10. Summary and Conclusions

Project MOHAVE sponsors and participants designed and operated an air quality monitoring program, including perfluorocarbon tracer studies in the winter and summer of 1992, and conducted extensive data analysis and modeling with the primary goal of characterizing the impact of MPP emissions on visibility at Grand Canyon National Park. The project had five specific objectives to meet in order to achieve its goal:

1. Evaluate the measurements for applicability to modeling and data analysis activities.
2. Describe the visibility, air quality and meteorology during the field study period and determine the degree to which these measurements represent typical visibility events at the Grand Canyon.
3. Further develop conceptual models of physical and chemical processes which affect visibility impairment at the Grand Canyon.
4. Estimate the contributions from different emissions sources to visibility impairment at the Grand Canyon, and quantitatively evaluate the uncertainties of those estimates.
5. Reconcile different scientific interpretations of the same data and present this reconciliation to policy-makers.

This section summarizes the results of Project MOHAVE in terms of these objectives and comments on lessons learned during the project.

10.1 Evaluate the measurements for applicability to modeling and data analysis activities.

Project MOHAVE measurements were acquired over the entire 1992 calendar year. In particular, detailed meteorology, visibility, air quality, and tracer measurements were collected during a winter intensive sampling period (1/14/92 to 2/15/92) in a 31 site network and a summer intensive sampling period (7/12/92 to 9/2/92) in a 34 site network. These measurements were organized into a consistent and documented database and subjected to tests to determine their completeness, precision, lower quantifiable limit, and accuracy. Validation tests were applied to address the uncertainties that the data impart to data analysis and mathematical simulations. Where possible, the sensitivity of Project MOHAVE conclusions to measurement uncertainty was evaluated.

10.2 Describe the visibility, air quality and meteorology during the field study period and determine the degree to which these measurements represent typical visibility events at the Grand Canyon.

Measured light extinction (a parameter that is inversely related to the visual range) is lower at Grand Canyon National Park (GCNP) than at most other sites in the United States. Median light extinction levels were lower during the winter intensive sampling period than during the summer period. At Meadview, on the western border of the GCNP, the closest park location to MPP, the light extinction coefficient averaged 27.6 Mm^{-1} in winter and 32.5 Mm^{-1} in summer; at Hopi

Point, on the southern rim toward the eastern end of the canyon, it averaged 20.2 Mm^{-1} in winter and 22.7 Mm^{-1} in summer; and at Indian Gardens, within the canyon near Hopi Point, the values were 33.5 Mm^{-1} in winter and 35.5 Mm^{-1} in summer. Visibility was generally worse within the canyon than on the rim.

At Meadview, median PM_{10} concentrations were 3.9 $\mu g/m^3$ in winter and 14 $\mu g/m^3$ in summer. Median $PM_{2.5}$ concentrations were 1.6 $\mu g/m^3$ in winter and 5.4 $\mu g/m^3$ in summer. Rayleigh scattering (the extinction of light due to clean air) accounted for the largest fraction of calculated light extinction: 54 ± 11% in winter and 42 ± 8% in summer. Organic material and ammonium sulfate aerosol were major contributors to the calculated light extinction (15 ± 4% and 13 ± 6%, respectively) during the winter sampling period. Coarse mass and ammonium sulfate were the major contributors (21 ± 8% and 18 ± 5%) to light extinction during the summertime sampling period.

Perfulorocarbon tracer (PFT) measurements indicated that emissions from the Dangling Rope release point, near the eastern end of the canyon, were typically transported downriver within the Grand Canyon during the winter sampling period. Emissions from the MPP were also transported southward down the Colorado river, in winter. In summer, flows were generally reversed from the winter. Tracer released from El Centro was predominantly detected at monitoring stations north and east of the release site. Emissions from Tehachapi Pass were transported east toward Las Vegas. The MPP tracer was transported north over Lake Mead.

These findings are consistent with visibility, air quality, and meteorological observations conducted over a longer time period. Between 1987 and 1994, the summer seasonal median extinction on the rim ranged from 21 to 27 Mm^{-1}. Within the canyon, summer median extinction ranged from 30-36 Mm^{-1}. The winter seasonal median ranged from 17 to 20 Mm^{-1} on the rim. Within the canyon, the median winter time extinction ranged from 25 to 33 Mm^{-1}.

Aerosol sulfate levels measured as part of SCENES (1984 through 1989) and IMPROVE (1987 to 1997) were comparable to those measure during Project MOHAVE study. For the period corresponding to the winter intensive monitoring period (January 14-February 13), the SCENES 50th percentile was 0.22 $\mu g/m^3$ compared to Project MOHAVE's 0.19 $\mu g/m^3$ at Meadview. Summertime median sulfate concentrations at Meadview were 0.51 $\mu g/m^3$ during Project MOHAVE and 0.44 $\mu g/m^3$ during SCENES. At Hopi Point, Project MOHAVE summer intensive study median was 0.38 $\mu g/m^3$ compared to SCENES 0.40 $\mu g/m^3$ and IMPROVE 0.30 $\mu g/m^3$.

1992 was a moderate El Niño year in the southwestern United States, which led to above normal precipitation and clouds, particularly during the winter season. Most of this moisture emanated from atypically high "thermal low" patterns (strong westerlies in the desert Southwest) which occurred nearly 40% of the winter compared to the climatological average of 25%.

Tracer transport through the monitoring network was qualitatively consistent with seasonal synoptic scale transport patterns developed from back trajectory calculations for the period 1979 to 1992. The 13 year transport record indicates that in winter there are no prevailing winds at the rim of the canyon at Hopi Point. In summer, transport is usually from the southwest.

10.3 Further develop conceptual models of physical and chemical processes which affect visibility impairment at the Grand Canyon.

Because of the tendency for MPP emissions to be transported in the direction of the Grand Canyon principally in summer, the major focus of project analyses and mathematical simulations of the air quality was the summertime period. During the summer, the dominant contributors to visibility impairment at Meadview were coarse particles, ammonium sulfate, and carbon.

Modeling of MPP emissions indicated that the formation of sulfate particles was small in dry conditions, but was much greater when the plume interacted with liquid water in clouds. Analysis of the optical effects of the size spectrum of sulfate particles in the desert produced the conclusion that they were smaller than the most efficient size, and had a dry scattering efficiency of about 2 m^2/g.

Thus the conceptual model that evolved for determining the impact of MPP emissions on GCNP visibility was the following: (1) MPP emissions were transported toward GCNP mainly when the flow at MPP was from the south, which occurred mostly in the summer; (2) The SO_2 emitted by MPP was converted to sulfate in appreciable amounts only when the plume interacted with clouds; (3) The resulting sulfate particles had a dry scattering efficiency of 2 m^2/g, which is less than the value of 3 m^2/g that is typically used; and (4) The impact of the emissions was greatest at the western end of GCNP, the location closest to MPP.

10.4 Estimate the contributions from different emissions sources to visibility impairment at the Grand Canyon, and quantitatively evaluate the uncertainties of those estimates.

Detailed analysis of field measurements was unable to link elevated sulfate concentrations with MPP emissions. In general, the concentrations of visibility-impairing species seemed to be affected by regional sources and regional meteorology. Several analyses of concentration patterns and of distributions of the PFT and of other natural tracers all concluded that the dominant sources of GCNP visibility impairment were area sources (principally urban) in Southern California, Arizona, and northern Mexico. The Las Vegas urban area was also implicated in some analyses.

Modeling of the MPP contribution by various methods concluded that the 50th percentile impact of MPP emissions to the 12-hour average measured light extinction at Meadview in the summer is between 0.2 and 0.6% with upper bound as high as 1.0%. The 90th percentile impact is between 1.3 and 2.8% with upper bound as high as 5.0%. The shorter term impacts may be, perhaps, twice these values. Contributions at Hopi Point were estimated to be somewhat smaller.

The uncertainties in these values have not been quantified, but the range of results represents the conclusions of four different methods and thus that range can be considered an index of the uncertainty in any particular estimate.

10.5 Reconcile different scientific interpretations of the same data and present this reconciliation to policy-makers.

Initial assessments of the impact of MPP on GCNP extinction differed widely and the models used were not effective at predicting the concentrations of the perfluorocarbon tracer.

Subsequent methods, which relied on the tracer data to provide information on transport and dilution, had better agreement with each other. As the discussion above has indicated, the 50th percentile MPP extinction impact at Meadview was 0.6 ± 0.4% and the 90th percentile impact was 3 ± 2%. Thus all results were within about 70% of a mean value, which indicates that the methods agreed relatively well in this comparison. Unfortunately, comparisons of results at specific locations at specific times did not agree as well as the comparisons of values at the same percentile level.

In light of the good agreement in contribution statistics, the results of all methods have been included in the presentation of study results in this report, with no effort made to assign more or less credibility to any specific method.

10.6 Technical Lessons Learned as a Result of Project MOHAVE

Project MOHAVE reflects the combined efforts of many investigators in many organizations. Although the project was successful overall, not all approaches that were used were successful and some findings indicated that a different measurement or analysis might have been more appropriate. As an epilogue, it may be useful to review some of these lessons learned.

Perhaps the most important technical lessons learned had to do with the benefits and limitations of using tracer technology. Project MOHAVE demonstrated that, contrary to the experience in several previous studies, high quality tracer data for study of the transport and dispersion characteristics of point source emissions can be practically achieved in a large field program. Some of the more useful features of the tracer component of Project MOHAVE are the extensive background (no tracer released) monitoring with collocated samplers to document background variability and measurement precision near background concentrations, and use of collocated sampling during the entire tracer release period at a few sites. Both of these allowed the quality control performance characteristics of the tracer component of the study to be determined.

Without the tracer data the range of results from various source contribution methods would have been substantially larger, the advocates of the various methods would have been energetically defending their results and there would have been no way to establish the crediblity of any of the methods. This in fact happened as part of the preliminary assessment conducted several years after the field study but prior to the release of the tracer data to the analysts, as described in Section 8.1. Comparison of the preliminary analysis methods' predictions of tracer concentration to the tracer measurements demonstrated the poor performance of those methods. These comparisons did not include any consideration of the transformation of SO_2 to sulfate, because the PFT is inert, a limitation that prevents full evaluation of the performance of all modules of the models.

At the time of the evaluation of the preliminary methods, the very low correlation coefficients between predicted and measured tracer (Table 8.1) were given the greatest attention as indicators of this poor performance of the methods. Subsequent to the comparison of the various post-tracer release assessment method results, use of a range of results from the various models' cumulative frequency distributions was adopted because of the inability to resolve which methods were more likely to be correct for sample periods where there were significant disagreements. However, agreement among cumulative frequency distribution curves is a much less rigorous criterion than the correlation criterion applied to the pre-tracer release methods.

Could roughly the same findings have been developed using the preliminary assessment methods' predictions of primary transport of MPP instead of the tracer data? Figure 10-1 and Figure 10-2 show frequency distributions of the preliminary assessment methods' predictions of tracer and measured tracer. They show a range of a results at the 90th percentile of about a factor of 10 at Meadview and 6 at Hopi Point that would replace the estimated combined uncertainty of $\pm$15% for the measured tracer and ratio of tracer to SO_2 in the MPP plume. In other words, the MPP potential impact step in the assessment process would have nearly comparable uncertainty with the SO_2 to particulate sulfate yield step, and the overall results would have been much less credible.

Its interesting to note that the only models in the final analysis that came close to reproducing the cumulative frequency distribution of the measured tracer data at Meadview used wind fields developed from a very high spatial resolution model (<1 km grid spacing). However, these only agree well over about 20% of the time periods and substantially under-predict for 40% or more of the time. At Hopi Point the MCMB estimates have a cumulative frequency distribution that is most nearly like the measured tracer, but is still about a factor of two too low on average. It would have been interesting to have compared the results of the higher spatial resolution models for Hopi Point, but computational limitation precluded such high spatial resolution over the larger domain required to include the more distant site.

Reasons for the poor performance vary depending on the type of assessment method. Inadequate resolution of meteorological data and spatial resolution that is inadequate to account for the terrain are thought to be the principal reasons that air quality models performed poorly. Both during the winter and summer intensive periods, spatial patterns of tracer revealed that terrain channeling of flow is an important phenomenon. Models that cannot correctly simulate flow are unlikely to perform well. There are a greater variety of possible causes for poor performance among the empirical models. For those that quantify source influence to an ambient particle sample by using source compositional characteristics, the possible problems arise from inadequate uniqueness and insufficiently known or non-conserved source characteristics. Spatial analysis methods may have performed poorly due to insufficient spatial data (i.e. insufficient numbers of sites) or substantial vertical gradients of pollutants.

Some of the methods used in the preliminary assessment were ultimately used in the final assessment with some method modification or changed input data. It is not clear that any of the method adaptations employed to improve performance can be generalized and transferred to other situations without tracer data to test performance. As an example consider the experience of the CALPUFF modeler, whose results were improved by using upper air wind data from the radar wind profiler. However, the best performance by CALPUFF came using data from only one of several wind profiler sites. In a different modeling domain or with different source and receptor locations the optimal choice of wind data for input might be different. In other words a future source contribution study in complex terrain conducted without tracer data could not apply the lessons learned in Project MOHAVE with any great assurance that they would improve the results.

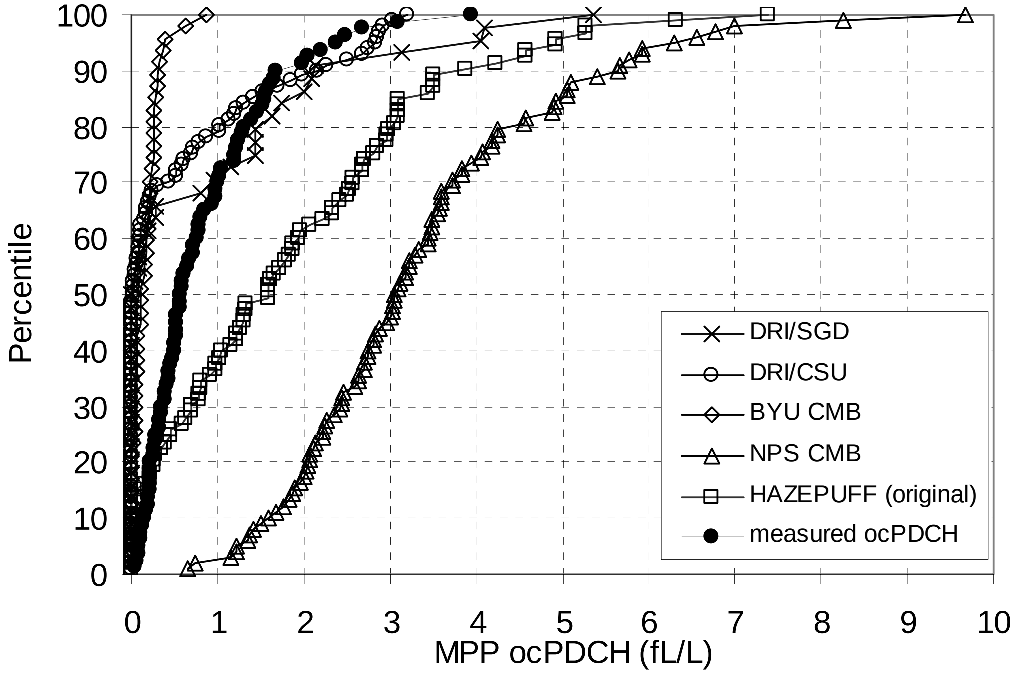

Figure 10-1 Cumulative frequency distributions of predicted and measured ocPDCH concentrations at Meadview for the summer intensive study period. Model predictions were made before the tracer data were available.

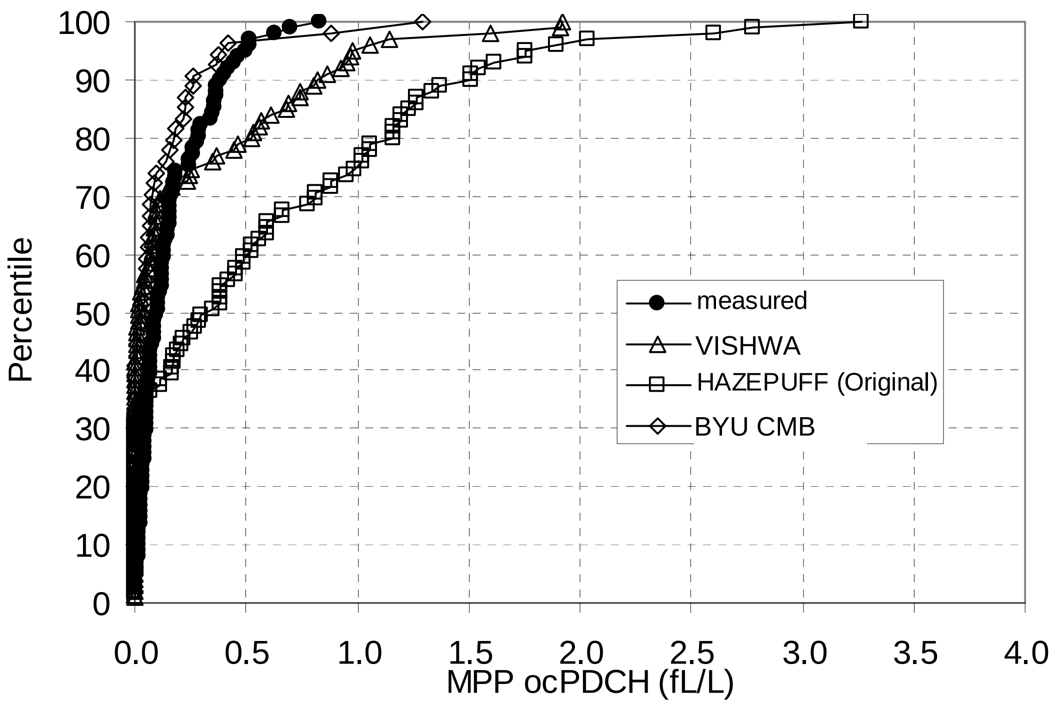

Figure 10-2 Cumulative frequency distributions of predicted and measured ocPDCH concentrations at Hopi Point for the summer intensive study period. Model predictions were made before the tracer data were available.

Availability of tracer data resulted in an expansion of the number of independent contribution assessment methods (i.e., independent assumptions and data requirements) employed. New source contribution methods were developed and applied that used the tracer data as input to account for the primary MPP impact step. The greatest limitation of these methods is the inability to operate except for periods and times with tracer data. The TAGIT assessment method used tracer data in a unique way to merely determine which monitoring locations were being influenced by MPP during any sampling period. To assess the net impact of MPP, TAGIT treated data from the unimpacted sites as background that can be subtracted from the data at MPP impacted sites. Though assessment method results do not agree on a sample period by sample period basis, the use of many independent attribution methods that provided similar distributions of results was an important process for building confidence among the technical analysis team that the range of results was credible.

The dominant cause of the differences between the various methods that were ultimately used for estimating the MPP contribution appears to be the representation of the chemistry of sulfate formation in clouds, and the related parameterization of such factors as amount of time spent in clouds. Project MOHAVE provided little experimental data to use as inputs for such calculations or to use for checking outputs, a limitation that has also been present in several other recent source attribution studies.

Consequently, the particulate sulfate yield from the MPP SO_2 emissions is the greatest source of uncertainty in the findings. Unfortunately, use of tracers did nothing to reduce this uncertainty for Project MOHAVE. If the MPP contributions had been a much larger fraction of the particulate sulfate, it might have been possible to detect a relationship between tracer and sulfate concentrations that could have shed some light on the typical yield. In future studies, high time resolution tracer data might be used to show a relationship to high time resolution SO_2, particulate sulfate and nephelometer data at a receptor site and allow a substantial insight into the conversion issue. By having high time resolution data of that type at several sites near the receptor sites, a TAGIT approach would have a much-improved chance to use spatial gradients to explore particulate sulfate yield.