EXECUTIVE SUMMARY

This executive summary presents the Mt. Zirkel Visibility Study (MZVS) objectives, describes the measurement program, presents a conceptual model of visibility impairment, and summarizes major MZVS findings relevant to the objectives.

S.1 MT. ZIRKEL VISIBILITY STUDY (MZVS) OVERVIEW AND TECHNICAL OBJECTIVES

The Mt. Zirkel Wilderness Area (MZWA) in the Routt National Forest of northwestern Colorado is one of 156 Class I areas in the United States in which visibility is protected. Current regulations, promulgated by U.S. EPA in 1980, address visibility impairment in such areas that is "reasonably attributable" to an existing industrial source or a group of sources (these are often called "plume blight" regulations).

In 1993, the U.S. Forest Service (USFS) certified that occasions existed during which visibility was significantly impaired in the MZWA. The Colorado Department of Public Health and Environment's Air Pollution Control Division determined that existing information was insufficient to reasonably attribute observed visibility impairment to specific sources. As a result, the Mt. Zirkel Visibility Study (MZVS) was commissioned to obtain more information. Potential contributors include sources in the Yampa Valley, which is west of the MZWA and contains the Hayden and Craig coal-fired generating stations, and more distant emitters in Colorado, southern Wyoming, western Utah, and outlying areas.

The purpose of the MZVS was to determine, using scientifically sound principles and established methods and procedures: 1) the extent of visibility impairment, if any, within the MZWA; 2) whether the cause of, or contribution to, any visibility impairment within the MZWA may be reasonably attributed to emissions from any source or group of sources; and 3) the relative contribution of emissions from each source or group of sources to visibility impairment. Specific technical objectives of the MZVS were to:

1. Obtain a documented data set of specified precision, accuracy, and validity that supports modeling and data analysis efforts.

2. Document the frequency, intensity, and character of haze in the MZWA, within the Yampa Valley, and outside of the Yampa Valley and relate these to meteorological conditions.

3. Quantify the contributions from scattering by gases, absorption by gases, scattering by particles, and absorption by particles to different levels of light extinction in the MZWA.

4. Quantify contributions from particulate chemical components to light extinction.

5. Describe the behavior of generating station plumes in the Yampa Valley.

6. Estimate contributions to light extinction in the Wilderness from different emissions sources within and outside of the Yampa Valley.

7. Reconcile results from different modeling and data analysis methods and assign confidence levels to source contribution estimates.

Measurements to address these objectives were made during a one-year period, starting in December 1994. Measurements were made in a "core" study area that included source, receptor, and background measurement sites. Additional data were collected from existing data sources throughout a larger area.

The measurement program included an annual monitoring network, intensive studies during the winter, summer, and fall, and selected emissions measurements. The annual monitoring network was designed to obtain data on the frequency and intensity of the haze in the MZWA and the Yampa Valley, as well in the surrounding upwind background areas. It also documented the behavior of the plumes from the Hayden and Craig generating stations in the Yampa Valley and the surface and upper-air meteorology associated with haze events. The annual measurements included photographic and time lapse video measurements of appropriate views, including the MZWA and the Hayden and Craig stations, and continuous measurements of visibility related parameters (e.g., light scattering) and surface and upper-air meteorology.

During intensive study periods the annual network was supplemented with additional measurements to determine the causes of the haze. These measurements included increased densities of aerosol concentration and chemistry measurements throughout the study region. In the summer and fall intensive periods, continuous measurements of sulfur dioxide (SO_2) and fine-particle light scattering at three wavelengths were made next to the southern boundary of the Wilderness, and ozone was measured at an elevated site in the region.

Selected emissions measurements were made at appropriate times during the year to develop chemical profiles of nearby emissions sources. A regional emissions inventory was acquired and modified for modeling purposes.

Modeling and analysis efforts focused on the core study area, but took into account emissions and transport from the larger study area. Both source and receptor models were applied for source apportionment during selected episodes. Chemical abundances, including isotopic content, were measured in representative emissions sources including the generating station effluents. These same chemical species were analyzed in aerosol samples taken during intensive monitoring periods near the Wilderness, within the Yampa Valley, and outside the Valley to determine contributions from primary emissions.

Plume modeling and trajectory analyses of Yampa Valley generating station emissions were performed for the study year to estimate SO_2 concentrations in the MZWA and their frequency of occurrence. An aerosol evolution model was applied for different plume aging periods to place upper and lower limits on the amount of SO_2 that is likely to be converted to particulate sulfate under the meteorological conditions associated with haze events.

A conceptual model of the causes of visibility impairment in the MZWA is presented below. It derives from specific results and conclusions of the study which are summarized in the sections that follow.

S.2 CONCEPTUAL MODEL OF VISIBILITY IMPAIRMENT

The following elements describe the prevalent causes of visibility impairment within the Mt. Zirkel Wilderness Area and the contribution of the Hayden generating station and Craig Units 1 and 2 (Yampa Project) to this impairment.

- Light extinction in the MZWA is among the lowest measured in U.S. Class I areas. Winter is the clearest season and summer the haziest. The average light extinction in the MZWA, including scattering by particle-free air, is approximately half that in the Grand Canyon. Most hazes in the MZVS study area are regional, with light extinction comparable at locations that are separated by more than 150 km. Contributions from nearby sources are measurable and perceptible on occasion, and are superimposed on the contributions from a mixture of source emissions from within and outside the region.

- Haze in the Yampa Valley typically appears uniform visually, vertically, and horizontally. Surface layers are sometimes perceptible, especially during morning when a surface temperature inversion is present. Elevated layers are noticeable when noncontinuous emissions such as fires occur or when generating stations malfunction. Although appearing visually uniform, light extinction in the Yampa Valley is often much higher than that measured in the Wilderness and surrounding areas.

- Prescribed burns and wildfires cause visible plumes within and outside of the Yampa Valley. The most visible plumes within the Yampa Valley are those from the Hayden and Craig coal-fired generating stations. The most noticeable of these are steam emissions from cooling towers that rapidly evaporate upon dilution with ambient air. Primary particles that are not captured by the electrostatic precipitators are the main cause of visible emissions from stacks. These primary particle plumes become more visible when precipitators malfunction. The majority of pollutant emissions from generating stations consist of SO_2 and nitric oxide that can be detected instrumentally but not visually.

- Emissions from motor vehicles and residential burning can accumulate at night and during the morning near the floor of the Yampa Valley, to be mixed above the surface when the morning sun heats the surface layer. The time and nature of this coupling determines how these pollutants are transported to the Wilderness.

- The major and most frequent contributors to light extinction in the MZWA are particle-free air (Rayleigh scattering), motor vehicle exhaust and secondary organics (formed from heavy gaseous hydrocarbons), vegetative burning, and regional secondary ammonium sulfate. These contributors are for the most part of regional origins, resulting from a mixture of emissions from source areas that are hundreds of kilometers distant from the MZWA. Liquid water is a major component of particles that cause extinction when relative humidities exceed 80%. The visibility-reducing effects of water-soluble particles such as ammonium sulfate and ammonium nitrate are enhanced when humidities exceed 80%.

- SO_2 and oxides of nitrogen (NO_x), along with ammonia (NH_3), can change into particulate ammonium sulfate and ammonium nitrate that contribute to light extinction. These transformation rates are highly variable, but they can be expected to be slow in clear air and rapid when plumes encounter fogs or clouds.

- Significant, though not major, contributions to light extinction in the MZWA from local power generating stations occur occasionally. These contributions are always superimposed on contributions to extinction from other sources. In the absence of relative humidities larger than 80% (an indicator for passage of plumes through fog or clouds), the Yampa Valley generating station plumes seldom cause perceptible increases in light scattering in the Wilderness, although they regularly arrive in the Wilderness. After passage through fogs or clouds, sufficient transformation of SO_2 to sulfate can take place in generating station plumes to cause perceptible changes in light scattering in the Wilderness.

- Yampa Valley generating station plumes are usually confined below 400 m (1,300 ft) above ground level and flow to the west (down the Valley) at night and in the early morning. In midday, they mix aloft and couple with the upper level winds, which typically transport the plumes to the east, toward the southern end of the Wilderness. The generating station plumes tend to arrive in the Wilderness in pulses with typical durations of less than one to a few hours at any location.

- The largest perceptible effects of the Yampa Valley generating stations on visibility in the Wilderness occur when the emissions accumulate in fogs or low clouds in the early morning or interact with higher clouds after mixing aloft and are subsequently transported to the Wilderness in the afternoon. Pulses of haze attributable to generating station emissions can be seen from the Wilderness on some occasions under these conditions. When they arrive under these conditions, the hazes appear well mixed vertically, rather than as a layer or plume.

- Under nonroutine operating conditions, primary particle emissions from the Yampa Valley generating station stacks can cause perceptible, layered hazes with durations of several hours. These are not due to SO_2 emissions. On one occasion in 1995, a clearly-defined, coherent plume from the Hayden generating station could be seen in a west-facing video view from a camera on Storm Peak (which is south of the Wilderness boundary). The plume was moving toward Storm Peak at nearly the same elevation as the camera. The extent to which the plume reached or rose over the Continental Divide could not be determined because it could not be seen in views to the north. However, it is clear that the potential existed for the plume to reach the Storm Peak area. This was the only occasion when a clearly-defined, coherent generating station plume was documented coming close to the Wilderness.

- High relative humidity and SO_2 concentrations greater than about 1-2 ppb indicate when generating station emissions might cause visible effects. Model results and measured relative humidity at the southern Wilderness boundary suggest that the plumes arrive in the Wilderness at these concentrations during conditions when relative humidity is larger than 80% on approximately 3% - 8% of the daylight hours during the year. For 1995, the highest incidence (10% - 16%) of these conditions was in May (which was the wettest May on record) and the lowest (0.5% - 2%) in August. During many of these hours, views may be obscured by weather.

- Plumes from the Hayden and Craig stations arrive in the Wilderness together most of the time. Model results suggest that concentrations of Hayden station SO_2 emissions arriving in the Wilderness are three to four times higher than concentrations from the Craig station emissions. This difference is caused by larger dispersion and dilution of Craig station emissions, due to its greater distance from the Wilderness boundary, and SO_2 emission rates during the periods studied that were approximately half the emissions from the Hayden station. On rare occasions, however, for some portions of the Wilderness, the emissions from the two generating stations can arrive separately, and Craig emissions can cause more light extinction than Hayden emissions.

- For the largest documented impact of the Yampa Valley generating stations on visibility in the Wilderness during the study, light scattering peaked at about 60 Mm^{-1} at the southern Wilderness boundary. The relative contribution to six-hour average extinction estimated by a plume chemistry model for the Yampa Valley generating stations for this occasion was 46%. The modeled source contributions were, respectively: particle-free air: 15%; fires, 6%; non-Yampa-Valley sources, 31%; Hayden, 32%; Craig Units 1 & 2, 12%; Craig Unit 3, 2%; and other Yampa Valley sources, 4%. Receptor modeling results differed from the plume model. Receptor model apportionments for this episode were: particle-free air, 17%; fires, 15%; vehicle exhaust, 13%; regional ammonium sulfate, 33%; ammonium nitrate, 7%; and Yampa Valley generating stations, 14%.

- Yampa Valley generating stations have their largest effects on extinction over periods of one or two hours. The same event noted above also included the highest one-hour relative contribution to extinction estimated for Hayden and Craig Units 1 and 2 (the Yampa Project) along any modeled sight path. This contribution was 27% of total extinction, with 21% due to Hayden station and 6% to the Yampa Project. This is equivalent to a 38% increase in the light extinction that would have occurred without the generating station emissions. The average modeled extinction was 26 Mm^{-1} along the sight path compared to about ~60 Mm^{-1} modeled and measured at the southern Wilderness boundary. The equivalent deciview changes along the same sight path due to Hayden and Yampa Project were 2.39 dv and 0.67 dv, respectively. The sight-path extinction and generating-station percentages were lower than for the southern boundary. This is probably because the southern boundary site is often near the location of the maximum extinction, while the sight paths cover a larger area. Contrast calculations for the above sight path indicate that the total generating station contribution to extinction might be perceptible if images with and without the contribution were viewed side-by-side in a split screen image. It is likely that the Hayden contribution would be perceptible on its own. It is not certain that the Yampa Project contribution would be perceptible.

- The highest deciview contribution of the Yampa Project occurred for a view with an extinction of 16.5 Mm^{-1} and extinction contributions of 0.33 Mm^{-1} (2% of the extinction or 0.2 dv) from the Hayden station and 1.8 Mm^{-1} (11% or 1.16 dv) from the Yampa Project. For the short sight paths within the Wilderness, it is not likely that changes in extinction of these magnitudes would be perceptible.

- For all episodes and views modeled, the greatest changes in the apparent contrasts of ridges against the horizon sky caused by omitting the effects of both the Hayden station and Yampa Project emissions was 0.066 units. The greatest changes in contrast transmittances for features on the surfaces of the targets was 0.092. For Hayden alone, the comparable greatest changes for contrast and contrast transmittance were 0.039 and 0.063, respectively. For Yampa Project alone, the comparable greatest changes for contrast and contrast transmittance were 0.027 and 0.032, respectively.

- These calculated contrast changes are large enough to be perceived if they were displayed in a split-screen image, but it is not known if they are large enough to be perceived by an observer in the MZWA comparing observations made at different times. Of more than 3,000 cases of days/hours/sight-paths modeled, several dozens of cases for Hayden exceeded 2% contrast, while only 10 cases (2 days) exceeded this value for the Yampa Project.

- The views discussed above were for endpoints within the Wilderness. Other views that extended outside the Wilderness were examined; however, by agreement of the sponsors, the effect of removing generating station emissions was only calculated for those portions of sight paths within the boundaries of the Wilderness (or between endpoints that were within the Wilderness). Due to the small proportions of the long sight paths that were within the Wilderness, these sight paths are less sensitive to the removal of generating station emissions than sight paths with both endpoints in the Wilderness. Also by agreement of the study sponsors, estimates of the contributions of the generating stations were focused on the contributions of Hayden and the Yampa Project, omitting the contribution of Craig Unit 3.

S.3 STUDY FINDINGS

MZVS findings are keyed to sections of the MZVS final report and its appendices to facilitate further investigation of specific topics. Though these findings are specific for the 1995 MZVS period, and the specific magnitudes and frequencies apply only to that year, they are expected to be generally valid for prior and subsequent years providing there are no major changes in emissions and meteorology between those years. Some of the findings listed in this section have already been highlighted as elements of the conceptual model.

S.3.1 MEASUREMENTS

- The measurement network was adequate to detect occurrences of visibility impairment and to assess their causes. (All Sections)

- The major types of visibility impairment were encountered – including regional haze from transport of secondary aerosol, fire emissions, and other particulate matter; local haze from fires, local ground-level emissions, and secondary sulfates from generating station emissions; and surface and elevated haze layers from fires and generating station primary emissions. (Sections 4 & 5)

- The measurement year and the intensive operating periods were reasonably representative of the conditions encountered in other years, except that May was exceptionally stormy. No more than 6% of the days during the study showed major deviations from long-term averages for temperatures, cloud-cover, or rainfall. However, May was the wettest on record for the upper Yampa Valley. (Section 2.2)

- The observables measured were sufficient to detect the presence or absence of major source contributions, including continental dust, vehicle exhaust, vegetative burning, and primary and secondary coal-fired generating station emissions. (Section 6.5)

S.3.2 FREQUENCY, CHARACTER, AND INTENSITY OF HAZE

- Light extinction in the MZWA was among the lowest measured in U.S. Class I areas. Winter is the clearest season and summer the haziest. In winter, the median light extinction at Buffalo Pass (next to the southern boundary of the Wilderness) for days not affected by weather was 11 Mm^{-1}, only 30% above that of clean air. In summer, the median was 16 Mm^{-1}. For comparison, these values are about half those measured at the Grand Canyon. (Section 3.1, Table 3.1.1)

- High mountain views were obscured by weather for either all morning or all afternoon periods on about 25% to 50% of winter and spring days, about 5% of summer days, and 10% to 20% of fall days. (Section 3.2, Figure 3.2.1)

- Haze in the Yampa Valley typically appeared uniform visually, vertically, and horizontally. Surface layers were sometimes perceptible, especially during morning. Layers were noticeable when noncontinuous emissions occurred, especially fires. Although appearing visually uniform, light extinction in the Yampa Valley was often much higher than that measured in the Wilderness and surrounding areas. (Sections 3.1, 3.2, 3.4, 3.5)

- Most hazes were regional, with light extinction comparable at locations separated by more than 150 km. On some days, however, contributions to extinction from nearby sources were measurable and perceptible, and these contributions were superimposed on the contributions from a mixture of emissions from within and outside the region. (Section 3.1, Table 3.1.1, Figure 3.1.1)

S.3.3 COMPONENTS OF LIGHT EXTINCTION

- Clean-air scattering was a large or major component of light extinction in the Wilderness for the most daylight hours not affected by weather. (Section 3.1, Table 3.1.1; Section 3.5, Figures 3.5.1 and 3.5.2)

- Particle light absorption (caused primarily by soot) constituted less than 20% of extinction for most cases, but contributed nearly 50% of extinction during some events. Except during the spring, particle light absorption at Buffalo Pass was almost always less than 15% of total extinction. In spring, it was about 25% of total extinction. In winter and spring at Gilpin Creek (a lower-elevation, more-northerly site next to the Wilderness), light absorption was often one-third of total extinction but much less in other seasons. The high level at Gilpin Creek may be due to local wood or vegetative burning in the Elk River Valley below the site. (Section 3.5, Section 4.3)

- With the exception of the Gilpin Creek site in winter and spring, fine-particle light scattering was the major contributor to extinction that exceeded 20 Mm^{-1}. Coarse particle scattering in the Wilderness was negligible, as evidenced by comparable light scattering measurements from nephelometers with and without $PM_{2.5}$ inlets. (Section 3.5)

S.3.4 CHEMICAL COMPONENTS OF LIGHT EXTINCTION

- When light extinction exceeded 20 Mm^{-1}, organic carbon, and ammonium sulfate each commonly contributed more than 10% of extinction, and together often exceeded 50% of extinction, at all measurement locations for those six-hour and twelve-hour $PM_{2.5}$ samples submitted to chemical analysis. The proportions of their contributions varied from case to case. (Section 4.3, Table 4.3.8)

- $PM_{2.5}$ ammonium nitrate contributed less than 10% of extinction for almost all samples that were chemically analyzed at all sites. Ammonium nitrate was estimated to contribute more than 10% of six-hour average extinction on only two occasions at Buffalo Pass. (Section 4.3, Table 4.3.8)

- Extinction from $PM_{2.5}$ dust seldom contributed more than 10% of extinction. Nine out of 64 aerosol samples at Buffalo Pass showed $PM_{2.5}$ dust contributions that slightly exceeded 10% of extinction, substantially higher and more frequent than dust contributions at other sites in the MZVS. Frequent heavy-duty truck traffic along the unpaved road near the Buffalo Pass site, to facilitate nearby reservoir construction, may, have affected dust contributions, and probably do not appreciably affect extinction along sight paths. (Section 4.3, Table 4.3.8)

- Elemental carbon was a significant contributor in some events (especially at Gilpin Creek), but it was seldom a majority component of extinction. (Section 4.3, Table 4.3.8)

- Liquid water was a large component of particles that caused extinction when relative humidities exceeded 80%. The visibility-reducing effects of water-soluble particles such as ammonium sulfate and ammonium nitrate were enhanced at these humidities because they absorbed water and acted as nucleation sites for the formation of droplets. The conversion of gaseous SO_2 and oxides of nitrogen was also enhanced when they were absorbed in water drops. (Appendix B.4; Sections 4.3, 6.6, and 6.9)

- Average sulfate concentrations ranged from 0.81 $\mu g/m^3$ at the Buffalo Pass site to 1.09 $\mu g/m^3$ at the Hayden VOR site. Maximum sulfate concentrations ranged from 1.8 $\mu g/m^3$ at Juniper Mountain to 4.5 $\mu g/m^3$ at Hayden Waste Water, with maxima of 2.1 $\mu g/m^3$ at Buffalo Pass and 1.9 $\mu g/m^3$ at Gilpin Creek. Though Buffalo Pass did not experience the highest sulfate concentrations in the network, it did experience higher contributions of sulfate to extinction because it recorded the highest relative humidities. The highest sulfate contributions to extinction often occurred when sulfate concentrations were below average, but relative humidity exceeded 95% and large nephelometer readings showed Buffalo Pass to be enveloped in a cloud or fog. (Section 4.2, Table 4.2.1; Section 4.3, Tables 4.3.1 to 4.3.6)

S.3.5 YAMPA VALLEY PLUME BEHAVIOR

- In the absence of overriding synoptic influences, Yampa Valley generating station plumes were usually confined below about 400 m (1,300 ft) above ground level and drained down the Valley at night and in the early morning. In midday, they mixed aloft and coupled with the upper level winds, that typically transported the plumes toward the southern end of the Wilderness. (Sections 5.1, 5.2.3, 5.4.6)

- Both measurements and everyday plume modeling showed that SO_2 arrived at Buffalo Pass in pulses with typical durations of less than one to a few hours. SO_2 is a colorless gas that causes negligible light extinction. SO_2 pulses rarely lasted more than six hours, and SO_2 concentrations were negligible (i.e., below 0.2 ppbv) between pulses. The calculated magnitude and frequency of SO_2 pulses was in qualitative agreement with the measurements. The agreement between the timing of the modeled and measured pulses was often good and sometimes excellent. (Section 5.4)

- Cumulative frequency distributions of SO_2 concentrations calculated by everyday plume modeling showed them to be largest at the southern end of the MZWA, near Buffalo Pass. SO_2 levels decreased uniformly with distance north in the MZWA. Detailed modeling with multiple source emissions showed the same results. This is consistent with the prevailing daytime winds. Receptor sites near the southern end of MZWA provide an upper limit for the concentrations of emissions from Yampa Valley generating stations in the MZWA. (Section 5.2.1, Figure 5.2.6; Section 5.4.6)

- The highest modeled SO_2 concentrations were at Mad Creek, a low-elevation receptor site in a canyon in the southwest corner of the MZWA. The distance to Yampa Valley generating stations is at a minimum in this corner of the MZWA. (Section 5.4.6)

- Model results indicated that the emissions from the Hayden and Craig stations arrived in the MZWA together most of the time. Emissions from only one of these stations rarely arrived at the Wilderness in significant amounts without being accompanied by emissions from the other station. (Section 5.4.7)

- Trajectory analyses for episodes indicated that Yampa Valley generating station emissions can be transported directly to Buffalo Pass in midday in 2 to 5 hours, but emissions that are emitted into the early morning drainage flows could take 6 to 11 hours to arrive. Craig station emissions typically took 1 to 2 hours longer in transit than Hayden station emissions. (Section 5.2)

- The modeled percentage contribution of each generating station unit to SO_2 concentrations in the MZWA was approximately the same for all locations in the MZWA, both for all hours and for only hours with SO_2 concentrations greater than 2 ppbv. The approximate percentage contributions were: Hayden Unit 1, 40 to 45%; Hayden Unit 2, 35 to 40%; Craig Unit 1, 6 to 8%; Craig Unit 2, 7 to 9%; and Craig Unit 3, 3 to 4%. (Section 5.4.1, Table 5.4.1)

- The calculated plume rise for Hayden Unit 2 was greater than for Unit 1, causing more dilution before the emissions reach ground level. (Section 5.4)

- In the absence of relative humidities greater than 80% (a possible surrogate for passage through fog or clouds), the Yampa Valley generating station plumes rarely cause perceptible increases in light scattering in the Wilderness. (Sections 6.4, 6.5, 6.6)

- After passage through fogs or clouds, sufficient transformation of SO_2 to sulfate can take place to cause perceptible changes in light scattering in the Wilderness. On at least two days (09/18/95 and 08/23/95), increases in haze of one to a few hours duration that coincided with the arrival of SO_2 attributed to the Yampa Valley generating stations were noticeable on video views of the Wilderness and detectable by the nephelometers at Buffalo Pass. (Sections 5.6, 6.4, 6.5, 6.6)

- The largest perceptible effects of the Yampa Valley generating stations on visibility in the Wilderness (including the two events noted above) occurred when the emissions accumulated in fogs or low clouds in the early morning or were mixed into higher clouds after mixing aloft and were subsequently transported to the Wilderness in the afternoon. The interaction of the emissions with fogs or clouds allowed wet conversion of SO_2 to sulfate. (Sections 5.6, 6.6)

- Various analyses suggest that high relative humidity and SO_2 concentrations greater than about 1-2 ppb may be a reasonable surrogate for conditions when generating station emissions might have visible effects. Trajectory model results for each study day and measured relative humidity at Buffalo Pass suggest that the plumes arrived in the Wilderness at these concentrations during conditions when relative humidity was greater than 80% on 3% - 8% of the daylight hours during the year, with the highest incidence (10% - 16%) in May (which was the wettest May on record) and the lowest (0.5% - 2%) in August. During many of these hours, views would have been obscured by weather. (Sections 6.6, 5.4)

- The Buffalo Pass site near the southern Wilderness boundary measured among the highest concentrations of generating station emissions found in the Wilderness. Everyday model results also suggest that the highest concentrations of generating station emissions should be found int he southern portion of the Wilderness. The Buffalo Pass site should be representative of high-altitude sites in the southern portion of the Wilderness. (Section 5.4)

- The addition of ammonia to the Hayden plumes has a negligible effect on transformation rates or the formation of ammonium nitrate. (Sections 6.4, 6.9).

- Under nonroutine operating conditions, primary particle emissions from generating station stacks caused perceptible, layered hazes with durations of several hours. These were not due to SO_2 emissions. For example on 01/03/95, a clearly defined, coherent plume from the Hayden station could be seen in a west-facing video view from a camera on Storm Peak (which is south of Buffalo Pass). The plume moved toward Storm Peak at nearly the same elevation as the camera. The extent to which the plume reached or rose over the Continental Divide could not be determined because it could not be seen in views to the north. However, it is clear that the potential existed for the plume to reach the Storm Peak area. This was the only time the time-lapse videos showed that a layered haze or well-defined plume attributed to one of the Yampa Valley generating stations reached the vicinity of the Wilderness Area. (Sections 5.3, 5.5)

- Haze events associated with the formation of secondary particles (sulfate and associated water) that could be detected in the time-lapse videos showed a haze that was mixed to the ground and did not have apparent edges or top. Therefore, haze pulses identified from nephelometer measurements of light scattering at elevated locations were considered to be uniform haze rather than layered haze. (Sections 3.2, 5.5, and 6.8)

- Chemical compositions of primary particle emissions were sufficient to separate coal-fired generating stations from other contributors, but not from each other. Abundances of sulfur-32 and sulfur-34 measured in source samples were sufficient to distinguish coal-fired power station, motor vehicle exhaust, and geothermal hot springs from one another. The abundance of these isotopes in coal-fired generating station emissions were too variable, and too similar to those in background air, to improve the resolution between Yampa Valley generating station and regional sulfate contributions. (Section 6.3,6.5, Appendix B.3)

- Craig Unit 3 emissions contain no selenium, and its profile is too similar to geological material to be distinguished from that contributor. (Section 6.3)

S.3.6 SOURCE CONTRIBUTIONS TO LIGHT EXTINCTION

- For primary particles in the $PM_{2.5}$ size fraction, a multi-state (major parts of Colorado, Wyoming, and Utah) emissions inventory showed that motor vehicles accounted for ~46% of primary $PM_{2.5}$, with summer emissions distributed among vehicle exhaust, paved road dust, and unpaved road dust. Another 21% of $PM_{2.5}$ in the summer was emitted from natural dust sources, while 11% was emitted from agricultural tilling. During the winter months, residential wood and coal combustion were significant $PM_{2.5}$ sources, constituting 11% of the emissions. (Section 6.2)

- Residential coal combustion and hot springs were minor contributors to ammonium sulfate. Emissions surveys showed them to constitute less than 1% of sulfur emissions in northwestern Colorado and a multi-state region. Coal combustion, mostly in power generation stations, was the largest sulfur emitter in the Yampa Valley and in a multi-state region. Yampa Valley SO_2 emissions were estimated to be ~6% of all SO_2 emissions in the multi-state region. (Section 6.2)

- Sulfur-32 and sulfur-34 isotopic abundances in emissions from Yampa Valley coal-fired generating stations, motor vehicle exhaust, and geothermal hot springs differed sufficiently to allow contributions to sulfur from any two of these sources to be distinguished from each other. Isotopic abundances in sulfur emissions from Yampa coal-fired generators and sulfur in background air were too similar, within measured variability, to allow their separation into separate categories. This is possibly due to the dominance of coal-burning as the major SO_2 emitter in the region. (Sections 6.3, 6.5)

- Motor vehicle exhaust and fires (residential, wildfires, and prescribed burning) were the major contributors to the highest organic carbon concentrations. Secondary organic carbon could not be separately resolved and is most probably apportioned as vehicle exhaust by receptor models. (Section 6.5, Appendix D)

- A plume chemistry model was applied to four periods of interest corresponding to 28 days, including five visibility episodes in four modeled periods. Other data analyses and receptor modeling of source contributions to extinction were also applied to data from these periods. Calculations of contrast and the deciview haze index along selected Wilderness sight paths were made for the same days. These periods included several events of elevated light extinction in the Wilderness. Some of these events occurred during dry conditions (08/08/95, 10/19/95) and others occurred under high humidity (08/23/95, 09/18/95, 09/19/95, 10/12/95). Buffalo Pass SO_2 concentrations of about 2 ppb or more were predicted by the everyday modeling and the plume chemistry model, and were measured for all of these events except 10/12/95 and 10/19/95. For 10/12/95, a value of about 2 ppb was estimated by the plume model, but only about 0.5 ppb was measured. These days were examined to assess the source contributions to extinction in the Wilderness. They include the days of the highest estimated generating station contributions to extinction during the summer and fall. (Sections 5.6, 6.5, 6.6, 6.7, 6.8)

- For the dry periods of 08/08/95 and 10/19/95, data analyses, plume modeling, and receptor modeling agree that the Yampa Valley generating stations were negligible contributors to extinction in the Wilderness. These events were dominated by fires, motor vehicle emissions or secondary organic aerosol, and secondary sulfate transported from outside the local region. For example, receptor modeling indicates that for the 08/08/95 afternoon sample at Buffalo Pass (with measured light extinction of 36 ± 6 Mm^{-1}), 23 ± 7% of the extinction derived from clean-air scattering, 20 ± 1% was contributed by fires, 29 ± 29% came from motor vehicle exhaust or secondary organics (note the large uncertainty estimate), 0.6 ± 0.3% was attributable to local coal-fired generating stations; 13 ± 2% was from regional ammonium sulfate, 1.7 ± 0.8% was from secondary ammonium nitrate; and 13 ± 1% was from suspended dust. The suspended dust contribution was real, but was probably very local and did not affect concentrations along long sight paths. (Sections 5.6, 6.5, 6.7; Table 6.5.6)

- For 08/23/95, trajectory analyses, correlation between SO_2 and particle scattering (b_{sp}), and video images indicated a possible significant contribution to extinction at Buffalo Pass from the Yampa Valley generating stations. Regional background conditions, high values of aerosol light absorption, and the chemistry of the filter samples, however, indicated that geological material, regional sulfate, fires, and motor vehicles or secondary organics were the dominant contributors to extinction for the six-hour afternoon period. The plume model substantially underestimated the extinction because it did not adequately account for regional transport. The receptor model attributed only 3.5 ± 1.7% of the 37 ± 7 Mm^{-1} measured extinction to the Yampa Valley generating stations. It should be noted, however, that the models were applied for six-hour samples and will underestimate the contribution of the generating stations to extinction for shorter time periods. From the high correlation between SO_2 and b_{sp} seen for this event, it is likely that the generating station contribution to extinction was higher than estimated by the models, but for a short portion of the six-hour averaging interval. A corresponding correlation between light absorption and b_{sp} indicates that other sources than the generating stations also contributed to the event. (Sections 2, 5.6, 6.5, 6.6, 6.7)

- The afternoons of 09/18/95 and 09/19/95 were the times of the largest documented contributions of Yampa Valley generating stations to light extinction in the Wilderness. For these afternoons, light scattering at Buffalo Pass peaked at about 60 Mm^{-1} and 25 Mm^{-1}, respectively, and the plume-model extinction estimates (for a six-hour period) agreed with the peak values. (Sections 5.6, 6.6, 6.7, and 6.8)

- For 09/18/95 and 09/19/95, the percentage contributions to afternoon six-hour-average extinction estimated by the plume chemistry model for the Yampa Valley generating stations were 46% for 09/18/95 and 26% for 09/19/95. The modeled component contributions for these days were, respectively: clean air, 15% and 44%; fires, 6% & 4%; non-Yampa-Valley sources, 31% and 19%; Hayden, 32% and 20%; Craig Units 1 and 2; 12% and 5%; Craig Unit 3, 2% and 1%; and other Yampa Valley sources, 4% and 6%. The receptor model found the following contributions, respectively: clean air, 17 ± 4% and 38 ± 10%; fires, 15 ± 1% and 17 ± 1%; vehicle exhaust and secondary organics, 13 ± 20% and 24 ± 25%; suspended dust, 2 ± 0.4%; background ammonium sulfate, 33 ± 7% and 10 ± 4%; secondary ammonium nitrate, 7 ± 2% and 2 ± 1%; and Yampa Valley generating stations, 14 ± 7% and 7 ± 3%. (Sections 6.5, 6.7)

- For the afternoons of 09/18/95 and 09/19/95, receptor modeling results differed from plume model results. Observations of the magnitude of the changes in b_{sp} coincident with changes in SO_2 from 1200 to 1500 MST on 09/18/95 and from 1400 through 1600 MST on 09/19/95 were closer to the six-hour average plume model results than to the corresponding receptor model results. The plume model may more closely represent the peak light extinction values seen for these days. (Sections 5.6, 6.5, 6.6, Appendix D, Figure 5.6.2)

- The contributions to extinction of Hayden and Craig Units 1 and 2 (the Yampa Project) were calculated using the plume chemistry model for a variety of sight paths. The changes in light extinction and contrast that would occur along the sight paths from eliminating those emissions from the Hayden station and Yampa Project that were within the Wilderness boundaries were modeled. The highest one-hour percentage contribution estimated for these generating units along any modeled sight path on any day was 27% of total extinction (b_{ext}) on 09/18/95, with 21% due to Hayden station and 6% to the Yampa Project. This is equivalent to a 38% increase in the extinction that would have occurred without the generating station emissions. For this sight path (from Mt. Ethel to the Continental Divide Trail), the average modeled b_{ext} was 26 Mm^{-1}, compared to about 60 Mm^{-1} at Buffalo Pass. The equivalent deciview changes along the same sight path due to the Hayden station and Yampa Project were 2.39 dv and 0.67 dv, respectively. Sight-path extinction and generating-station percentages would be lower than for Buffalo Pass, because the Buffalo Pass site is generally near the location of the maximum extinction, while the sight paths cover a larger area. (Sections 6.7 and 6.8; Tables 6.6.5b, 6.7.9, 6.8.4, and 6.8.5)

- Contrast calculations for 09/18/95 for the above sight path indicated that the total generating station contribution to extinction might be perceptible if images with and without the contribution were viewed side-by-side. (Section 6.8)

- Changes in b_{ext}, measured and modeled, correspond with observed and perceptible changes in contrasts. The OPTEC nephelometer at Buffalo Pass measured a change of total scattering of approximately 36 Mm^{-1} from 1100 to 1300 MST during the 09/18/95 event, accompanied by a 2.1 ppb increase in SO_2. This light scattering change is much larger than the 7.3 Mm^{-1} maximum change along a sight path due to Hayden and Yampa Project emissions calculated by the plume chemistry model. It is also large compared to commonly-discussed perception thresholds. In addition, an obvious haze pulse was perceptible in the time-lapse videos taken from Storm Peak during this event. Given the relative contributions of Hayden station and the Yampa Project to this event, it is likely that the Hayden station contribution would have been perceptible in the absence of the Yampa Project contribution. It cannot be determined that the Yampa Project contribution would have been perceptible on its own. (Section 6.8.4)

- For the 10/12/95 event, the afternoon extinction at Buffalo Pass estimated by the plume model was about 21 Mm^{-1}. This is similar to the extinction measured at the site in midday while clouds were not present. Most of this extinction was attributed to clean-air scattering and a mixture of regional sources. Receptor modeling estimated the significant and large contributors to be clean-air scattering, suspended dust, motor vehicle or secondary organics, fires, and regional sulfate. The Yampa Valley generating station contributions were estimated to be about 14% by the plume model and less than 1% by the receptor model. For the same day, the average extinction calculated by the plume model for the sight paths varied from 12 to 16.5 Mm^{-1}. (Section 6.8.7)

- 10/12/95 is of interest because the maximum deciview change due to the Yampa Project was estimated to occur on that day. On most days, the contribution of Hayden station was about three times that of the Yampa Project. On this day, 9% of the 14% at Buffalo Pass was attributed to Hayden station and 5% to Yampa

Project by the plume chemistry model. For the Mt. Ethel to the Continental Divide Trail View, a b_{ext} of 16.5 Mm^{-1} was estimated with about 13**%** of this attributed to Hayden station and the Yampa Project. For this view, the contribution of the Yampa Project was estimated by the plume model to exceed that of Hayden station. Unit 2 at Hayden station had been shut down for maintenance from 10/07/95 through 10/11/95, just prior to this event. The 13**%** was attributed as 0.33 Mm^{-1} or 2% to Hayden station and 1.8 Mm^{-1} or 11% to the Yampa Project, or alternatively, 0.2 dv to Hayden station and 1.16 dv to the Yampa Project. For this view, the Yampa Project contribution exceeded 1 dv. This value has been discussed as a change that can be noticed by casual observers. This applies, however, for views over distances close to the visual range of the objects observed. For short views such as those within the Wilderness, it is unlikely that the above 1.8 Mm^{-1} b_{ext} change corresponding to the 1.16 dv change would be perceptible by most observers. (Sections 6.5, 6.7, and 6.8; Tables 6.5.7, 6.7.7b, and 6.8.6)

- For the periods modeled above, there were large differences in the calculated apparent contrast and contrast transmittance for different sight paths in the MZWA. These differences were primarily caused by differences in the brightness of the target, which depend on its reflectance and orientation to the sun. For most sight paths, diurnal changes in illumination caused changes in the calculated apparent contrast and contrast transmittance that were far greater than any changes due to changes in the emissions. (Section 6.8)

- Values of the deciview haze index changed by as much as 3.2 units when the effects of the emissions of both the Hayden station and the Yampa Project were omitted. When only the effects of the Hayden station emissions were omitted, the largest change in dv was 2.4 units, and the largest change from omitting the effects Yampa Project emissions was 1.16 units. A one-unit change in dv corresponds to a 10% change in b_{ext}. (Section 6.8)

- For all episodes and views modeled, the largest change in apparent contrast of ridges against the horizon sky caused by omitting the effects of both the Hayden station and Yampa Project emissions was 0.066 units. The largest change in contrast transmittance for features on the surfaces of the targets was 0.092. For Hayden station alone, the comparable largest changes for contrast and contrast transmittance were 0.039 and 0.068, respectively. For the Yampa Project alone, the comparable largest changes for contrast and contrast transmittance were 0.027 and 0.032, respectively. (Section 6.8)

- These calculated contrast changes are large enough to be perceived if they were displayed in a split-screen image, but it is not known if they are large enough to be perceived by an observer in the MZWA comparing observations made at different times. Of more than 3,000 cases of days/hours/sight-paths modeled, several dozens of cases for Hayden station exceeded 2% contrast, while only 10 cases (2 days) exceeded this value for the Yampa Project. (Section 6.8)

- The maximum values of the calculated changes in contrast and contrast transmittance due to changes in generating station emissions were very nearly the same for clear skies and for completely overcast skies. (Section 6.8)

- Yampa Valley generating station contributions are always superimposed on contributions to extinction from other sources. For more than 90% of the daylight hours, their contribution to visibility impairment in the Wilderness was probably negligible. However, during the August-October period, when fine-particle light scattering was measured, approximately twelve events were identified with measurable increases in light scattering accompanying SO_2 pulses. Haze pulses were observed in the time-lapse videos during two of these events (08/23/95 and 09/18/95). In both, the light extinction increased from ~20 to ~60 Mm^{-1} over a few hours. In the remaining cases, the camera views were obscured by weather or changes in haze could not be distinguished in the videos. For the two events noted, the Yampa Valley generating stations plumes passed through clouds or fog, and ammonium sulfate was a large contributor to the extinction. (Sections 5.4, 5.6, 6.5, 6.6, 6.7)

- Increasing ammonia does not effectively increase ammonium nitrate concentrations to significant levels. An aerosol evolution and equilibrium model demonstrated that doubling ammonia concentrations increased particulate nitrate concentrations only when liquid water contents were low. This increase was offset by the small amounts of particle nitrate contained in the smaller amounts of liquid water, with the result that, on average, the increase in particle nitrate was less than 0.1 $\mu g/m^3$. (Section 6.9, Table 6.9.1)

- Increases in particulate nitrate did not exceed 0.1 $\mu g/m^3$ with decreases in sulfate concentrations. Reducing sulfate concentrations frees up ammonia for potential reaction with nitric acid to form particulate ammonium nitrate, but sulfate reductions also reduce the liquid water available for reactions. These phenomena counteract each other. (Section 6.9, Table 6.9.1)

S.3.7 LIMITATIONS OF MODEL RESULTS

- Aside from local generating station emissions that were directly measured, emission rate estimates were only qualitatively accurate in space and time, and may differ from reality by up to an order of magnitude for specific visibility events. This is especially true of fires that are episodic and may have regional, as well as local, influence. (Section 6.2).

- Chemical-specific extinction efficiencies were very sensitive to changes in particle size for the distributions with modes <0.3 μm found during the MZVS. They were also inaccurate for very high humidities (>95%), but views were often obscured by weather under these conditions. (Section 4.1)

- Chemical Mass Balance modeling did not distinguish between separate generating station contributions. Both dry- and wet-aged profiles provided adequate fits to the data. The profile used to apportion contributions from Yampa Valley generating stations was selected for a sample based on evidence of plume processing by fogs and clouds, even though a profile that did not undergo such processing would explain the measurements equally well. Lacking measurement of specific organic compounds, the motor vehicle source contributions probably explain secondary organic aerosol contributions as well as those from directly emitted exhaust. Uncertainties for motor vehicle contributions were high, often exceeding the source contribution estimate. (Section 6.5).

- Since modeled hourly SO_2 concentrations from the Hayden and Craig generating stations showed reasonable agreement with the measured SO_2 concentrations, everyday plume modeling results should be reliable for drawing conclusions related to the frequency of occurrence and locations of SO_2 emissions from the two generating stations and their relative contributions to SO_2. (Section 5.4)

- CALMET/CALPUFF plume chemistry modeling often underestimated measured $PM_{2.5}$ and extinction. This is probably due to source contributions from outside the emissions domain, inaccurate emissions estimates for intermittent sources during episodes, and inadequate mechanisms for determining aqueous-phase conversions of SO_2 to sulfate, that are the cause of most events with perceptible visibility impairments. (Sections 6.4, 6.7)

- Results obtained from CALMET/CALPUFF, CMB, and continuous measurements are qualitatively comparable in terms of timing and magnitude of nearby generating station contributions, but they show substantial quantitative differences. Results are most comparable for dry situations when local generating station contributions to ammonium sulfate were low. They were in greatest disagreement for those cases where transformations in fogs and clouds occurred. (Sections 5.4, 6.5, 6.7)

- Most relations used in the contrast calculations were accurate, but the diffuse skylight flux and horizon sky radiance were calculated from simplified relations of uncertain accuracy. The effect of these simplifications on the calculated contrasts has not been determined. (Section 6.8)