0	1.9	1.6	1.5	1.6	1.7	1.9	2.4	3.0
Diamond Peak	Crater Lake	86	CRLA1	OR	43.53	122.10	4.5	4.0	3.6	3.7	3.2	3.1	2.9	2.9	3.1	3.7	4.6	4.6
Dolly Sods	Dolly Sods	8	DOSO1	WV	39.11	79.43	3.0	2.8	2.8	2.6	3.1	3.4	3.5	3.9	3.9	3.3	3.0	3.1

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Class I Area	Site Name	Map ID	Code	Site St	LAT	LONG	Jan f(RH)	Feb f(RH)	Mar f(RH)	Apr f(RH)	May f(RH)	Jun f(RH)	Jul f(RH)	Aug f(RH)	Sep f(RH)	Oct f(RH)	Nov f(RH)	Dec f(RH)
Dome Land	Dome Land	109	DOME1	CA	35.70	118.19	2.5	2.3	2.2	1.9	1.8	1.8	1.8	1.8	1.6	1.9	2.0	2.2
Eagle Cap	Starkey	76	STAR1	OR	45.10	117.29	3.0	3.2	2.6	2.1	2.0	1.9	1.6	1.6	1.6	2.3	3.4	4.0
Eagles Nest	White River	56	WHRI1	CO	39.59	106.25	2.2	2.2	2.0	2.0	2.1	1.9	1.8	2.0	2.0	1.8	2.1	2.1
Emigrant	Yosemite	95	YOSE1	CA	38.20	119.75	3.2	2.8	2.5	2.1	1.9	1.7	1.5	1.6	1.6	1.9	2.4	2.9
Everglades	Everglades	19	EVER1	FL	25.39	80.60	2.7	2.6	2.6	2.4	2.4	2.7	2.6	2.9	3.0	2.8	2.6	2.7
Fitzpatrick	Bridger	65	BRID1	WY	43.27	109.57	2.5	2.3	2.2	2.1	2.1	1.8	1.5	1.5	1.7	2.0	2.4	2.4
Flat Tops	White River	56	WHRI1	CO	39.97	107.25	2.3	2.2	2.0	2.0	2.0	1.8	1.7	1.9	1.9	1.9	2.2	2.2
Galiuro	Chiricahua	39	CHIR1	AZ	32.56	110.32	2.0	1.8	1.5	1.2	1.2	1.1	1.5	1.8	1.8	1.5	1.8	2.1
Gates of the Mountains	Gates of the Mountains	74	GAMO1	MT	46.07	111.01	2.9	2.6	2.4	2.3	2.3	2.0	2.0	1.9	2.1	2.4	2.8	2.8
Gearhart Mountain	Crater Lake	85	CRLA1	OR	42.48	120.85	4.0	3.4	3.1	2.8	2.7	2.5	2.3	2.3	2.4	2.8	3.7	3.8
Gila	Gila Cliffs	42	GICL1	NM	33.22	108.25	2.1	1.9	1.6	1.3	1.4	1.2	2.1	2.0	1.8	1.6	1.8	2.2
Glacier	Glacier	72	GLAC1	MT	48.51	114.00	4.0	3.5	3.2	3.1	3.2	3.4	2.8	2.6	3.2	3.5	3.8	3.9
Glacier Peak	North Cascades	81	NOCA1	WA	48.21	121.04	4.2	3.7	3.4	3.8	2.9	3.2	2.9	3.1	3.3	3.9	4.4	4.4
Goat Rocks	White Pass	79	WHPA1	WA	46.54	121.48	4.3	3.8	3.4	4.2	2.8	3.4	3.0	3.2	3.1	3.8	4.4	4.5
Grand Canyon	Grand Canyon, Hance	48	GRCA2	AZ	35.97	111.98	2.4	2.3	1.9	1.5	1.4	1.2	1.4	1.7	1.6	1.6	1.9	2.3
Grand Teton	Yellowstone	66	YELL2	WY	43.89	110.73	2.6	2.4	2.2	2.1	2.1	1.8	1.5	1.5	1.7	2.0	2.4	2.6
Great Gulf	Great Gulf	4	GRGU1	NH	44.31	71.22	2.8	2.8	2.6	2.8	2.9	3.2	3.6	3.8	4.0	3.4	3.1	2.9
Great Sand Dunes	Great Sand Dunes	53	GRSA1	CO	37.73	105.52	2.4	2.3	2.0	1.9	1.9	1.8	1.9	2.3	2.2	1.9	2.4	2.4
Great Smoky Mountains	Great Smoky Mountains	10	GRSM1	TN	35.63	83.64	3.3	3.0	2.9	2.7	3.2	3.8	3.8	4.0	4.2	3.8	3.3	3.4
Guadalupe Mountains	Guadalupe Mountains	32	GUMO1	TX	31.83	104.80	2.0	2.0	1.6	1.5	1.6	1.6	1.9	2.2	2.2	1.8	1.9	2.2
Haleakala	Haleakala	100	HALE1	HI	20.81	156.20	2.7	2.8	2.6	2.5	2.4	2.3	2.6	2.4	2.4	2.6	2.8	2.7
Hawaii Volcanoes	Hawaii Volcanoes	107	HAVO1	HI	19.43	155.27	3.2	2.9	3.0	3.0	3.0	2.9	3.1	3.2	3.2	3.2	3.7	3.2
Hells Canyon	Hells Canyon	77	HECA1	OR	45.34	116.57	3.7	3.1	2.5	2.2	2.1	2.0	1.6	1.6	1.8	2.4	3.5	3.9
Hercules - Glade	Hercules - Glade	28	HEGL1	MO	36.69	92.90	3.2	2.9	2.7	2.7	3.3	3.3	3.3	3.3	3.4	3.1	3.1	3.3
Hoover	Hoover	97	HOOV1	CA	38.14	119.45	3.1	2.8	2.5	2.1	1.8	1.6	1.5	1.5	1.6	1.8	2.3	2.8
Isle Royale	Isle Royale	25	ISLE1	MI	47.99	88.93	3.1	2.5	2.7	2.4	2.2	2.6	3.0	3.2	3.8	2.7	3.3	3.3
James River Face	James River Face	7	JARI1	VA	37.62	79.48	2.8	2.8	2.7	2.4	3.0	3.3	3.4	3.7	3.6	3.2	2.8	3.0
Jarbidge	Jarbidge	68	JARB1	NV	41.89	115.43	3.0	2.6	2.1	2.1	2.2	2.2	1.5	1.4	1.4	1.6	2.4	2.8
John Muir	Kaiser	110	KAIS1	CA	37.39	118.64	2.9	2.6	2.4	2.1	1.9	1.7	1.7	1.7	1.7	1.9	2.2	2.6
Joshua Tree	Joshua Tree	101	JOSH1	CA	34.03	116.18	2.4	2.3	2.2	2.0	2.0	1.9	2.0	2.0	2.0	2.0	1.9	2.0
Joyce Kilmer - Slickrock	Great Smoky Mountains	10	GRSM1	TN	35.43	84.00	3.3	3.1	2.9	2.7	3.3	3.8	4.0	4.2	4.2	3.8	3.3	3.5
Kaiser	Kaiser	110	KAIS1	CA	37.28	119.18	3.0	2.7	2.6	2.1	1.9	1.7	1.6	1.7	1.7	1.9	2.3	2.7
Kalmiopsis	Kalmiopsis	80	KALM1	OR	42.27	123.93	4.5	3.9	3.8	3.6	3.5	3.3	3.2	3.2	3.3	3.6	4.4	4.3
Kings Canyon	Sequoia	98	SEQU1	CA	36.82	118.76	2.8	2.6	2.4	2.1	1.9	1.8	1.7	1.7	1.8	1.9	2.3	2.5
La Garita	Weminuche	55	WEMI1	CO	37.86	106.01	2.3	2.2	1.9	1.8	1.8	1.6	1.7	2.1	2.0	1.8	2.2	2.3
Lassen Volcanic	Lassen Volcanic	90	LAVO1	CA	40.54	121.57	3.8	3.2	2.9	2.5	2.4	2.2	2.1	2.1	2.2	2.4	3.1	3.5

Table A-3 Monthly Site-Specific f(RH) Values for Each Mandatory Federal Class I Area, Based on the Centroid of the Area (Supplemental Information)

Class I Area	Site Name	Map ID	Code	Site St	LAT	LONG	Jan f(RH)	Feb f(RH)	Mar f(RH)	Apr f(RH)	May f(RH)	Jun f(RH)	Jul f(RH)	Aug f(RH)	Sep f(RH)	Oct f(RH)	Nov f(RH)	Dec f(RH)
Lava Beds	Lava Beds	67	LABE1	CA	41.71	121.34	4.0	3.4	3.1	2.7	2.6	2.4	2.3	2.3	2.4	2.7	3.5	3.8
Linville Gorge	Linville Gorge	13	LIGO1	NC	35.89	81.89	3.3	3.0	3.0	2.7	3.3	3.9	4.1	4.5	4.4	3.7	3.2	3.4
Lostwood	Lostwood	62	LOST1	ND	48.60	102.48	3.0	2.9	2.9	2.5	2.3	2.6	2.7	2.4	2.3	2.4	3.2	3.2
Lye Brook	Lye Brook	3	LYBR1	VT	43.15	73.12	2.7	2.6	2.6	2.6	2.5	3.0	3.3	3.6	3.7	3.3	2.9	2.8
Mammoth Cave	Mammoth Cave	9	MACA1	KY	37.22	86.07	3.4	3.1	2.9	2.6	3.2	3.5	3.7	3.9	3.9	3.4	3.2	3.5
Marble Mountain	Trinity	104	TRIN1	CA	41.52	123.21	4.4	3.8	3.7	3.3	3.4	3.2	3.2	3.2	3.2	3.4	4.1	4.2
Maroon Bells - Snowmass	White River	56	WHRI1	CO	39.16	106.82	2.2	2.1	2.0	2.0	2.1	1.7	1.8	2.2	2.1	1.9	2.1	2.1
Mazatzal	Ike's Backbone	46	IKBA1	AZ	33.92	111.43	2.3	1.9	1.7	1.3	1.3	1.1	1.5	1.7	1.6	1.5	1.7	2.1
Medicine Lake	Medicine Lake	63	MELA1	MT	48.60	104.28	3.0	2.9	2.8	2.3	2.2	2.6	2.5	2.2	2.2	2.4	3.2	3.2
Mesa Verde	Mesa Verde	54	MEVE1	CO	37.20	108.49	2.5	2.3	1.9	1.5	1.5	1.3	1.6	2.0	1.9	1.7	2.1	2.3
Mingo	Mingo	26	MING1	MO	36.98	90.20	3.3	3.0	2.8	2.8	3.0	3.2	3.3	3.5	3.5	3.1	3.1	3.3
Mission Mountains	Monture	73	MONT1	MT	47.40	113.05	3.6	3.1	2.7	2.5	2.6	2.6	2.3	2.2	2.5	2.9	3.5	3.6
Mokelumne	Bliss	86	BLIS1	CA	38.68	120.03	3.2	2.8	2.4	2.0	1.9	1.6	1.5	1.6	1.7	1.9	2.4	2.0
Moosehorn	Moosehorn	2	MOOS1	ME	45.12	67.26	3.0	2.7	2.7	3.0	3.0	3.1	3.4	3.8	3.9	3.5	3.2	3.2
Mount Adams	White Pass	79	WHPA1	WA	46.19	121.50	4.3	3.8	3.4	4.4	2.8	3.5	3.1	3.3	3.1	3.9	4.5	4.5
Mount Baldy	Mount Baldy	43	BALD1	AZ	34.12	109.57	2.2	2.0	1.7	1.4	1.3	1.2	1.8	1.9	1.7	1.6	1.8	2.2
Mount Hood	Mount Hood	65	MOHO1	OR	45.30	121.69	4.3	3.0	3.5	3.9	3.0	3.2	2.9	3.0	3.1	3.9	4.5	4.6
Mount Jefferson	Three Sisters	84	THSI1	OR	44.55	121.63	4.4	3.0	3.6	3.7	3.1	3.1	2.9	2.9	3.0	3.8	4.6	4.6
Mount Rainier	Mount Rainier	78	MORA1	WA	46.76	122.12	4.4	4.0	3.6	4.7	3.1	3.7	3.3	3.5	3.4	4.1	4.7	4.7
Mount Washington	Three Sisters	84	THSI1	OR	44.30	121.07	4.4	3.9	3.6	3.7	3.1	3.1	3.0	2.8	3.0	3.8	4.6	4.6
Mount Zirkel	Mount Zirkel	50	MOZI1	CO	40.65	106.70	2.2	2.2	2.0	2.1	2.2	1.9	1.7	1.9	2.0	1.9	2.1	2.1
Mountain Lakes	Crater Lake	66	CRLA1	OR	42.34	122.11	4.3	3.6	3.3	3.0	2.6	2.6	2.5	2.5	2.6	3.1	4.1	4.3
North Absaroka	North Absaroka	67	NOAB1	WY	44.77	109.70	2.4	2.3	2.2	2.2	2.1	1.9	1.7	1.6	1.8	2.0	2.4	2.4
North Cascades	North Cascades	81	NOCA1	WA	48.54	121.44	4.1	3.7	3.4	3.7	2.9	3.2	2.9	3.2	3.5	3.9	4.4	4.4
Okefenokee	Okefenokee	16	OKEF1	GA	30.74	82.13	3.5	3.2	3.1	3.0	3.8	3.7	3.7	4.1	4.0	3.8	3.5	3.5
Olympic	Olympic	83	OLYM1	WA	47.32	123.35	4.5	4.1	3.8	4.1	3.2	3.5	3.1	3.5	3.7	4.4	4.8	4.8
Otter Creek	Dolly Sods	6	DOSO1	WV	39.00	78.65	3.0	2.8	2.8	2.8	3.2	3.5	3.7	4.1	4.0	3.3	3.0	3.1
Pasayten	Pasayten	82	PASA1	WA	48.85	120.52	4.2	3.7	3.4	3.7	2.9	3.2	2.9	3.2	3.3	3.9	4.4	4.5
Pecos	Wheeler Peak	35	WHPE1	NM	35.83	105.64	2.3	2.1	1.8	1.7	1.7	1.5	1.9	2.1	2.0	1.7	2.0	2.2
Petrified Forest	Petrified Forest	41	PEFO1	AZ	35.08	109.77	2.4	2.2	1.7	1.4	1.3	1.2	1.5	1.8	1.7	1.6	1.8	2.3
Pine Mountain	Ike's Backbone	46	IKBA1	AZ	34.31	111.80	2.2	2.0	1.7	1.4	1.3	1.1	1.4	1.8	1.6	1.5	1.7	2.1
Pinnacles	Pinnacles	92	PINN1	CA	36.49	121.16	3.2	2.8	2.6	2.4	2.3	2.0	2.0	2.1	2.1	2.3	2.5	2.9
Point Reyes	Point Reyes	91	PORE1	CA	38.12	122.90	3.6	3.3	3.1	2.7	2.6	2.3	2.5	2.6	2.8	2.7	2.9	3.3
Presidential Range - Dry River	Great Gulf	4	GRGU1	NH	44.31	71.35	2.0	2.6	2.6	2.6	3.0	3.4	3.7	4.0	4.3	3.6	3.1	3.0
Rawah	Mount Zirkel	58	MOZI1	CO	40.70	105.94	2.1	2.1	2.0	2.1	2.3	2.0	1.8	2.0	2.0	1.8	2.1	2.0
Red Rock Lakes	Yellowstone	65	YELL2	WY	44.67	111.70	2.7	2.5	2.3	2.1	2.1	1.9	1.7	1.8	1.8	2.1	2.6	2.7

Table A-3 Monthly Site-Specific f(RH) Values for Each Mandatory Federal Class I Area, Based on the Centroid of the Area (Supplemental Information)

Class I Area	Site Name	Map ID	Code	Site St	LAT	LONG	Jan f(RH)	Feb f(RH)	Mar f(RH)	Apr f(RH)	May f(RH)	Jun f(RH)	Jul f(RH)	Aug f(RH)	Sep f(RH)	Oct f(RH)	Nov f(RH)	Dec f(RH)
Redwood	Redwood	88	REDW1	CA	41.56	124.06	4.4	3.9	4.5	3.9	4.6	4.7	4.9	4.7	4.3	3.7	3.8	3.4
Rocky Mountain	Rocky Mountain	57	ROMO1	CO	40.28	105.55	1.7	1.9	1.9	2.1	2.3	2.6	1.8	2.0	1.8	1.8	1.8	1.7
Roosevelt Campobello	Moosehorn	2	MOOS1	ME	44.88	66.95	3.0	2.7	2.7	3.0	3.0	3.1	3.4	3.8	3.9	3.5	3.3	3.2
Saguaro	Saguaro	40	SAGU1	AZ	32.25	110.73	1.8	1.6	1.4	1.1	1.1	1.1	1.4	1.8	1.6	1.4	1.6	2.1
Saint Marks	Saint Marks	17	SAMA1	FL	30.12	84.00	3.7	3.4	3.4	3.4	3.5	4.0	4.1	4.4	4.2	3.8	3.7	3.8
Salt Creek	Salt Creek	35	SACR1	NM	33.61	104.37	2.1	1.9	1.5	1.5	1.7	1.6	1.8	2.0	2.1	1.8	1.8	2.1
San Gabriel	San Gabriel	93	SAGA1	CA	34.27	117.84	2.5	2.5	2.4	2.2	2.2	2.1	2.2	2.2	2.2	2.3	2.1	2.2
San Gorgonio	San Gorgonio	99	SAGO1	CA	34.10	116.90	2.7	2.6	2.8	2.3	2.2	1.9	1.8	1.9	1.9	1.9	1.9	2.2
San Jacinto	San Gorgonio	99	SAGO1	CA	33.75	116.65	2.5	2.4	2.4	2.2	2.1	2.0	2.1	2.1	2.1	2.1	2.0	2.4
San Pedro Parks	San Pedro Parks	34	SAPE1	NM	36.11	106.81	2.3	2.1	1.8	1.6	1.6	1.4	1.7	2.0	1.9	1.7	2.1	2.2
San Rafael	San Rafael	84	RAFA1	CA	34.78	119.83	2.8	2.7	2.7	2.4	2.3	2.3	2.5	2.5	2.4	2.5	2.3	2.5
Sawtooth	Sawtooth	70	SAWT1	ID	44.10	114.93	3.3	2.9	2.3	2.0	2.0	1.8	1.4	1.4	1.5	2.0	2.9	3.3
Scapegoat	Monture	73	MONT1	MT	47.17	112.73	3.2	2.0	2.6	2.4	2.6	2.4	2.1	2.0	2.3	2.6	3.1	3.1
Selway - Bitterroot	Sula	71	SULA1	MT	45.06	114.00	3.6	3.0	2.8	2.3	2.4	2.3	1.9	1.9	2.1	2.6	3.3	3.5
Seney	Seney	22	SENE1	MI	46.25	86.03	3.3	2.8	2.9	2.7	2.6	3.1	3.6	4.0	4.1	3.4	3.6	3.5
Sequoia	Sequoia	98	SEQU1	CA	35.50	118.82	2.5	2.4	2.4	2.2	1.9	1.8	1.7	1.6	1.8	1.9	2.3	2.3
Shenandoah	Shenandoah	6	SHEN1	VA	38.52	78.44	3.1	2.8	2.8	2.5	3.1	3.4	3.6	3.9	3.8	3.2	3.0	3.1
Shining Rock	Shining Rock	11	SHRO1	NC	35.39	82.78	3.3	3.0	2.8	2.7	3.4	3.8	4.1	4.5	4.4	3.8	3.3	3.4
Sierra Ancha	Sierra Ancha	45	SIAN1	AZ	33.82	110.80	2.1	2.0	1.7	1.3	1.3	1.1	1.5	1.8	1.8	1.5	1.7	2.1
Simeonof	Simeonof	105	SIME1	AK	54.92	159.28	4.3	4.1	3.6	3.8	3.9	4.3	5.0	5.2	4.5	3.8	4.0	4.3
Sipsey	Sipsey	21	SIPS1	AL	34.34	87.34	3.4	3.1	2.9	2.8	3.3	3.7	3.9	3.8	3.9	3.6	3.3	3.4
South Warner	Lava Beds	87	LABE1	CA	41.33	120.26	3.6	3.1	2.7	2.4	2.3	2.1	1.8	1.8	2.0	2.3	3.1	3.4
Strawberry Mountain	Starkey	79	STAR1	OR	44.30	118.73	3.9	3.3	2.8	2.9	2.3	2.4	2.0	2.0	1.9	2.6	3.7	4.1
Superstition	Tonto	44	TONT1	AZ	33.63	111.10	2.1	1.9	1.6	1.3	1.3	1.1	1.5	1.7	1.6	1.5	1.7	2.1
Swanquarter	Swanquarter	14	SWAN1	NC	35.31	76.28	2.9	2.7	2.6	2.6	2.9	3.2	3.4	3.5	3.4	3.1	2.8	2.9
Sycamore Canyon	Sycamore Canyon	47	SYCA1	AZ	34.03	116.18	2.4	2.3	2.2	2.0	2.0	1.9	2.0	2.0	2.0	2.0	1.9	2.0
Teton	Yellowstone	66	YELL2	WY	44.08	110.10	2.6	2.4	2.2	2.1	2.1	1.9	1.6	1.5	1.7	2.0	2.4	2.5
Theodore Roosevelt	Theodore Roosevelt	61	THRO1	ND	47.30	104.03	2.9	2.6	2.6	2.3	2.3	2.5	2.4	2.2	2.2	2.3	3.0	3.0
Thousand Lakes	Lassen Volcanic	80	LAVO1	CA	40.70	121.50	3.0	3.2	2.8	2.5	2.4	2.2	2.1	2.1	2.2	2.4	3.1	3.5
Three Sisters	Three Sisters	84	THSI1	OR	44.28	122.01	4.5	4.0	3.8	3.7	3.1	3.1	3.0	2.9	3.0	3.8	4.6	4.6
Tuxedni	Tuxedni	103	TUXE1	AK	60.15	152.60	3.6	3.3	2.9	2.7	2.7	2.9	3.6	4.0	3.9	3.5	3.5	3.7
UL Bend	UL Bend	64	ULBE1	MT	47.56	107.87	2.7	2.5	2.5	2.3	2.2	2.2	2.0	1.8	1.8	2.2	2.7	2.7
Upper Buffalo	Upper Buffalo	27	UPBU1	AR	35.83	93.21	3.3	3.0	2.7	2.8	3.4	3.4	3.4	3.4	3.6	3.3	3.2	3.3
Ventana	Pinnacles	92	PINN1	CA	36.22	121.69	3.2	2.8	2.8	2.5	2.3	2.1	2.2	2.3	2.2	2.4	2.5	2.8
Virgin Islands (b)	Virgin Islands	108	VIIS1	VI	18.35	64.78												
Voyageurs	Voyageurs	24	VOYA2	MN	48.59	93.17	2.8	2.4	2.4	2.3	2.3	3.1	2.7	3.0	3.2	2.6	2.8	2.8

Guidance for Tracking Progress Under the Regional Haze Rule

Table A-3 Monthly Site-Specific f(RH) Values for Each Mandatory Federal Class I Area, Based on the Centroid of the Area (Supplemental Information)

Class I Area	Site Name	Map ID	Code	Site St	LAT	LONG	Jan f(RH)	Feb f(RH)	Mar f(RH)	Apr f(RH)	May f(RH)	Jun f(RH)	Jul f(RH)	Aug f(RH)	Sep f(RH)	Oct f(RH)	Nov f(RH)	Dec f(RH)
Washakie	North Absaroka	67	NOAB1	WY	43.95	109.59	2.6	2.3	2.2	2.1	2.1	1.8	1.6	1.5	1.8	2.0	2.4	2.5
Weminuche	Weminuche	66	WEMI1	CO	37.65	107.80	2.4	2.2	1.9	1.7	1.7	1.5	1.6	2.0	1.9	1.7	2.1	2.3
West Elk	White River	56	WHRI1	CO	38.69	107.19	2.3	2.2	1.9	1.8	1.9	1.7	1.8	2.1	2.0	1.8	2.1	2.2
Wheeler Peak	Wheeler Peak	35	WHPE1	NM	36.57	105.42	2.3	2.2	1.9	1.8	1.8	1.6	1.8	2.2	2.1	1.8	2.2	2.3
White Mountain	White Mountain	37	WHIT1	NM	33.49	105.83	2.1	1.9	1.6	1.5	1.5	1.4	1.6	2.0	2.0	1.7	1.9	2.1
Wichita Mountains	Wichita Mountains	30	WIMO1	OK	34.74	98.59	2.7	2.6	2.4	2.4	3.0	2.7	2.3	2.5	2.9	2.6	2.7	2.8
Wind Cave	Wind Cave	60	WICA1	SD	43.55	103.48	2.5	2.6	2.5	2.6	2.7	2.5	2.3	2.3	2.2	2.2	2.6	2.6
Wolf Island	Okefenokee	14	OKEF1	GA	31.31	81.30	3.4	3.1	3.1	3.0	3.3	3.7	3.7	4.1	4.0	3.7	3.5	3.5
Yellowstone	Yellowstone	66	YELL2	WY	44.66	110.40	2.5	2.4	2.3	2.2	2.2	1.9	1.7	1.6	1.9	2.1	2.5	2.6
Yolla Bolly - Middle Eel	Trinity	104	TRIN1	CA	40.11	122.96	4.0	3.4	3.1	2.8	2.7	2.5	2.4	2.5	2.6	2.7	3.3	3.6
Yosemite	Yosemite	86	YOSE1	CA	37.71	119.70	3.3	3.0	2.8	2.3	2.1	1.8	1.5	1.5	1.5	1.8	2.4	2.8
Zion	Zion	51	ZION1	UT	37.25	113.01	2.7	2.4	2.0	1.6	1.5	1.3	1.2	1.4	1.4	1.6	2.0	2.4

a: No particulate matter sampling or visibility monitoring is conducted in the Bering Sea Wilderness.
b: *f(RH)* values for Virgin Islands National Park were not calculated because of the limited RH data available.

Attachment 4

Table 1
Facility Basin Baseline Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning

	2001		2002		2003	
Class I Area	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv
Badlands	0.917	28	1.156	20	0.923	26
Wind Cave	0.951	25	1.546	27	1.117	21

Table 2
Facility Basin BART Control Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning
For Badlands

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	1.199	33	1.360	22	1.049	30	1.203	1.360
NO_x - 4	1.013	29	0.999	20	0.967	24	0.993	1.013
NO_x - 5	0.868	23	0.894	17	0.824	21	0.862	0.894

Table 3
Facility Basin BART Control Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning
For Wind Cave

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	1.155	32	1.715	29	1.373	26	1.414	1.715
NO_x - 4	0.936	24	1.194	23	0.997	19	1.042	1.194
NO_x - 5	0.788	19	1.036	22	0.857	15	0.894	1.036

Table 4
Unit 1 Basin Baseline Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning

	2001		2002		2003	
Class I Area	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv
Badlands	0.417	4	0.470	7	0.422	4
Wind Cave	0.439	4	0.587	9	0.544	8

Table 5
Unit 1 Basin BART Control Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning
For Badlands

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.395	4	0.423	6	0.411	4	0.410	0.395
NO_x - 4	0.321	3	0.314	2	0.316	2	0.317	0.321
NO_x - 5	0.279	3	0.286	1	0.272	2	0.279	0.279

Table 6
Unit 1 Basin BART Control Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning
For Wind Cave

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.394	3	0.531	9	0.493	7	0.473	0.531
NO_x - 4	0.303	3	0.396	6	0.354	4	0.351	0.396
NO_x - 5	0.255	2	0.337	3	0.292	3	0.295	0.337

Table 7
Unit 2 Basin Baseline Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning

	2001		2002		2003	
Class I Area	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv
Badlands	0.414	4	0.463	7	0.421	4
Wind Cave	0.439	4	0.588	9	0.541	8

Table 8
Unit 2 Basin BART Control Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning
For Badlands

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.392	4	0.418	6	0.410	4	0.407	0.418
NO_x - 4	0.318	3	0.313	2	0.316	2	0.316	0.318
NO_x - 5	0.279	3	0.285	1	0.270	2	0.278	0.285

Table 9
Unit 2 Basin BART Control Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning
For Wind Cave

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.394	3	0.531	9	0.491	7	0.472	0.531
NO_x - 4	0.303	3	0.399	6	0.354	4	0.352	0.399
NO_x - 5	0.254	2	0.337	3	0.291	3	0.294	0.337

Table 10
Unit 3 Basin Baseline Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning

	2001		2002		2003	
Class I Area	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv
Badlands	0.431	4	0.474	7	0.428	4
Wind Cave	0.427	4	0.631	10	0.500	8

Table 11
Unit 3 Basin BART Control Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning
For Badlands

	2001		2002		2003		Average Impact	Maximum Impact
	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.405	4	0.429	7	0.406	3	0.413	0.429
NO_x - 4	0.337	3	0.343	2	0.315	2	0.332	0.343
NO_x - 5	0.295	3	0.313	1	0.263	2	0.290	0.313

Table 12
Unit 3 Basin BART Control Visibility Modeling Results
Variable Ammonia Background and Nitrate Repartitioning
For Wind Cave

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.383	3	0.570	9	0.464	7	0.472	0.570
NO_x - 4	0.307	3	0.401	6	0.334	4	0.347	0.401
NO_x - 5	0.257	2	0.355	4	0.304	3	0.305	0.355

Table 13
Visibility Improvement Cost Effectiveness for Each Class 1 Area (Based on Maximum Visibility Modeling Results)
Variable Ammonia Background and Nitrate Repartitioning

Class 1 Area	Maximum Visibility Modeling Results (dv) (98th Percentile, see Note 1)				Visibility Improvements (dv) Calculated from Maximum Visibility Results (for each Class I Area)					Improvement ($/dv) (see Note 4)				
	Baseline	Scenario 1 (OFA)	Scenario 4 (SNCR)	Scenario 5 (SCR)	Baseline to Scenario 1 (OFA)	Baseline to Scenario 4 (SNCR)	Baseline to Scenario 5 (SCR)	Scenario 1 (OFA) to Scenario 4 (SCNR)	Scenario 1 (OFA) to Scenario 5 (SCR)	Baseline to Scenario 1 (OFA)	Baseline to Scenario 4 (SNCR)	Baseline to Scenario 5 (SCR)	Scenario 1 (OFA) to Scenario 4 (SCNR)	Scenario 1 (OFA) to Scenario 5 (SCR)
	Facility													
Badlands	1.16	1.36	1.01	0.89	NI	0.14	0.26	0.35	0.47	NA	154,510,490	160,767,176	61,674,352	97,609,442
Wind Cave	1.55	1.72	1.19	1.04	NI	0.35	0.51	0.52	0.68	NA	62,169,886	92,864,706	42,408,829	66,989,691
	Unit 1													
Badlands	0.47	0.40	0.32	0.28	0.08	0.15	0.19	0.07	0.12	8,333,333	49,429,530	83,654,450	99,527,027	130,706,897
Wind Cave	0.59	0.53	0.40	0.34	0.06	0.19	0.25	0.14	0.19	11,162,714	38,560,209	63,148,000	54,555,556	78,154,639
	Unit 2													
Badlands	0.46	0.42	0.32	0.29	0.05	0.15	0.18	0.10	0.13	13,888,889	50,793,103	88,691,011	73,650,000	114,000,000
Wind Cave	0.59	0.53	0.40	0.34	0.06	0.19	0.25	0.13	0.19	10,964,912	38,968,254	62,896,414	55,795,455	78,154,639
	Unit 3													
Badlands	0.47	0.43	0.34	0.31	0.05	0.13	0.16	0.09	0.12	13,888,889	56,231,374	98,055,901	85,639,535	130,706,897
Wind Cave	0.63	0.57	0.40	0.36	0.06	0.23	0.28	0.17	0.22	10,245,903	32,021,739	57,199,275	43,579,882	70,520,930

Notes:

1. Visibility improvement for each class I area for the period 2001-2003 was calculated by comparing the maximum impact from the baseline and control scenario for any of the three years regardless of which year the impact occurred.
2. NI = No Improvement
3. NA = Not Applicable
4. Total Annualized Costs used in calculating Improvement are as follows (in $1,000):

	Facility	Unit 1	Unit 2	Unit 3
Baseline to Scenario 1 (OFA)	$1,875	$625	$625	$625
Baseline to Scenario 4 (SNCR)	$22,095	$7,365	$7,365	$7,365
Baseline to Scenario 5 (SCR)	$47,361	$15,787	$15,787	$15,787
Scenario 1 (OFA) to Scenario 4 (SCNR)	$22,095	$7,365	$7,365	$7,365
Scenario 1 (OFA) to Scenario 5 (SCR)	$45,486	$15,162	$15,162	$15,162

Attachment 5

Table 1
Baseline Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning

	2001		2002		2003	
Class I Area	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv
Badlands	2.008	49	1.981	34	1.539	37
Wind Cave	1.812	46	2.376	34	1.722	37

Table 2
BART Control Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning
For Badlands

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	1.834	46	1.770	30	1.403	34	1.669	1.834
NO_x - 4	1.263	34	1.134	24	1.042	28	1.146	1.263
NO_x - 5	1.101	27	0.955	21	0.882	25	0.979	1.101

Table 3
BART Control Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning
For Wind Cave

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	1.628	41	2.166	33	1.540	34	1.778	2.166
NO_x - 4	1.141	32	1.571	25	1.022	26	1.245	1.571
NO_x - 5	0.947	24	1.199	22	0.896	18	1.014	1.199

Table 4
Unit 1 Basin Baseline Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning

	2001		2002		2003	
Class I Area	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv
Badlands	0.732	17	0.700	17	0.542	17
Wind Cave	0.643	14	0.841	14	0.599	14

Table 5
Unit 1 Basin BART Control Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning
For Badlands

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.662	15	0.619	11	0.496	7	0.643	0.662
NO_x - 4	0.455	5	0.387	4	0.366	3	0.451	0.455
NO_x - 5	0.378	3	0.320	1	0.307	3	0.381	0.384

Table 6
Unit 1 Basin BART Control Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning
For Wind Cave

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.574	12	0.761	16	0.532	9	0.622	0.761
NO_x - 4	0.392	5	0.540	8	0.374	6	0.435	0.540
NO_x - 5	0.322	4	0.402	4	0.303	5	0.342	0.402

Table 7
Unit 2 Basin Baseline Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning

	2001		2002		2003	
Class I Area	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv
Badlands	0.725	17	0.699	16	0.546	9
Wind Cave	0.642	14	0.842	17	0.594	10

Table 8
Unit 2 Basin BART Control Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning
For Badlands

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98^{th} Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98^{th} Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98^{th} Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.658	15	0.615	11	0.498	7	0.590	0.658
NO_x - 4	0.451	5	0.384	4	0.367	3	0.401	0.451
NO_x - 5	0.384	3	0.319	1	0.310	3	0.338	0.384

Table 9
Unit 2 Basin BART Control Visibility Modeling Results
Constant Ammonia Background and No Nitrate Repartitioning
For Wind Cave

	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98^{th} Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98^{th} Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98^{th} Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.573	12	0.762	16	0.530	9	0.622	0.762
NO_x - 4	0.390	5	0.541	8	0.374	5	0.435	0.541
NO_x - 5	0.320	4	0.399	4	0.302	5	0.340	0.399

Table 10 Unit 3 Basin Baseline Visibility Modeling Results Constant Ammonia Background and No Nitrate Repartitioning						
	2001		2002		2003	
Class I Area	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv
Badlands	0.680	17	0.717	16	0.553	10
Wind Cave	0.639	14	0.886	18	0.630	8

Table 11 Unit 3 Basin BART Control Visibility Modeling Results Constant Ammonia Background and No Nitrate Repartitioning For Badlands								
	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.609	14	0.643	13	0.502	8	0.585	0.643
NO_x - 4	0.446	5	0.406	7	0.366	3	0.406	0.446
NO_x - 5	0.381	4	0.348	2	0.297	3	0.342	0.381

Table 12 Unit 3 Basin BART Control Visibility Modeling Results Constant Ammonia Background and No Nitrate Repartitioning For Wind Cave								
	2001		2002		2003		Average Impact	Maximum Impact
Scenario	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	98th Percentile Value (dv)	No. of Days Exceeding 0.5 dv	(dv)	(dv)
NO_x - 1	0.572	11	0.803	17	0.561	8	0.645	0.803
NO_x - 4	0.403	5	0.575	8	0.369	7	0.449	0.575
NO_x - 5	0.336	4	0.446	4	0.323	4	0.368	0.446

Table 13

Visibility Improvement Cost Effectiveness for Each Class 1 Area (Based on Maximum Visibility Modeling Results)

Constant Ammonia Background and No Nitrate Repartitioning

	Maximum Visibility Modeling Results (dv) (98th Percentile, see Note 1)				Visibility Improvements (dv) Calculated from Maximum Visibility Results (for each Class 1 Area)					Improvement ($/dv) (see Note 4)				
Class I Area	Baseline	Scenario 1 (OFA)	Scenario 4 (SNCR)	Scenario 5 (SCR)	Baseline to Scenario 1 (OFA)	Baseline to Scenario 4 (SNCR)	Baseline to Scenario 5 (SCR)	Scenario 1 (OFA) to Scenario 4 (SCNR)	Scenario 1 (OFA) to Scenario 5 (SCR)	Baseline to Scenario 1 (OFA)	Baseline to Scenario 4 (SNCR)	Baseline to Scenario 5 (SCR)	Scenario 1 (OFA) to Scenario 4 (SCNR)	Scenario 1 (OFA) to Scenario 5 (SCR)
								Facility						
Badlands	2.01	1.83	1.26	1.10	0.17	0.75	0.91	0.57	0.73	10,715,862	29,657,718	52,217,200	38,695,271	62,054,570
Wind Cave	2.38	2.17	1.57	1.20	0.21	0.81	1.18	0.60	0.97	8,928,571	27,447,205	40,238,741	37,134,454	47,038,263
								Unit 1						
Badlands	0.73	0.66	0.46	0.38	0.07	0.28	0.35	0.21	0.28	8,928,571	26,588,448	45,364,943	35,579,710	54,539,568
Wind Cave	0.83	0.76	0.54	0.40	0.08	0.30	0.44	0.22	0.36	7,812,500	24,468,439	35,961,376	33,325,792	42,233,983
								Unit 2						
Badlands	0.73	0.66	0.45	0.38	0.07	0.27	0.34	0.21	0.27	9,328,358	26,879,562	45,396,188	35,579,710	55,335,766
Wind Cave	0.84	0.76	0.54	0.40	0.08	0.30	0.44	0.22	0.36	7,812,500	24,468,439	35,636,569	33,325,792	41,768,595
								Unit 3						
Badlands	0.72	0.64	0.45	0.38	0.07	0.27	0.34	0.20	0.26	8,445,946	27,177,122	46,985,119	37,185,787	57,870,229
Wind Cave	0.89	0.80	0.58	0.45	0.08	0.31	0.44	0.23	0.36	7,530,120	23,681,672	35,879,545	32,102,632	42,470,588

Notes:

1. Visibility Improvement for each class I area for the period 2001-2003 was calculated by comparing the maximum impact from the baseline and control scenario for any of the three years regardless of which year the impact occurred.
2. NI = No Improvement
3. NA = Not Applicable
4. Total Annualized Costs used in calculating Improvement are as follows (in $1,000):

	Facility	Unit 1	Unit 2	Unit 3
Baseline to Scenario 1 (OFA)	$1,875	$625	$625	$625
Baseline to Scenario 4 (SNCR)	$22,095	$7,365	$7,365	$7,365
Baseline to Scenario 5 (SCR)	$47,361	$15,787	$15,787	$15,787
Scenario 1 (OFA) to Scenario 4 (SCNR)	$22,095	$7,365	$7,365	$7,365
Scenario 1 (OFA) to Scenario 5 (SCR)	$45,486	$15,161	$15,162	$15,162