1.0 INTRODUCTION

This section provides an opening overview of the report. The purpose of the study is defined, and the technical objectives are outlined. The technical approach to achieving each of these objectives is briefly summarized. Also included is a guide to the organization of this report as well as of other materials used in conducting the study but not contained in the report. In addition, terms used in the study are defined.

1.1 Study Purpose 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. In Class I areas, such as national parks and wilderness areas, industrial activities are not permitted and emissions from new sources outside the Class I boundaries must cause no adverse impact. Current regulations, promulgated by U.S. EPA in 1980, address visibility impairment that is "reasonably attributable" to an existing industrial source or a group of sources (these are often called "plume blight" regulations). Uniform, regional hazes caused by a multitude of sources located near and far from Class I areas are considered under the 1990 Clean Air Act Amendments and are to be treated by visibility transport commissions (VTC). A VTC exists for the Grand Canyon National Park, but no VTC has been established to evaluate regional haze in northwestern Colorado.

Ely *et al.* (1993) assembled available technical information on visibility, air quality, and meteorology in and near the MZWA, including color slides, meteorological data, and emission inventories. The designated land manager for the MZWA, the U.S. Forest Service (USFS), used this information to certify that occasions existed during which visibility was significantly impaired and named the Craig and Hayden coal-fired power generating stations as possible sources. The State of Colorado determined that information was insufficient to reasonably attribute observed visibility impairment to specific sources, and the Mt. Zirkel Visibility Study (MZVS) was commissioned to obtain this information. Potential contributors include sources in the Yampa Valley, which is west of the MZWA and contains the Craig and Hayden generating stations and the Steamboat Springs, Hayden, and Craig population centers, and more distant emitters in Colorado, southern Wyoming, western Utah, and outlying areas.

The purpose of the MZVS (Blumenthal *et al.*, 1995; Watson *et al.*, 1995) is 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 are 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 Mt. Zirkel Wilderness, 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 Mt. Zirkel Wilderness.

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 emission 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.

1.2 Technical Approach

There is no single, foolproof method for attaining these objectives. Emission rates, air flow in complex terrain, and chemical transformations of emitted pollutants in the atmosphere are complicated phenomena that are not entirely understood. Even with complete understanding of the processes involved, it is not technically or economically feasible to obtain measurements that fully describe all of the relevant atmospheric variables in space and time.

The MZVS program plan (Watson *et al.*, 1995) examined several previous visibility and particulate source apportionment studies, as well as existing information from the study area. The plan specified measurements, data analyses, and modeling methods that address each of the first six technical objectives. Several different data analysis and modeling methods were identified for each objective, and each of these methods was to be evaluated with respect to its applicability in the study area, completeness and uncertainty of available data, and its relevance to each study objective.

Measurements were taken as part of the MZVS, as well as acquired from existing meteorological, air quality, and visibility monitoring networks. To attain the first technical objective, these measurements were organized into a consistent and documented data base and subjected to several tests to determine their validity, precision, and accuracy. Validation tests are applied to determine which data can be used for other objectives and the uncertainties that they impart to data analysis and modeling. The following measurements were submitted to several comparison and validation tests: nephelometer measurements for light scattering; aethelometer measurements for light absorption; radar profiler and radioacoustic sounding system (RASS) measurements of upper air winds and temperature; meteorological tower measurements of winds, temperatures, and relative humidities; filter-based measurements of aerosol and precursor gas composition; and continuous measurements of sulfur dioxide. All but the following measurement methods had been applied in prior quantitative source apportionment studies: 1) high time-resolution (every 15 minute) particle sulfur concentrations at levels below 0.1 $\mu g/m^3$; and 2) isotopic abundances of S^{32} and S^{34} in potential primary source emissions as well as in secondary particle sulfate measured at receptors. These methods had high risk of failure, but very high value for attaining the source apportionment objective if they succeeded. The climatology of the 12/01/94 through 11/30/95 study period was examined to determine the extent to which conditions found during that year can be extrapolated to earlier and later years.

The second technical objective of documenting the frequency, intensity, and character of the haze was addressed by visually examining photographs and videos as well as instrumental light scattering measurements. Frequencies of visual and instrumental haze occurrences were compiled for each measurement location. These were compared with each other and with simultaneous light scattering and extinction measurements from other Class I areas. Visual records and relative humidity measurements allow weather-related excursions in light extinction to be separated from haze caused by air pollution. Comparisons of simultaneous visibility measures near the Mt. Zirkel Wilderness, in the Yampa Valley, and outside the Yampa Valley allowed effects of regional and local emissions on visible haze to be discerned. From these analyses, several haze events were identified for more detailed examination to attain subsequent objectives.

The third technical objective of estimating the relative contributions of scattering and absorption was attained by summing the contributions from clean air (Rayleigh) scattering determined from atmospheric temperature and pressure, fine particle scattering determined by nephelometry, and fine particle absorption determined by densitometry measurements of particle deposits on Teflon-membrane filters. Nitrogen dioxide, the major contributor to absorption by gases, has been shown to be a minor contributor even in urban areas where concentrations are high, and its contribution to light extinction is assumed to be negligible in the study area.

The fourth technical objective of attributing light extinction to chemical components was addressed by estimating extinction efficiencies for each of the major aerosol components measured on daytime filter samples of six- and twelve-hour duration. These estimates make use of multi-wavelength nephelometer measurements to infer particle size distributions, relationships between particle size and relative humidity established in this and other studies to estimate particle growth from liquid water absorption, and the Elastic Light Scattering Interactive Efficiencies (ELSIE) (Sloane *et al.*, 1991; Lowenthal *et al.*, 1995) light scattering model to determine the change in extinction associated with changes in chemical concentrations.

The fifth technical objective of documenting generating station plume behavior was addressed by drawing examples from the time-lapse videos of the plumes during daylight hours, estimating transport and mixing within the Yampa Valley from vertically stratified meteorological measurements, identifying variations in generating station emissions of primary particles and sulfur dioxide, applying the CALMET/CALPUFF dispersion model to daily emissions and meteorological measurements for the entire study period, and examining continuous sulfur dioxide, light scattering, and light absorption measurements near the Wilderness boundary.

The sixth objective of source apportionment presented the greatest challenge to this study. The attainment of the second technical objective identified cases representing different emissions, transport, and aerosol transformation situations. Both primary particles, those directly emitted from sources, and secondary particles, those formed from directly-emitted gases, were believed to be major components of suspended particles that cause light extinction (Watson *et al.*, 1995). Both Yampa Valley and more distant emitters were suspected of contributing the suspended particle concentrations. Emissions, especially intermittent emitters such as fires, were tabulated for the Yampa Valley and a larger domain that included large parts of Colorado, Wyoming, and Utah. Examples of emissions from coal-fired generating stations, vehicle exhaust, residential coal and wood combustion, geothermal springs, wildfires, and suspended dust were acquired and chemically characterized. Source characterizations included measurements of isotopic abundances in sulfur as well as elemental, ionic, carbonaceous, and sulfur dioxide abundances.

An aerosol evolution model (Robinson and Whitbeck, 1985) was applied to the generating station profiles to determine how the abundances of sulfur dioxide, sulfate, and elements might change with time under dry and moist conditions. The Chemical Mass Balance receptor model (Watson *et al.*, 1990) was used with these "aged" and unaged profiles to estimate source contributions for the all of the six- and twelve-hour average aerosol samples that were chemically characterized. Short-term (an hour or two) increments in light scattering and absorption near the Wilderness were determined to estimate maximum impacts from plumes originating in the Yampa Valley, especially when light scattering excursions corresponded to short-term excursions in continuous light absorption and sulfur dioxide. The CALMET/CALPUFF (U.S. EPA, 1995a, 1995b) wind field and air quality models were applied, using emission rates and meteorological data from the MZVS, to independently estimate source contributions from Yampa Valley and regional sources during five multi-day visibility episodes that illustrated different types of events. Nonlinearities associated with emissions changes were examined for perception by calculating changes in contrast along sight paths associated with views from the Wilderness, and by equilibrium modeling of ammonium nitrate concentrations when sulfate, ammonia, and nitric acid precursors are reduced (Kim *et al.*, 1993a, 1993b).

The final technical objective of reconciliation was approached by combining information from each of the previous analyses. Several episodes were selected for detailed analysis, especially ones in which different combinations of source contributions were observed. A conceptual model was formed that explained these episodes, and the ability of each of the simulation models to simulate these episodes was critically examined. The best estimates of each source contribution were selected, with objective and subjective estimates of the uncertainties of these contributions.

1.3 Guide to MZVS Project Documents

This report and its executive summary present the results of the MZVS, the methodology followed to achieve those results, and the rationale for the study conclusions. This section summarizes the technical objectives and the approach to attain them. Section 2 describes the measurement network, with reference to the program plan (Watson *et al.*, 1995) which contains details about the measurement methods, site selection, data analysis and modeling plans, and the data base. Subsequent sections treat each technical objective, following the approach outlined in Section 1.2. Section 3 determines the frequency, character, and intensity of hazes and justifies the selection of visibility episodes that are submitted to further study. Section 3 also quantifies the contributions from clean air scattering, particle scattering, and particle absorption for aerosol measurement periods. Section 4 estimates the contributions from different chemical constituents in suspended particles to those extinction components. The behavior of Yampa Valley plumes and the characteristics of the episodes selected for analysis are discussed in Section 5. Section 6 addresses the source apportionment objectives. Results of the previous sections are summarized and reconciled in Section 7 to support the conclusions in the executive summary. Appendices contain details about data quality and management, data analysis and modeling methods, and presentations of detailed modeling results

Many data volumes, task reports, and plots were generated as part of the MZVS. These are too voluminous to be presented as part of the final report, though they are identified by reference in the body of this report and its appendices, with their detailed citations in Section 9. Copies of these reports are maintained as part of the centralized data base at the Desert Research Institute (DRI). Digital data files, available via Internet in xBase format, constitute the bulk of the MZVS data base. In addition, the data base contains: 1) model input and output files; 2) modeling software; 3) detailed time-lapse videos in VHS format; 4) 35-mm photographs in CD format; 4) a summary time-lapse video with examples of views and visibility events in VHS format; and 5) animation of everyday plume modeling results in CD format.

The digital data base has been organized so that all data are in common units, for common time periods, and with common data validation flags and missing value codes. Traceability files were compiled that allow conversions and validation changes to be traced to the data as originally received from the provider.

1.4 Definitions

Though every attempt is made to be precise and quantitative in terms of statements and conclusions made in this report, it is necessary to use descriptive terms that may have different meanings to different people. Several commonly used, but imprecise terms, are defined for the MZVS as follows:

In references to relative amounts, such as contributions of chemical species to mass concentration, source contributions to light extinction, and components of light extinction, "negligible" means <1%, "minor" means 1% to 10%, "significant" means 10% to 25%, “large” means 25% to 50%, and “major” means >50%. These terms are defined solely for use in this report, and are not based on any legal definitions used in the federal Clean Air Act or in Colorado’s visibility regulations.

In references to frequencies of occurrence, the period of occurrence will be specified (year, season, intensive monitoring period). “Never” means 0% of the time, “rarely” means >0% to 1% of the time, “seldom” means 1% to 10% of the time, “often” means 10% to 25% of the time, “commonly” means 25% to 50% of the time, “most of the time” means >50% of the time, and “always” means 100% of the time. These terms are defined solely for use in this report, and are not based on any legal definitions used in the federal Clean Air Act or in Colorado’s visibility regulations.

The term “plume” refers to ducted and nonducted bodies of pollutants in air that are detectable by visual observation or by instrumentation. Plumes do not necessarily originate in well-defined point sources, nor can they necessarily be detected by the naked eye. In particular, the presence of Yampa Valley generating station plumes are often detected in the MZVS near the Wilderness by “pulses” of elevated sulfur dioxide concentrations detected by the continuous sulfur dioxide measurements. These pulses are typically separated by sulfur dioxide readings equal to the instrument baseline. Some sulfur dioxide pulses were accompanied by pulses of elevated light scattering, but many pulses were not accompanied by measurable changes in light scattering.