In recognition of the value of good visibility in areas set aside for their scenic splendor, Section 169A of the 1977 U.S. Clean Air Act Amendments established a national goal of remedying existing visibility impairment and preventing future visibility impairment resulting from man-made air pollution emissions at 156 national parks and wilderness areas, referred to as visibility-protected federal Class I areas (see Figure 1). Particulate matter (PM) is the principal air pollutant responsible for visibility impairment through the scattering of light by both fine (PM$_{2.5}$) and coarse (PM$_{10-2.5}$) particles and through the absorption of light by black carbon particles.

The U.S. Environmental Protection Agency (EPA) issued initial visibility regulations in 1980$^1$ that address visibility impacts that could be “reasonably attributed” to individual emissions sources. In 1999, EPA issued further regulations, known as the Regional Haze Rule (RHR),$^2$ that address visibility impairment over a broad geographic region that is attributable to emissions from multiple sources. The RHR calls for each state to adopt emissions control strategies that would reduce haze at every Class I area impacted by its emissions (even if the area is in another state) on the 20% haziest days at that area, without degrading visibility on the 20% clearest days.

This concept is illustrated in Figure 2. The degree of haziness is represented by a haze index, in units of deciviews, which increases with the degree of visibility impairment and in which equal increments are intended to represent approximately equally perceptible changes in visibility. The straight solid diagonal line represents the “uniform rate of progress” (in deciviews) from five-year (2000–2004) baseline visibility conditions to the natural visibility conditions goal in 2064. States must establish a “reasonable rate of progress” toward the national visibility goal for each Class I area by considering the uniform rate of progress and then factoring in the cost, time, and other consequences associated with the requisite emissions controls needed to attain that rate of progress.

The first RHR-required State Implementation Plans (SIPs), which address the emissions strategies for the first phase of haze mitigation (up to 2018), are due at the end of 2007. During the course of the 60-year program, the performance of the emissions controls in yielding visibility improvements at the state-selected reasonable rate of progress is to be evaluated every five years and emissions reduction strategies are to be revised (and new SIPs submitted) every 10 years.

**QUANTIFYING THE HAZE**

Instead of characterizing the haze by means of an optical measurement, the RHR calls for measuring aerosol species concentrations to estimate average daily haze levels. This estimate is possible because particle sizes, composition, and concentrations affect the amount of light that is scattered and absorbed by particles. The combined effect constitutes particle light extinction, which is
defined as the fraction of light that is attenuated over a unit distance (typically expressed as per million meters [Mm⁻¹]). The amount of particle light extinction is estimated by multiplying the concentration of each of the major components of PM (i.e., fine sulfates, nitrates, organics, black carbon, fine soil, coarse matter, and sometimes fine sea salt) by an extinction efficiency factor that accounts for the typical particle size and composition of each component. The extinction efficiency represents the amount of light extinction per unit mass concentration of the component under the assumed conditions. The light extinction contributions by each component can then be summed to get a measure of the total extinction by the haze.

Two formulas, both of which represent a combination of theoretical insight and measured information, are being used for this purpose in the current RHR planning cycle: (1) the original IMPROVE algorithm, which has been in use for more than a decade and is described in EPA regional haze guidance documents; and (2) a refined IMPROVE algorithm developed in 2005, which incorporates recent improvements in understanding of the optical effects of the aerosol.

Depending on the form of the IMPROVE algorithm that is used, the extinction efficiency factors are considered either constants or functions of concentration for most PM components. They also increase with increasing ambient relative humidity for sulfates, nitrates, and sea salt. Under low relative humidity conditions, the most efficient PM species is black carbon (also called elemental carbon or soot); organic carbon is the next most effective; while particulate sulfate and nitrate are even less efficient at low relative humidity, but by 90% relative humidity their extinction efficiency increases greatly and can considerably exceed that of black carbon.

In general terms, the eastern United States is hazier than the West. Rural haze in the East is dominated by particulate sulfate, while the less-hazy rural atmosphere in the western United States results from more even contributions of particulate sulfates, nitrates, organic and elemental carbon, and dust (i.e., fine soil and coarse matter). Moore and Brewer discuss the implications of regional differences on the approaches needed to improve visibility in the following article in this issue (see page 13). For a thorough discussion of visibility science and of the history of the regulation of visibility, see the 2002 A&WMA Critical Review by Watson.

**NATURAL CONDITIONS**

The haze at any Class I area is caused by aerosol from both natural and anthropogenic sources; the contribution from each of those sources can, in turn, be divided...
into a portion that is from sources in the United States (the “local domestic” portion) and a portion that is from sources outside the United States (the “transported” portion). As the matrix in Figure 3 shows, only one of those four categories (local domestic, anthropogenic) is amenable to emissions reduction via actions taken in the United States. The other three categories (local domestic, natural; transported, natural; and transported, anthropogenic) are either beyond the political jurisdiction of the United States or are of natural origin.

The total aerosol from these three categories can be considered to represent uncontrollable contributions to visibility impairment, which reflect the atmosphere at the Class I areas in the absence of any U.S. anthropogenic emissions, but in the presence of anthropogenic emissions transported from sources in other countries. These uncontrollable background conditions differ from the natural conditions goal for the RHR, which is considered to be the atmospheric state where the visibility would be imperceptibly different from that which would exist in the absence of any man-made emissions anywhere in the world.

Examples of transported emissions from natural sources that have been observed to have significant impact on visibility in the United States include smoke from agricultural fires in Central America and wildfires in Canada, and dust from the Sahara Desert in Africa and the Gobi Desert in Asia. Effects of transported anthropogenic emissions have been observed from Mexican, Canadian, and Asian cities and industry, and from oceanic shipping lanes.

In this light, the national visibility goal is an ambitious goal that is not likely to be fully achieved due to impacts from man-made pollutants emitted beyond U.S. borders and residual impacts from domestic emissions that are beyond achievable control. However, the general perception is that most, if not all, Class I areas currently have visibility impacts caused by controllable U.S. pollution emissions, and substantial decreases in haziness are therefore feasible.

The regional haze mitigation process is shown in Figure 4, where hypothetical reductions in U.S. anthropogenic emissions in various source sectors over the next 60 years result in reductions in haze until ideally (but perhaps not realistically) the natural conditions goal is reached. To minimize the effects of interannual variations in haze caused by meteorology and emission episodes such as wildfires, tracking of progress under the RHR is done using five-year averages.

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Estimating what the natural conditions goal might be is far from straightforward because today virtually
Table 1. EPA’s default natural conditions concentrations and corresponding dry extinction values, as calculated using the traditional IMPROVE algorithm.

<table>
<thead>
<tr>
<th>Component</th>
<th>Average Concentration (µg/m³)</th>
<th>Trijonis’ Error Factor</th>
<th>Dry Extinction Efficiency (m²/g)</th>
<th>Dry Extinction (Mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium sulfate</td>
<td>0.12</td>
<td>2</td>
<td>3</td>
<td>0.36</td>
</tr>
<tr>
<td>Ammonium nitrate</td>
<td>0.10</td>
<td>2</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>Particulate organic matter</td>
<td>0.47</td>
<td>2</td>
<td>4</td>
<td>1.88</td>
</tr>
<tr>
<td>Black carbon</td>
<td>0.02</td>
<td>2 – 3</td>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td>Soil</td>
<td>0.50</td>
<td>1.5 – 2</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Coarse matter</td>
<td>3.0</td>
<td>1.5 – 2</td>
<td>0.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Sum</td>
<td>4.21</td>
<td>1.5 – 2</td>
<td>5.04</td>
<td>9.08</td>
</tr>
</tbody>
</table>

every location on the globe is to some degree impacted by man’s emissions. In 1990, in connection with the U.S. National Acid Precipitation Assessment Program, Dr. John Trijonis estimated average natural background concentrations of visibility-impairing pollutants for the eastern United States and for the mountain/desert regions of the West. He derived his results by analyzing measurements in remote areas, considering the chemical composition of the aerosol, and examining results from regional air quality modeling. EPA has expanded the region of applicability of Trijonis’ natural background concentrations to cover the entire country and has adopted them as default values that can be used by the states for planning purposes (see Table 1).

The default values in Table 1 are only crude approximations of the averages for any given Class I area because they do not vary with location or topography, and have considerable uncertainty (note the error factors), but nevertheless serve as useful starting points for defining the 2064 regional haze end point. Interestingly, as our understanding of the aerosol in Class I areas has improved, many of the default values have turned out to be quite robust.

Since the emissions management strategy of the RHR is based on the 20% haziest days, statistical approaches have been developed to construct synthetic frequency distributions of concentrations under natural conditions, from which the 20% haziest days under natural conditions can be postulated.

Recent research has provided insights on natural conditions that were not available to Trijonis. For example, improved understanding of the formation and composition of organic aerosol is showing that most of the rural organic aerosol tends to be of natural origin (although anthropogenic acids may catalyze aerosol production beyond natural levels), while global photochemical air quality modeling is beginning to provide credible estimates of regional air pollutant concentrations with various types of anthropogenic emissions turned off. Also, considerable research on background aerosol by the global climate change research community in the past decade has produced a wealth of information about the aerosol in remote areas that is useful for estimating natural conditions. Therefore, before the next regional haze planning cycle begins in less than a decade, the natural conditions question should be revisited, with the goal of developing new, more refined, and spatially more detailed natural conditions estimates to replace the current default values.

**PERSPECTIVES AND EXPECTATIONS**

The regional haze program differs from other national pollution management programs in several important ways.

The program laid out under the RHR rule is a prototype of one that meets the objectives the National Research Council published in a major assessment of U.S. air quality management practices in 2004. The long-term objectives recommended in that assessment included taking an integrated multipollutant approach to controlling emissions and dynamically adjusting and correcting the system as data on progress are assessed. These objectives are satisfied in the regional haze program. The IMPROVE formula explicitly identifies the multiple pollutants of concern (or the products of those pollutants) and provides a basis for a multipollutant control strategy. The five-year progress checks and 10-year plan revisions in the RHR reflect the desired dynamic adjustments and corrections.

Unlike other federal air quality regulations where EPA provides a specific, well-quantified standard that is uniform across the country, the RHR requires states to make progress toward a conceptual goal that is expected to vary by location and over time. EPA has provided nominal Class I area-specific natural haze level values that are admittedly
Table 2. The five RPOs and their visibility information exchange data site.

<table>
<thead>
<tr>
<th>Name</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>WRAP — Western Regional Air Partnership; <a href="http://www.wrapair.org">www.wrapair.org</a></td>
<td>All five RPO Web sites contain the organizational structure, plans, projects, reports, and links to other sites with additional information.</td>
</tr>
<tr>
<td>CENRAP — Central Regional Air Planning Association; <a href="http://www.cenrap.org">www.cenrap.org</a></td>
<td>MANE-VU works in close cooperation with the Northeast States for Coordinated Air Use Management (NESCUM; <a href="http://www.nescaum.org/topics/regional-haze">www.nescaum.org/topics/regional-haze</a>) and the Mid-Atlantic Regional Air Management Association (MARAMA; <a href="http://www.marama.org/visibility">www.marama.org/visibility</a>).</td>
</tr>
<tr>
<td>MRPO — Midwest Regional Planning Organization; <a href="http://www.ladco.org">www.ladco.org</a></td>
<td>VIEWS contains all IMPROVE data and most other speciated PM data, RHR-compatible derived parameters, and user-friendly tools to summarize and display data.</td>
</tr>
<tr>
<td>VISTAS — Visibility Improvement State and Tribal Association of the Southeast; <a href="http://www.vistas-sesarm.org">www.vistas-sesarm.org</a></td>
<td></td>
</tr>
<tr>
<td>MANE-VU — Mid-Atlantic/Northeast Visibility Union; <a href="http://www.manevu.org">www.manevu.org</a></td>
<td></td>
</tr>
<tr>
<td>VIEWS — Visibility Information Exchange Web Site; <a href="http://vista.cira.colostate.edu/views">http://vista.cira.colostate.edu/views</a></td>
<td></td>
</tr>
</tbody>
</table>

crude, though states are permitted to refine them. EPA calls for states, in consultation with federal land managers, to develop emissions control plans to show progress toward implementation of a long-term goal. By requiring states to determine a reasonable rate of progress for each Class I area, EPA is, in effect, permitting them to set individual standards for each area, which can then be refined on a decadal schedule. The nominal 60-year period suggested by the RHR for reaching the goal, when combined with required periodic technical assessments and presumed advances in air quality assessment and emissions control technology, offers the ability to refine our understanding of natural conditions and an improved likelihood that we can more nearly meet the goal.

In a sense, the RHR outsourced to the states the setting of regional haze standards for each Class I area, as well as the development of approaches for reaching them. In 2001, EPA established five Regional Planning Organizations (RPOs) to serve as centers for conducting the coordinated RHR technical assessments and policy development required in each region of the United States (see Table 2). The RPOs have generated an enormous amount of new information through additional monitoring, extensive data analyses, improved emissions inventories, and the use of global- and continental-scale air quality simulation modeling.

For example, models have shown that for western Class I areas, most of the carbonaceous particle-caused haze is from biogenic smoke from wildfire (natural haze). Assessments of the composition of crustal PM and airflow patterns have been used to identify and quantify Asian and African dust impacts and separate them from regional windblown dust and local sources. Global air quality modeling has provided boundary conditions for continental modeling that are being used to quantify the haze contributions from beyond U.S. borders.

While the information developed by the RPOs can be used to address many of the issues for the first round of RHR SIPs, future challenges remain. Among these are the inevitable escalating costs and difficulties of reducing man-made emissions to near zero to reach the visibility goal, growth of impacts from expanding international emissions, and the possible effects of climate change on the frequency and magnitude of dust and smoke caused haze. The solution to such challenges is not currently apparent. However, the 60-year schedule of the RHR provides the time needed for our knowledge and technology to improve. In addition, there will need to be a commitment by EPA and the states to continue supporting technical assessment activities after the imminent round of RHR SIP submissions.

REFERENCES

1. 45 Fed. Regist. 80084 (December 2, 1980).
2. 64 Fed. Regist. 35715 (July 1, 1999) and 40 CFR 51.300-309.

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