Virginia Mercury Study

A Report to the Honorable Timothy M. Kaine, Governor and the House Committee on Agriculture, Chesapeake and Natural Resources and the Senate Committee on Agriculture, Conservation and Natural Resources

Virginia Department of Environmental Quality

Revised October 21, 2008

Report Revisions

This report has been revised due to corrected information received from ICF, Resources, LLC on October 20, 2008.

Appendix A has been updated by ICF, Resources, LLC.

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List of Acronyms and Abbreviations

ACI - Activated Carbon Injection
AERMOD- AMS/EPA Regulatory Model
APC - Air Pollution Control
B-PAC - Brominated Powdered Activated Carbon (product name from Sorbent Technologies Corp, Twinsburg, OH)
CAIR- Clean Air Interstate Rule
CAMR- Clean Air Mercury Rule
CAVR- Clean Air Visibility Rule
CMAQ- Community multiscale air quality model
CS-ESP - Cold-side Electrostatic Precipitator
DEQ- Department of Environmental Quality (Virginia)
DGIF- Department of Game and Inland Fisheries (Virginia)
DOE- U.S. Department of Energy
EGUs- Electric Generating Units
EPA- U. S. Environmental Protection Agency
EPRI - Electric Power Research Institute
ESP - Electrostatic Precipitator
g/km^2- grams per square kilometer
FF - Fabric Filter (baghouse)
FGD - Flue Gas Desulfurization
FIP- Federal Implementation Plan
GDP- Gross Domestic Product
Hg- Mercury
HGP- particulate mercury
HG2- reactive gaseous mercury
HG0- elemental mercury
HS-ESP - Hot-side Electrostatic Precipitator
IC/BC- Initial condition/boundary condition
ICF- ICF Resources, LLC
IECM - Integrated Environmental Control Model
Kw-hr - Kilowatt per hour
MDN- Mercury Deposition Network
MW - Megawatt
NEI- National Emission Inventory
NETL - National Energy Technology Laboratory
NLSY- National Longitudinal Study of Youth
NOx - Nitrogen Oxides
NRC- National Research Council
PAC - Powdered Activated Carbon
PADEP - Pennsylvania Department of Environmental Protection
PM - Particulate Matter
ppm- parts per million
PPTM- Particle and precursor tagging methodology

PS - Particulate Scrubber
R&D - Research and Development
RfD- Reference Dose
RFP- Request for Proposal
SAPCB- State Air Pollution Control Board
SCR - Selective Catalytic Reduction
SDA - Spray Dryer Absorber
SDA/FF - Spray Dryer Absorber with downstream Fabric Filter
SEA - Sorbent Enhanced Additive
TMDL-Total Maximum Daily Load
ug/m^2 – micrograms per square meter
USGS - United States Geological Survey
VDH- Virginia Department of Health
VCU-CES Virginia Commonwealth University Center for Environmental Studies

EXECUTIVE SUMMARY

This report has been prepared pursuant to the requirements of Chapter 867 of the 2006 Acts of Assembly (House Bill 1055). The Act directs the Department of Environmental Quality (DEQ) to conduct a detailed assessment of mercury deposition in Virginia in order to determine whether particular circumstances exist that justify, from a health and cost and benefit perspective, requiring additional steps to be taken to control mercury emissions within Virginia. The assessment included (i) an evaluation of the state of mercury control technology for coal fired boilers, including the technical and economic feasibility of such technology and (ii) an assessment of the mercury reductions and benefits expected to be achieved by the implementation of the Clean Air Interstate Rule (CAIR) and Clean Air Mercury Rule (CAMR) regulations. An interim report was provided by DEQ in October 2007 that provided a status report on the assessment. The interim report is available at http://www.deq.virginia.gov/export/sites/default/regulations/pdf/2007statusofhgstudy.pdf.

DEQ used a contractor experienced with performing mercury deposition modeling to assist with identifying the mercury reductions and benefits to be achieved in Virginia as a result of implementation of the CAIR and CAMR. The analysis DEQ performed differed from the analysis the U.S. Environmental Protection Agency (EPA) performed for the CAMR. As part of Virginia's study, the emission inventory for sources in Virginia was reviewed and modified to reflect the most up-to-date information concerning mercury emissions from stationary sources located within Virginia. Additionally, ICF worked with electric generating units (EGUs) to obtain information on the specific pollution control equipment industry plans to install in the future and the predicted emission reductions related to the installation and operation of those pollution control tools. In contrast, EPA's analysis made general assumptions concerning future controls and associated mercury reductions without obtaining information on facilities' future plans from industry. Virginia's report also focuses more closely on impacts to Virginia fish, the number of fish consumption advisories issued for Virginia fish and the potential for reduced fish advisories in the future as a result of less mercury deposition occurring in Virginia waters.

This study began in 2006 once the regulatory details of CAIR and CAMR were known. In February 2008, the U. S. Circuit Court of Appeals for the District of Columbia issued an opinion vacating CAMR. In July 2008 the U. S. Circuit Court of Appeals for the District of Columbia issued an opinion vacating the CAIR. Although the D.C. Circuit recently issued opinions vacating CAIR and CAMR, the agency has continued to move forward with completion of the report pursuant to the requirements and direction of House Bill 1055. As directed, this report examines modeling results anticipated to be achieved through the implementation of CAIR and CAMR requirements. Any reductions of mercury deposition and average mercury fish tissue concentrations identified in this report are based on modeling results and may not ultimately be achieved.

Mercury Deposition Modeling

The mercury deposition modeling conducted by ICF used data from the years 2001 and 2002 to develop a baseline year estimate for mercury deposition occurring in Virginia and surrounding states. This baseline year estimates the mercury deposition occurring before implementation of CAIR and CAMR. Modeling was performed to estimate the deposition of mercury occurring in

2018, after CAIR and CAMR had been implemented. The modeling conducted for this study indicates overall mercury deposition for Virginia would be lower by 20.4 percent for 2018, when compared to the base year. The greatest reduction in deposition comes from EGU sources located outside of Virginia (in the 12-km modeling domain that encompasses several nearby states), and 61 percent of the reduction in mercury deposition for Virginia is attributable to reductions in emissions from EGU sources in these nearby states. In addition, 7.2 percent of the overall simulated mercury reduction for Virginia is attributable to reductions in the emissions from EGU sources located within the state, 5.7 percent is attributable to reductions in the emissions from non-EGU sources in the state, 4.6 percent is attributable to reductions in non-EGU sources in nearby states, and 2.8 percent is attributable to emissions reductions in the remainder of the United States.

Fish Tissue Impacts

After examining the reductions of mercury deposition predicted to occur in Virginia as a result of implementation of measures to comply with CAIR and CAMR, there may be reductions in the number of mercury fish consumption advisories in place within Virginia. Of the 13 mercury-sensitive waterbodies in Virginia with current fish consumption advisories due to mercury contamination, the fish mercury levels may be lowered enough in the future (to below the 0.5 parts per million (ppm) mercury level currently used by the Virginia Department of Health (VDH)) such that three or four of these advisories may no longer be warranted. In all but two of the advisory areas, at least one species of fish may have reduced mercury levels in the future that could allow for its removal from the fish consumption advisory and in one case, (Dismal Swamp Canal), the advisory area may be reduced. Under the projected reduced air deposition rates for the future, nine to 10 of the current fish consumption advisories will likely remain in place for at least one species of fish.

It will take time for any reductions in mercury deposition to be reflected in fish tissue samples because the ecosystem must readjust to the lower mercury levels in the environment. Each individual water body will react slightly differently due to natural variances in the chemical and physical conditions and differences in food web structure. Lakes are expected to respond quickest (within a few years to decades) to reduced mercury deposition, with wetlands requiring more time to equilibrate to the lowered mercury inputs.

The DEQ has proposed the adoption of a fish tissue criterion for mercury of 0.30 ppm, which is lower than the fish tissue mercury level used by the VDH to determine when fish consumption advisories are issued. If the State Water Control Board adopts this criterion, waterbodies with average fish concentrations greater than 0.30 ppm will be classified as impaired. Even though reductions in mercury deposition may occur and some fish consumption advisories may be removed, the waterbodies examined in this study could remain classified as impaired by DEQ if average mercury concentrations for at least one species of fish remain higher than 0.30 ppm.

Cost Benefit Analysis

Virginia coal-fired power plants vary in the amount and type of mercury control equipment installed. Currently, all Virginia coal-fired power plants burn a low-sulfur, low-mercury, and high-chlorine bituminous coal, and most of the plants also burn coal that has been initially washed and processed after mining. Furthermore, some of the plants have technologies already in place to control nitrogen oxide (NO_x), sulfur dioxide (SO_2) and particulate matter (PM). As a result, a certain level of mercury (Hg) removal is achieved as a co-benefit of these controls; this report attempts to capture the costs of mercury control (costs of control technologies and also possible costs of control levels).

The costs of mercury control at coal-fired power plants are affected by a number of parameters, including what technologies are chosen, what regulations are in place, and the market-based determination of demand versus supply of energy. A number of options for reducing mercury emissions from coal-fired power plants are commercially available, and others are being developed. A number of control technologies for the reduction of mercury are available to coal-fired power plants, allowing the facility to choose the best fit in terms of cost-effectiveness. The DEQ cost assessment was based on a thorough review of existing and future projected mercury controls by Virginia-based electric generating units. Specifically, best available information on control technologies (performance, constraints, market prices of inputs and by-product disposal estimates) was used in this analysis. The results support the view, which is widely held by EPA, the U.S. Department of Energy (DOE), industry research and other state agencies, that mercury control is more cost-effective if coal-fired power plants adopt a multi-pollutant, post-combustion control technology sequence.

Fish Consumption Trends in Virginia's Waterways

As part of this study, DEQ contracted with Virginia Commonwealth University's Center for Environmental Studies (VCU-CES) to obtain Virginia-specific fish consumption data collected in areas where mercury fish consumption advisories are in effect. Additionally, VCU-CES was tasked with estimating the associated health risks from resulting methylmercury exposures. VCU-CES developed a fish consumption survey, and worked with DEQ staff to identify the launching and fishing locations where anglers could be surveyed. The survey was designed to obtain information on fishing behaviors, fish consumption, and demographic data on the anglers and families. During the summer of 2007, a team from VCU-CES administered the survey to 158 anglers at boat launching and fishing sites. Surveys were completed for anglers who were fishing at 17 locations on 5 rivers: the James River below Richmond, the Chickahominy, Pamunkey, Mattaponi, and upper Piankatank rivers. These rivers are affected by methylmercury contamination, have been surveyed in previous, similar investigations and are used by anglers for recreational fishing.

The surveys were administered to anglers predominantly on Friday, Saturday or Sunday. Approximately 44 percent of all respondents and their families consume the fish that they catch from these waters. Half (50 percent) of the anglers only, not family members, consume some fish that they catch, and more men (54 percent) than women (43 percent) were reported to consume the fish with elevated methylmercury levels. The most commonly consumed fish were catfish, spot or croaker, sunfish and largemouth bass; catfish and largemouth bass are two of the species on the fish consumption advisory. Catfish also represented the largest number of meals and total amount of self-caught fish consumed per year.

The data on fish consumption were analyzed with DEQ data on methylmercury concentrations in fish that had been collected in previous years to estimate the amount of methylmercury consumed in fish yearly. In order to estimate total methylmercury from all fish consumption, canned tuna and purchased fish consumption were added to mercury exposures from self-caught fish. Mercury levels in tuna and purchased fish were taken from national data.

The methylmercury exposures determined from survey data and DEQ fish tissue levels were compared to the dose of mercury exposure that EPA has set (and the VDH uses) as the dose without appreciable health risks.

The analysis of the fish consumption and fish tissue concentrations was performed using a probabilistic computer program that is used for risk assessments. This program randomly selects certain values, as defined, to use in the equations for determining total mercury from all fish consumed. The analysis indicates that a significant number of anglers who regularly catch and consume significant amounts of catfish and large mouth bass from the affected waters are exposed to methylmercury at levels above the EPA reference dose.

Using the information obtained from various statistical methods, VCU-CES modeled the loss of IQ points from prenatal exposure to methylmercury through the maternal diet, specifically mercury from consumption of mercury-contaminated fish. To model the loss of IQ points from prenatal exposure to methylmercury through the maternal diet, the target population of interest is women of childbearing age. With the survey results and fish mercury concentrations from DEQ's fish tissue database, a probability distribution of ingested doses was created. Based upon the estimated maternal exposure to current fish mercury concentrations, the VCU-CES study estimated future levels of IQ changes due to 2010 and 2018 levels of mercury controls to result in average (mean) avoided IQ deficits of 0.03 IQ points.

<u>Monetization of Human Health Risk Effects (IQ level)</u>

This report attempts to quantify and monetize, to the extent feasible, the economic benefits associated with modeled avoided IQ deficits due to reduced exposure from the consumption of recreationally caught freshwater fish. The monetization of the human health risk effects (IQ being the human health effects of measurement) builds upon the findings of the VCU-CES study (Appendix B) and adopts the approach used by EPA to conduct the economic benefit analysis at the federal level (U.S. EPA 2005). This regional assessment focused on estimating the changes in exposures to women of childbearing age because adverse health effects in children have been linked to prenatal mercury exposures (Sorenson et al. 1999). This report builds on the VCU-CES study that focused on select counties of eastern Virginia where fish advisories for mercury existed and using consumption surveys, where IQ losses were estimated. IQ losses were then monetized to evaluate the economic benefit of mercury emission controls (or impacts of no reduction in emissions).

EPA's CAMR analysis indicated a monetized impact of $15 million solely due to power plant emissions over the entire United States (3 percent discount rate and Year 2000 dollars); however, such an analysis is not representative of Virginia, Virginia-specific individual consumption patterns and DEQ's fish tissue data. The DEQ assessment used 10 years of birth data for only the select counties where fish consumption patterns were surveyed to quantify economic impacts associated with average avoided IQ deficits of 0.03 IQ points found in the VCU-CES study and associated with methylmercury consumption through 2010 and 2018. Economic losses to the exposed populations of interest involved an assessment of two scenarios – worst-case and most likely. Under the worst case scenario, the estimated net per capita income earning loss to children is $337.00, or $4.8 million across all 14,364 children born in the select counties. Under the "most likely" scenario, it was estimated that 6,104 pre-natal children (i.e., less than half of the 14,364 children born in the select counties) would be exposed to methylmercury and would thus have net income losses totaling $2.05 million. The two monetized scenarios are estimates of impacts for areas where risk assessment of methylmercury exposure due to fish consumption was undertaken.

Conclusions

As a result of conducting this study, specific information concerning mercury deposition in Virginia was obtained. Excluding background and natural sources of mercury, the largest percentage of mercury deposition within Virginia originates from EGUs in surrounding states (54 percent). The next largest geographic source contributing to mercury deposition in Virginia is EGUs located within Virginia (14 percent). Non-EGUs in surrounding states contribute to 13 percent of the deposition occurring within Virginia, and in-state non-EGUs contribute to 12 percent of the deposition occurring within Virginia.

As part of the mercury modeling conducted by ICF, emissions and deposition information from the 15 largest mercury emitters in the state was modeled using the AERMOD model to examine the direct impact these facilities have on the area within a three km area surrounding each source. This analysis yielded three key findings: (1) dry deposition is greater than wet deposition for all facilities, (2) maximum wet deposition tends to occur at locations closest to the facility, and (3) maximum dry deposition tends to occur farther away from the facility location. The AERMOD model also corroborated the findings of the regional-scale modeling. Specifically, individual facilities located in Virginia contribute to mercury deposition within the state, and the greatest impacts from the in-state sources are simulated near the source locations. This includes EGU sources and non-EGU sources.

As mercury deposition into waterbodies is reduced, each individual waterbody is expected to react slightly differently due to natural variances in the chemical and physical conditions and differences in food web structure. Lakes are expected to respond the most quickly (within a few years to decades) to reduced mercury deposition, with wetlands requiring more time to equilibrate to the lowered mercury inputs.

The VDH issues fish consumption advisories when average concentrations of mercury in fish exceed 0.50 ppm. Under the projected reduced mercury air deposition rates for the future, nine to 10 of the current fish consumption advisories will likely remain in place for at least one species of fish. The DEQ has recently proposed the adoption of a fish tissue criterion for mercury of 0.30 ppm, which is lower than the threshold concentration used by the VDH to issue fish consumption advisories. If the State Water Control Board adopts this fish tissue criterion for mercury, in the future DEQ may classify some waterbodies as impaired due to elevated mercury contamination in fish before the VDH would find it necessary to issue a fish consumption advisory.

Chapter 1- Introduction

Background

Human exposure to mercury is most commonly associated with the consumption of contaminated fish. Due to measured high levels of mercury in fish, at least 44 states have, in recent years, issued fish consumption advisories. These advisories may suggest limits on the consumption of certain types of fish or they may recommend limiting or not eating fish from certain bodies of water due to unsafe levels of mercury. States have identified more than 6,000 individual bodies of water as mercury-impaired and have issued mercury fish advisories for more than 2,000 individual bodies of water. Prior to 2002, significant mercury impairment of Virginia surface waters was known to affect only three rivers (the North Fork of the Holston River, the South River, and the South Fork of the Shenandoah River) with historic industrial releases. Since that time, however, state monitoring has identified impairment of a number of surface waters without readily identifiable sources of mercury releases.

Virginia expanded its mercury monitoring in 2002 based on an increasing scientific understanding of mercury's environmental chemistry and discoveries in other states (e.g., Florida and Maryland) of mercury pollution in waterbodies without direct source releases. The 2002 monitoring effort focused on rivers of the coastal plain, mostly to the east of I-95. As a result of this effort, Virginia found elevated mercury levels in some fish in the Blackwater River, the Great Dismal Swamp Canal, the Dragon Run Swamp and the Piankatank River. Consistent with findings from Florida and elsewhere, these waterbodies in Virginia possess characteristics favorable to the formation of methylmercury, the highly bio-accumulative form of mercury. These characteristics include low dissolved oxygen, high organic matter and low pH, and are most prevalent in "backwaters" of the southeastern portion of the Commonwealth.

The primary source of mercury to these waterbodies is suspected to be atmospheric deposition. Historically, there were three Mercury Deposition Network (MDN)[1] sites in Virginia located in the Shenandoah National Park, Culpeper[2], and Harcum. Data from these sites have contributed to DEQ's understanding of the regional characterization of mercury transport and deposition throughout the state. Additional monitoring at the Harcum site in 2005 revealed that dry deposition of reactive gaseous (divalent) mercury along the Piankatank River (near the Chesapeake Bay) and in upstream areas is an important contributor to the high mercury levels observed in the water and fish in the area. Global, regional and local sources of mercury emissions contribute to the deposition; therefore, understanding these contributions is an important step toward identifying measures that will effectively reduce mercury deposition and environmental mercury levels.

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[1] The Mercury Deposition Network (MDN) is the mercury wet-deposition monitoring arm of the National Atmospheric Deposition Program (NADP). The NADP is a cooperative monitoring program comprised of federal and state agencies, academic institutions, Native American tribal governments and private organizations.

[2] The Culpeper site, which had been funded by the United States Geological Survey, was shut down at the end of 2006 due to lack of funding.

Objectives

The second enactment clause of HB 1055 (2006) provides:

> That the Department of Environmental Quality shall conduct a detailed assessment of mercury deposition in Virginia in order to determine whether particular circumstances exist that justify, from a health and cost and benefit perspective, requiring additional steps to be taken to control mercury emissions within Virginia. The assessment shall also include (i) an evaluation of the state of mercury control technology for coal-fired boilers, including the technical and economic feasibility of such technology, and (ii) an assessment of the mercury reductions and benefits expected to be achieved by the implementation of the CAIR and CAMR regulations. The Department shall complete its preliminary assessment as soon as practicable, but not later than October 15, 2007, and shall report the final findings and recommendations made as a result of the assessment to the Chairmen of the House Committee on Agriculture, Chesapeake and Natural Resources and the Senate Committee on Agriculture, Conservation and Natural Resources as soon as practicable, but no later than October 15, 2008.

In response to this mandate, Virginia-specific mercury emissions inventory data was compiled, verified and utilized to perform a comprehensive mercury deposition modeling analysis. Both the data analysis and modeling components were intended to examine and quantify the contribution of regional and local emissions sources to mercury deposition throughout the Commonwealth, and to provide information to support further analysis of the impact of mercury deposition on the environment.

For each of the bodies of water listed as impaired by Virginia, the Clean Water Act calls for the calculation of a Total Maximum Daily Load (TMDL). TMDLs identify the pollutant reductions or limits that are needed in order to achieve water quality standards. TMDLs must also allocate the reductions to the different sources of pollution, including air sources. Thus, another key objective of the data and modeling analyses is to provide information that will enable DEQ to conduct TMDL studies.

Finally, the results of this study are being used to support DEQ's evaluation of available measures to reduce mercury emissions in Virginia. Specifically, the data analyses and modeling have allowed DEQ to evaluate the effectiveness of selected control measures and support the development of management strategies for meeting water quality criteria and protecting human health.

Initial Steps and Preliminary Information

DEQ identified the largest emitters of mercury in the Commonwealth and in August 2006 sent letters to 75 industrial facilities in Virginia requesting estimated mercury emissions for calendar years 2002 and 2005. The facilities chosen for this request were the largest known mercury emitters in Virginia. Information received from each of the facilities was used to estimate future-year emissions. The future-year estimates were then used in the air quality modeling and deposition analysis. In order to assess the mercury reductions and benefits expected to be achieved by the implementation of the Clean Air Interstate Rule (CAIR) and the Clean Air Mercury Rule (CAMR) regulations, DEQ staff issued a Request for Proposal (RFP) on September 25, 2006, for a detailed assessment of mercury deposition in Virginia. The scope of the RFP included an analysis of mercury air emissions data and an assessment of mercury deposition modeling, as well as the development of information on the human health risks from consuming methylmercury contaminated fish.

In February 2007, two contracts were awarded for the assessment. One contract was awarded to ICF Resources, LLC (ICF), for work on the mercury emissions data analysis and deposition modeling portions of the study. Specifically, ICF conducted mercury deposition model simulations to be used by DEQ to examine:

1. Air deposition as a contributor of mercury to Virginia's impaired waterbodies and other mercury sensitive waters;
2. Impacts of emissions from Virginia's electric generating units (EGUs) on mercury deposition in Virginia, including an evaluation of the benefits of CAMR and other federal and state programs which may impact or reduce mercury emissions;
3. Contributions of Virginia's non-EGUs to mercury deposition in Virginia; and
4. The individual impact of a selected number of Virginia facilities to local and regional scale mercury deposition.

DEQ also awarded a contract to the Center for Environmental Studies at the Virginia Commonwealth University (VCU) to assess the human health risks from consuming methylmercury contaminated fish. The study focused on understanding the risks of consuming methylmercury through ingestion of freshwater fish by sensitive sub-populations (such as children and pregnant women) in Virginia. This study used DEQ's fish tissue database and on-site fish consumption data to estimate risks to human health. These estimates of risks to human health were needed for DEQ to be able to monetize the potential economic benefits and costs of current levels of mercury and potential future reductions.

Data was collected from internal and external sources on control technologies used at all of Virginia's coal-fired power plants in order to understand expected mercury removal rates and costs of controls. This information was used to develop estimates that distinguish the portion of such control costs that can be ascribed to mercury from the co-benefits of controlling other pollutants. The team then analyzed the costs associated with mercury-specific control technologies for coal- fired power plants.

Virginia Mercury Symposium

Complementing the Virginia Mercury Study, the State Air Pollution Control Board and DEQ organized and hosted the Virginia Mercury Symposium on November 28-29, 2007, in Newport News, Virginia. In addition to providing a progress report on the status of the Virginia Mercury Study, the Symposium brought together regionally- and nationally-recognized speakers to provide information and perspectives on various aspects of the science, technology, economics and policy aspects of mercury emissions, abatement and impacts.

Conference attendees included a wide range of Virginia stakeholders, including representatives of state and local environmental and health agencies; nongovernmental organizations (NGOs); coal, utility and manufacturing sectors; seafood interests; vendors of pollution controls; academic researchers and the policy research community.

The goal of the symposium was to promote awareness of the multiple issues surrounding mercury. There was no attempt to develop a set of consensus findings or conclusions from the Symposium. Information presented at the symposium has been posted on DEQ's website at http://www.deq.virginia.gov/info/symposium.html for all interested parties to review and use.

Chapter 2- Summary of Differences Between Virginia's Study and EPA's CAMR Analysis

Prior to releasing CAMR, EPA performed its own analysis on the rule. In some ways, this report utilized similar approaches to those taken by EPA. The goal of this report was to specifically examine mercury as it relates to Virginia, which included mercury deposition modeling and impacts to Virginia waterways from such deposition, as well as potential impacts to Virginia citizens. The differences between EPA's analysis and this report are explained in this section of the report.

Revised Inventory

Prior to releasing the CAMR, EPA conducted an analysis on the impact mercury from coal-fired power plants in the United States has on the environment. DEQ's mercury deposition modeling utilized Virginia-specific information and differed from the emission inventory utilized in EPA's analysis. When conducting the mercury deposition modeling for this report, the emission inventory information utilized by EPA was updated and revised to reflect the most current information concerning sources in Virginia emitting mercury. This included verification of the total emissions, stack locations and stack parameters.

Individual Sources

In addition to utilizing a revised emission inventory, DEQ's modeling analysis not only examined the mercury deposition occurring within Virginia, but also estimated the mercury deposition occurring as a result of individual sources that operate within the Commonwealth through the use of source tagging. In order to predict the behavior of mercury emissions from individual sources, modeling was conducted utilizing a smaller grid size (12 km x 12 km) to examine impacts within Virginia. Therefore, DEQ's study contained a more narrow focus on the deposition of mercury occurring within areas of the state.

Fish Tissue Data

When EPA conducted its analysis of the CAMR, information on fish tissue samples was gathered from across the United States. Approximately 20 tissue samples from two types of fish from Virginia were utilized in EPA's analysis. In this study Virginia-specific fish tissue information was used to review the impacts mercury has on Virginia fish. This included over 2,100 samples that had previously been obtained by DEQ's fish tissue monitoring program.

Cost Analysis

The cost analysis conducted in this study focused on Virginia-specific information. Virginia power plants vary in the amount and type of mercury control equipment installed. All plants burn a low sulfur, low mercury, and high chlorine bituminous coal, and most of the plants also burn coal that has been initially washed and processed after mining. Furthermore, some of the plants have technologies already in place to control nitrogen oxide (NO_x), sulfur dioxide (SO_2), and particulate matter (PM). This information was utilized when examining the cost benefits of the different control technologies.

Additionally, the cost of IQ points lost as a result of consumption of mercury contaminated fish was able to be projected for a portion of river basins impacted by mercury contamination in

Virginia. This allowed an estimate of the monetary impacts of IQ losses for a select population of Virginians.

Human Health Impact to Virginia Citizens

EPA's analysis was not representative of the Commonwealth alone and did not take into account Virginia-specific individual consumption patterns and DEQ's fish tissue data. DEQ contracted with VCU to obtain information on recreational fishing and fish consumption patterns in areas of Virginia with mercury fish consumption advisories. This information enabled VCU to estimate the associated health risks from resulting methylmercury exposures by consumption of mercury contaminated fish.

Recent Federal Court Actions Concerning CAIR and CAMR

The EPA promulgated the Clean Air Interstate Rule (CAIR) and Clean Air Mercury Rule (CAMR) in the spring of 2005. CAIR established a cap-and-trade program to reduce emissions of NO_x and SO_2 from power plants in affected states to reduce interstate emissions contributing to fine particulate and ozone nonattainment. CAMR was designed to reduce emissions of mercury from coal-fired power plants through a cap-and-trade program. Because control technologies for NO_x and SO_2 may also reduce emissions of mercury, CAIR and CAMR were expected to work together to achieve mercury reductions.

The State Air Pollution Control Board (SAPCB) adopted its final regulation to implement the federal CAIR program on December 6, 2006. On January 16, 2007, the State Air Pollution Control Board adopted its final regulation to implement the federal CAMR program in Virginia.

In two separate actions during the spring and summer of 2008, the U.S. Circuit Court of Appeals for the District of Columbia issued decisions vacating the federal CAIR and CAMR. EPA's request for a rehearing on CAMR was denied and EPA currently is evaluating its options for appeal to the United States Supreme Court. With respect to CAIR, EPA has petitioned the D.C. Circuit Court for rehearing of the case. Because of the significant impacts of the Court's CAIR ruling, stakeholders, including the affected states and industry, have asked Congress to take action to legislatively reinstate CAIR in some form. These efforts are still underway.

The D.C. Circuit Court's very recent opinions vacating both the CAMR and the CAIR occurred after the air quality modeling and studies for this report had been completed. As a result, this report provides information on the predicted environmental changes that were expected to occur as a result of implementation of both CAIR and CAMR. This information will be a valuable resource for predicting environmental changes that may occur as a result of emission reductions occurring in the future.

Chapter 3- Emission Data Analysis and Mercury Deposition Modeling

The reliability of the mercury deposition assessments, including the modeling, is partially dependent on the quality and completeness of the emission inventory data. Thus, a key objective of the emissions data analysis component of the study was to assess and improve, as needed, the reliability of the mercury emissions data. The data analysis focused on the review and refinement of the mercury emissions data from a variety of source categories, including coal-fired utilities, medical waste incinerators and municipal waste incinerators. The emissions data analysis also required the reliable projection of these data to three future years (2010, 2015 and 2018), taking into account implementation of federal and state laws impacting emissions of mercury.

The modeling analysis included development of a conceptual description of mercury deposition, which improves the overall understanding of mercury impacts and the relationships between meteorology and mercury deposition. The modeling results provide a basis for quantifying the contribution of emissions sources to mercury deposition and examining the fate of mercury emissions from selected sources. For environmental planning purposes, modeling was used to examine the effectiveness of control measures in reducing mercury concentrations in contaminated bodies of water and improving or maintaining water quality within the designated areas of interest in Virginia. By quantifying deposition, the modeling results also provide a link between the analysis of mercury emissions and the assessment of the impacts of airborne mercury on fish tissue and human health.

Mercury Emissions Data Analysis

Literature Review
A literature review was conducted by ICF of recent research into atmospheric chemistry and reactivity, mercury deposition mechanisms, and physical and chemical characteristics of mercury as part of this study. Reports addressing mercury emissions issues, deposition modeling and modeling studies were reviewed to compile estimated global background values of mercury. Estimates of global background vary widely in the current literature, and outputs from various global models have been used in recent modeling studies as input for continental-scale mercury modeling studies. These findings were summarized as part of the interim report provided by DEQ in October 2007. This information is included in Attachment A of the interim report which is available at:
http://www.deq.virginia.gov/export/sites/default/regulations/pdf/2007statusofhgstudy.pdf

Virginia Point Source Mercury Inventory
DEQ solicited the 75 largest known point sources of mercury for updated mercury emission estimates for 2002 and 2005 as part of this study. Of those that provided updated information, some sources prepared emissions estimates based on measurements (stack tests), while others based their estimates on standard process-based emission factors for various source types (e.g., AP-42). Still others may have estimated emissions using alternative methods. For each facility, a thorough technical review of the emissions estimates was conducted, taking into account the important factors that affect mercury emissions such as process-type, boiler type, fuel type, equipment type and stack parameters (e.g., flow rate, exit temperature, exit velocity, etc.). For each facility, the accuracy of the emissions estimates and all of the facility-specific information

including location, stack parameters, hours of operation, maintenance schedules and estimated daily operating profiles were reviewed for accuracy. An investigation also was conducted to determine whether any emission control or other equipment was installed or replaced between 2002 and 2005 and whether there were plans to change/update equipment in the near future. Any new pollution control equipment or other equipment expected to be installed beyond 2005 was accounted for in the future year emission estimates.

Other Inventories – National Emission Inventory
In addition to the Virginia point source inventory, the EPA compiles and maintains the National Emission Inventory (NEI), which includes mercury emissions data. As part of this analysis, the latest version (Version 3) of the NEI mercury inventory was obtained from EPA. This inventory contains information for point sources and "non-point" sources, also referred to as area sources. These include various other types of fuel combustion sources. The NEI inventory was used in the modeling deposition portion of the study to account for other influences, such as mobile sources and landfills, affecting mercury deposition in Virginia.

Revisions to the Emissions Data Since the Interim Report
The interim report included an emission inventory for sources within Virginia. Since the publication of the interim report, Jewel Coke Company, L.P., provided revised information pertaining to the company's mercury emissions. The revised mercury emission information was submitted as a result of Jewel Coke Company's having performed coal analyses to determine the mercury content of the coal utilized at its facility. When calculating the revised mercury emissions, an assumption was made that 100 percent of the mercury content of the coal was emitted during the company's process. For the base year, emissions were estimated based on the actual coal throughput. Future year projections were calculated by using the permitted coal throughput limit for the facility. No other revisions were made to the emission inventory included in the interim report.

Interim Report
ICF submitted a report to DEQ in September 2007 titled, "The Virginia Mercury Study: Review and Assessment of Virginia Mercury Emissions Data and Recent Mercury Studies." This report summarized ICF's review and analysis of the sources of atmospheric mercury emissions located within the Commonwealth of Virginia and surrounding areas. This report also included a summary of recent mercury studies that were reviewed as part of the literature review. A copy of the report is available from DEQ's website at
http://www.deq.virginia.gov/export/sites/default/regulations/pdf/2007statusofhgstudy.pdf

Mercury Deposition Modeling

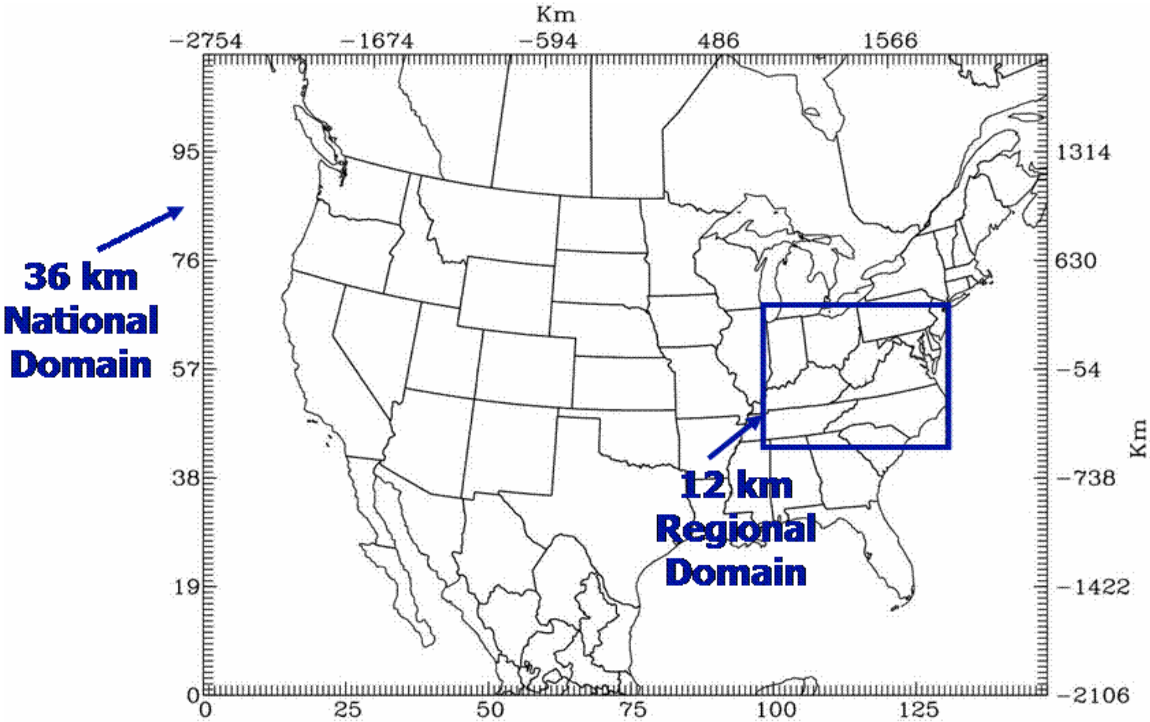
Overview
Atmospheric modeling is a tool that can predict how mercury behaves in the atmosphere and how the mercury will be deposited from the air to the land or water. Mercury deposition can be attributed to global, national, regional and local sources. As a result, several different types of modeling tools were considered in the development of the modeling methodology for this study. Modeling tools differ in terms of numerical formulation [e.g., grid based (Eulerian), trajectory (Lagrangian), plume (Gaussian) formulations], treatment of mercury chemistry and other

processes (such as deposition and the effects of meteorology), and applicable scales (e.g., global, regional, local). In addition, data analysis techniques such as receptor modeling have also been used to study mercury deposition. A portion of the literature review summarizes the ongoing development of mercury capabilities in air quality modeling and some recent national- and regional-scale applications.

The atmospheric modeling methodology for this study consists of two components: (1) regional-scale modeling and (2) local-scale modeling. Regional-scale modeling can provide information on the sources contributing to the deposition in a large geographical area (e.g., United States, Mid-Atlantic Region, Virginia) as a result of global, national, regional and local emissions sources. ICF utilized the Community Multi-scale Air Quality (CMAQ) model, a grid-based model, to conduct regional-scale modeling. The version of CMAQ includes the Particle and Precursor Tagging Methodology (PPTM), which is a feature that can track the contribution of emissions from selected sources (e.g., individual facilities), source categories (e.g., EGUs, non-EGUs), and/or source regions (e.g., nearby states, geographic regions) to simulated mercury (total, wet and dry) deposition.

CMAQ was selected for this study for several reasons. One of the primary goals of this study was to assess the contribution of various geographical regions and source categories to mercury deposition in Virginia. Grid-based models such as CMAQ are designed to simulate the physical and chemical processes that govern the formation, transport and deposition of gaseous and particulate species in the atmosphere. CMAQ is considered a "state-of-the-science" air quality model for mercury deposition and has been used by EPA and others for national- and regional-scale regulatory assessments. CMAQ specifically supports the detailed simulation of the emissions, chemical transformation, transport, and wet and dry deposition of elemental, divalent and particulate forms of mercury.

CMAQ uses grid patterns to assist with establishing boundaries in which air quality is evaluated and examined. The regional-scale modeling conducted for this study utilized two different-sized, horizontal grid patterns, 36 km x 36 km and 12 km x 12 km. The air quality model being utilized, the information available to be used in the modeling, as well as the size of the area being modeled all play a role in determining which grid size is utilized. The mercury deposition modeling performed by ICF used 36 km x 36 km grids to examine the deposition occurring over the entire continental United States. Next, modeling was performed using 12 km x 12 km grids over Virginia and surrounding states, which provides more specific, detailed information on the deposition that is occurring. The following figure displays the geographic areas and the grid sizes used in the modeling.



As previously mentioned, local-scale modeling also was conducted as part of this study. AERMOD, a Gaussian dispersion (or plume) model, was used to simulate the local-scale dispersion and deposition of pollutants for the top 15 mercury-emitting facilities (which make up approximately 85 percent of mercury point source emissions within the state) in Virginia. AERMOD was selected for this study for several reasons. AERMOD is currently the most widely-used Gaussian dispersion model for regulatory applications. It is designed to simulate the local-scale dispersion of pollutants from low-level or elevated sources in simple (i.e., terrain below stack-top elevation) or complex (i.e., terrain above stack-top elevation). It is an EPA "preferred" dispersion model and recent versions of AERMOD also include algorithms for simulating deposition of gaseous and particulate pollutants such as mercury. The model also can be used to simulate the effects of local emission changes for selected areas and sources.

Model Uncertainty

As with any modeling study, there are several areas of potential uncertainty that can affect the reliability of the modeling results. For the regional-scale CMAQ modeling, these include: (1) the representation of emissions (including natural emissions), boundary conditions (global emissions) and meteorology; (2) uncertainties in the chemical reaction rates; (3) representing the dispersion and chemistry in plumes; and (4) accounting for the deposition of elemental mercury and re-emission of mercury.

Uncertainties in the local-scale AERMOD modeling include: (1) AERMOD does not include a chemical mechanism for mercury. That is, AERMOD can be used to simulate the dispersion and deposition of mercury, but not the chemical transformation of mercury. However, this may not be an important limiting factor for near-source assessments. (2) Gaussian models such as AERMOD use a relatively simple representation of the meteorological conditions (important but complex meteorological features cannot be represented). Representing the effects of mountainous terrain (such as that found in western Virginia) and land use are also sources of uncertainty.

Other Modeling Techniques

Other modeling techniques were considered for use in this study including trajectory and receptor models. Trajectory models (e.g., CALPUFF and HYSPLIT) are alternatives to grid-based models. Although trajectory modeling has been used in other studies, it was not selected for this study because it is generally not well-suited for simulating contributions from distant sources. Specifically, the uncertainty of trajectory models increases with the time and distance between the source and location where concentrations are estimated.

Receptor models were also considered for use in this study. These models (e.g., PMF and UNMIX), are statistical-based tools that use a combination of observed wet deposition data, air quality data, meteorological data, and information about emissions source characteristics (e.g., location, emissions process, speciation) to identify potential sources or source categories that may be contributing to observed deposition. This approach was not selected because of the following: (1) meteorological conditions are generally not considered or are represented by a few simple parameters;(2) source-receptor models include the need for very high-resolution, comprehensive data to establish the contributing source profiles and reliance on statistical, rather than physical and chemical, relationships to infer source attribution.

Lastly, receptor modeling has been combined with trajectory modeling as a way to better incorporate the effects of meteorology and narrow down the source-receptor relationships. However, as noted earlier, the uncertainties associated with trajectory modeling, which increase with distance from the receptor location, may also add to the uncertainties in the hybrid source-receptor modeling results.

Conceptual Description of Mercury Model

Prior to conducting modeling, a conceptual description of a mercury model was developed to assist with understanding the project and the issues to be considered when working on the project. Issues such as data availability, accuracy of the data and potential sources that contribute to mercury deposition were studied. This included reviewing mercury deposition data, meteorological data, emission inventory information and recent mercury deposition modeling results. During the development of the conceptual model, issues such as which factors contribute to mercury deposition in Virginia, variations of mercury deposition over a period of time, variations of deposition from location to location, and impacts the variations in meteorology have on deposition were examined. A more in-depth discussion has been included as an attachment to ICF's final report provided in Appendix A of this report.

Modeling Protocol

The purpose of a modeling protocol is to document in detail how a modeling analysis will be performed and how the results will be presented. ICF submitted a modeling protocol to DEQ in April 2007. This protocol document outlined the methods and procedures to be followed in conducting mercury deposition modeling for the study. The protocol provided a basis for DEQ to review and comment on all aspects of the modeling analysis, including the modeling tools and databases, modeling domain and simulation period, modeling procedures, quality assurance procedures, schedule, and communication structures. The protocol was used to guide the progress of the modeling analysis and needed decisions to be made as the work progressed. Although there are no current EPA guidelines for mercury deposition modeling, the modeling protocol and the modeling practices were designed to be consistent, wherever applicable, with current EPA guidelines for other regional modeling applications [e.g., ozone and fine particulate matter (PM-2.5)]. The modeling protocol document has been included as an attachment to ICF's final report provided in Appendix A of this report.

Model Sensitivity Analysis

A sensitivity analysis is the process of varying model input parameters over a reasonable range (range of uncertainty in values of model parameters) and observing the relative change in model response. Sensitivity analyses were conducted for both the regional- and local-scale modeling. The regional-scale sensitivity analysis included an evaluation of meteorological data. It is widely understood that changes in the meteorological conditions input to a simulation have the potential to affect simulated mercury deposition in a variety of complex ways. This study did not include a detailed assessment of the differences between the meteorological inputs and their effects on simulating deposition. Instead, the assessment focused on whether use of a different simulation period (and its associated meteorological conditions) would produce very different CMAQ results. The results of the sensitivity analysis indicate that the model is sensitive to rainfall and possibly other meteorological conditions. One conclusion from this analysis is that the ability of CMAQ to simulate deposition is dependent on the ability of the meteorological inputs to represent key meteorological conditions, such as rainfall.

The local-scale AERMOD sensitivity analysis evaluated the sensitivity of the model to changes in mercury deposition parameters. The sensitivity analysis also included varying surface characteristics (e.g., land use), emission rates and stack parameters. One conclusion of the analysis is that the deposition simulated using AERMOD is sensitive to changes in stack parameters. For example, increasing stack height and exit velocity of particles tends to reduce the amount of deposition near the emission source.

The sensitivity results are provided in Appendix A to this report.

Model Performance Evaluation

A model performance evaluation was conducted for the regional-scale CMAQ modeling as recommended by EPA guidance. The CMAQ model is a multi-pollutant model and certain of the non-mercury species, especially ozone and other oxidants, may influence the simulation of mercury. In addition, examining model performance for a variety different species and for both air concentrations and deposition may aid the overall evaluation of the model results and specifically the identification of biases or deficiencies for certain regions, time periods and/or meteorological (or other) conditions. Thus, the evaluation of model performance for CMAQ considered concentration and deposition of both mercury and non-mercury species.

The model performance evaluation examined (1) whether the CMAQ model was able to replicate observed (and estimated) mercury deposition data, and (2) whether the response of the model to changes in mercury emissions was reasonable.

Overall model performance for mercury (wet deposition) and other modeled species (e.g., ozone) appears reasonable, especially when evaluating annual deposition. Differences between the modeled and observed values are attributable to a number of factors, including the numerical approximations and physical parameterizations used in the CMAQ model, imperfect representation of the meteorological conditions (in particular, the timing and amount of rainfall), uncertainties in the emission inventory and boundary condition estimates and even uncertainties in the measurements. Nevertheless, the simulated annual wet deposition mercury amounts on average are within 10 percent of the observed values for both the 36- and 12-km modeling domains. The complete model performance evaluation is provided in Section 5 of Appendix A to this report.

Modeling Simulations

ICF used the CMAQ model to examine regional-scale mercury deposition and the sources contributing to deposition for each river basin and the entire State of Virginia. AERMOD was used to evaluate local-scale deposition for the top 15 mercury-emitting facilities in Virginia (i.e., within a three-km radius of each plant).

CMAQ simulations were used by DEQ to:

1. Examine the contributions from mercury air emissions sources in (a) Virginia, (b) the remainder of the 12-km modeling domain, which includes several neighboring states, (c) all other U.S. states (outside of the 12-km domain), (d) Canada and Mexico, (e) global emissions sources, and (f) natural emissions.

2. Quantify the contributions from Electric Generating Unit (EGU) and non-EGU facilities in Virginia and the surrounding states, including (a) all of Virginia's EGU sources, (b) all of the Virginia non-EGU sources, (c) all EGU sources in the surrounding states (i.e., the remainder of the 12-km grid), and (d) all non-EGU sources in the surrounding states. The results were used to quantify and compare the contributions from the EGU and non-EGU source sectors to mercury deposition for any location (grid cell or group of grid cells) within Virginia and the 12-km modeling domain.

CMAQ modeling simulations were conducted for the baseline year (2001/2002) as well as three future projection years (2010, 2015 and 2018). The CMAQ PPTM methodology was applied to each of the two groups of scenarios listed above for the baseline year and one future year (2018). Future-year modeling inventories accounted for the impacts of federal and state laws to reduce emissions. Results of the modeling simulations were used as inputs into the other portions of the study.

Finally, local-scale modeling using AERMOD was applied for the 15 facilities in Virginia with the greatest mercury emissions. Average mercury deposition was calculated for the 3-km area surrounding each facility. AERMOD simulations were conducted for the baseline year as well as for three future projection years (2010, 2015 and 2018). Future-year modeling inventories for each of the individual facilities accounted for the impacts of federal and state laws to reduce emissions.

Differences from EPA's Regional-Scale Mercury Modeling Study

This report used some of the same procedures that EPA used when performing its CAMR analysis. EPA performed its analysis for CAMR by utilizing the CMAQ model. The modeling performed by ICF, however, utilized a different version of the CMAQ model - version 4.6 with PPTM. Additionally, in order to more closely examine the mercury deposition occurring within Virginia, a smaller grid size was used in part of this study. EPA utilized a 36 km x 36 km grid when it performed modeling for the CAMR analysis. ICF's use of the 12 km x 12 km grid size allowed more detailed historical Virginia meteorological information to be used. Revisions to emission estimates were made as part of this study, so the emission estimates used in this study differed from those used by EPA. Additionally, ICF was able to use PPTM modeling to quantify the contributions from several emissions categories located in Virginia and to examine the transport of mercury emissions from emissions categories outside Virginia.

Chapter 4- Mercury Deposition Modeling Results

The CMAQ modeling simulations conducted by ICF provided information on where mercury deposition is occurring, the predicted trends of mercury deposition, and predicted future mercury deposition in each of Virginia's major river basins. More detailed information on the modeling results can be found in the final report provided by ICF, which is included as Appendix A. The following is a summary of the results of ICF's study.

Sources of Mercury Deposition in Virginia

Base Year Regional-Scale Modeling Results

Mercury deposition occurring within Virginia originates from many places, from places around the globe to sources located within the state. The mercury deposition modeling conducted by ICF included PPTM, which allowed the contribution of mercury emissions from different geographic regions to be estimated. The modeling categorized the origin of the mercury deposition as global, national, regional, natural or Virginia emission sources. In general, global background refers to mercury that is circulated around the earth. Global background will include mercury emitted from sources outside of the continental United States, such as those in Asia. National emissions sources are those sources that are located within the continental United States and portions of Canada and Mexico that are near the United States border. Regional emission sources are located within the 12-km grid and include emissions from states surrounding Virginia. Natural sources include those mercury emissions caused from such things as volcanic activity. Virginia emissions sources include all emission sources that are located within the state of Virginia. The breakdown of the geographic areas contributing to mercury deposition in Virginia during the base year for this study is shown in Figure 4-1 below. Deposition is given in terms of the grams of mercury deposition per square kilometer. The base year was established by using 2001 and 2002 emissions inputs. Throughout the report, the base-year scenario is referred to as either the "base year" or the "2001/2002 base year." The first pie chart illustrates that 74 percent of the annual deposition in Virginia for the base year can be attributed to global background and 26 percent of the deposition occurring in Virginia is from emission sources. The pie chart labeled "Contribution by Geographic Area" provides the breakdown of the origin of the emission sources that contribute to mercury deposition within Virginia. For example, 3 percent of the mercury deposition occurring within Virginia can be attributed to EGUs located within Virginia. The third pie chart labeled "Contribution by Geographic Area w/o background and natural sources" further illustrates the contribution of emissions by geographic area that contribute to mercury deposition within Virginia without the inclusion of global background and natural emissions. This pie chart redistributes the 26 percent emissions contribution in the first pie chart (i.e., "Contribution by Geographic Area"). Specifically, this pie chart illustrates that of the 26 percent attributed to emission sources, 54 percent is attributed to EGUs in surrounding states, 14 percent is attributed to Virginia EGUs, 13 percent to non-EGUs in surrounding states and 12 percent to non-EGUs located in Virginia.

Figure 4-1. Summary of CMAQ/PPTM Mercury Contribution Results for Virginia for base year.

Simulated Annual Hg Deposition for 2001 for Virginia: 22.69 g/km²

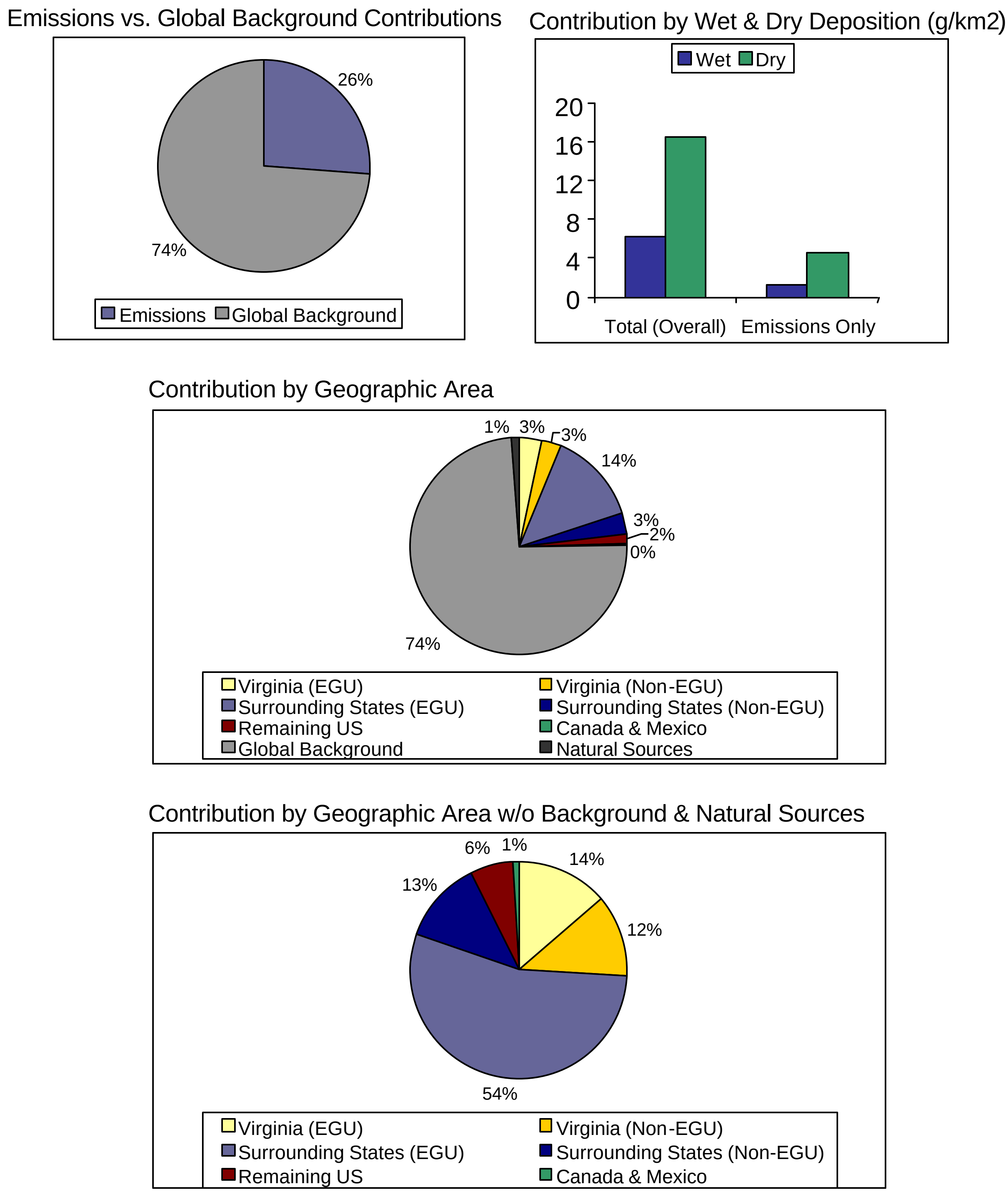


Figure 4-1 provided by ICF

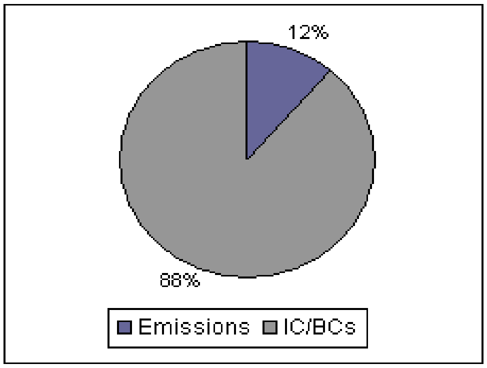
Future Year Regional-Scale Modeling Results

Once the base year mercury deposition modeling was completed, modeling was conducted to identify the mercury deposition estimated to occur in future years. Figure 4-2 below illustrates the breakdown of the origin of the emission sources that contribute to mercury deposition within Virginia that is expected to occur in 2018 after the implementation of CAIR and CAMR requirements. It is important to note that the pie charts in Figure 4-2 do not depict the change in the amount of deposition that is expected from the baseline year to 2018. These changes in mercury deposition are discussed below and illustrated in Figure 4-3.

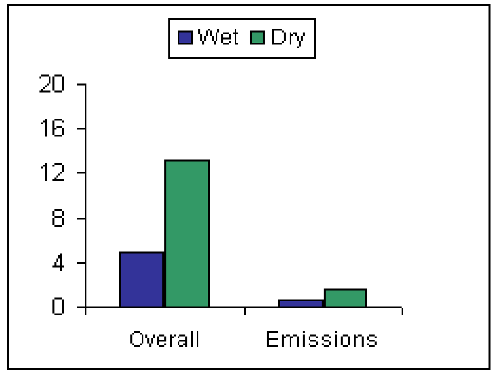
Figure 4-2 Summary of CMAQ/PPTM Mercury Contribution Results for Virginia for 2018.

Simulated Annual Hg Deposition for 2018 for Virginia: 18.07 g/km2

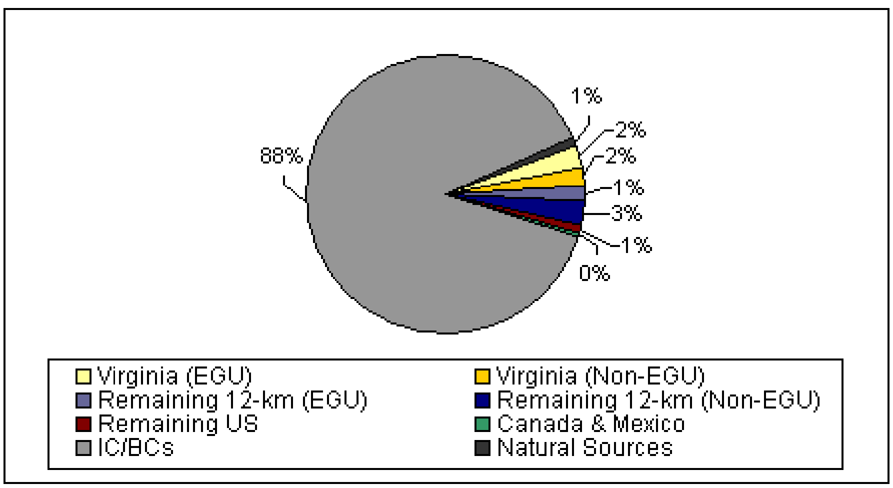
Emissions vs. Global Background Contributions



Contribution by Wet & Dry Deposition (g/km2)



Contribution by Geographic Area



Contribution by Geographic Area w/o Background & Natural Sources

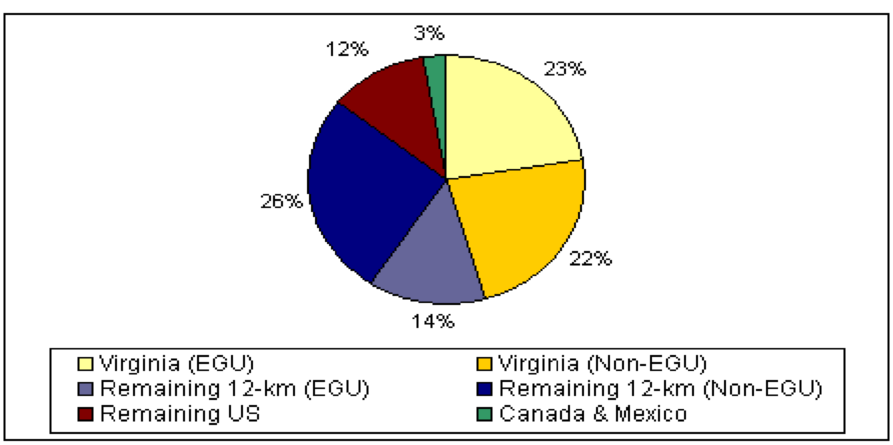
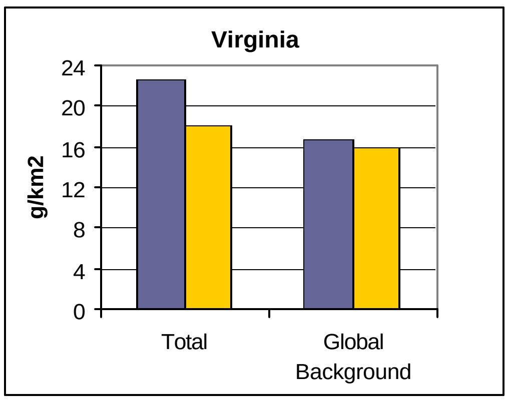


Figure 4-2 provided by ICF

Modeling predicts that a decrease in mercury emissions in all geographic categories (excluding natural sources) will occur in response to implementation of CAIR and CAMR requirements. The largest percentage of mercury deposition in Virginia in the baseline year is from global sources, and the largest percentage of mercury deposition in Virginia is predicted to continue to originate from global sources in 2018.

Figure 4-3 below illustrates the change in mercury deposition anticipated to occur as a result of implementation of CAIR and CAMR requirements. Figure 4-3 compares the mercury deposition occurring within Virginia in the base year and in 2018. This figure illustrates that, as a result of implementation of CAIR and CAMR, deposition in Virginia will decrease. Virginia will benefit from reductions in mercury emissions at EGUs located in surrounding states.

Figure 4-3 CMAQ/PPTM 12-km Mercury Contribution Results for Virginia for 2001/2002 and 2018.



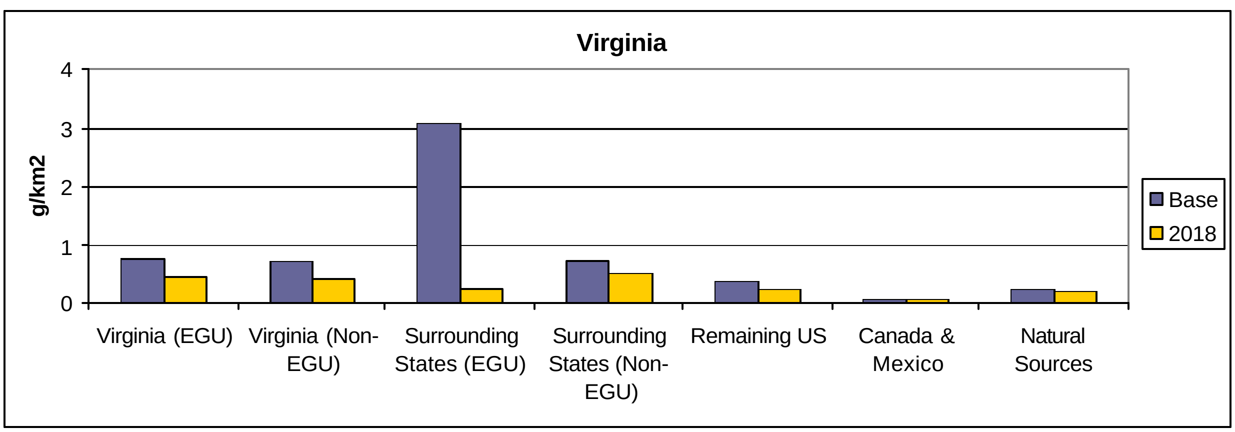


Figure 4-3 provided by ICF

The modeling conducted for this study indicates overall mercury deposition for Virginia is lower by 20.4 percent for 2018, when compared to the base year. The greatest reduction in deposition comes from EGU sources located outside of Virginia (in the 12-km modeling domain that encompasses several nearby states), and 61 percent of the reduction in mercury deposition for Virginia is attributable to reductions in emissions from EGU sources in these nearby states. In addition, 7.2 percent of the overall simulated mercury reduction for Virginia is attributable to reductions in the emissions from EGU sources located within the state, 5.7 percent is attributable to reductions in the emissions from non-EGU sources in the state, 4.6 percent is attributable to reductions in non-EGU sources in nearby states, and 2.8 percent is attributable to emissions reductions in the remainder of the United States.

CAIR regulates both EGUs and non-EGUs; however, CAMR regulates only EGUs. Some controls that are utilized to meet regulatory requirements of CAIR have the co-benefit of reducing mercury emissions. The decrease in mercury emissions will provide some benefit as far as reduced mercury deposition; however, there is not a one-to-one ratio between the reduction in mercury emissions and mercury deposition. Meteorological conditions, the type of mercury emitted, stack height, as well as other factors, influence where mercury is deposited.

In addition to examining the mercury deposition that is predicted to change within Virginia as a result of implementation of CAIR and CAMR, ICF also examined the change in deposition that is predicted to occur in Virginia waterways. This is important because Virginia currently has many waterways with fish consumption advisories that are assumed to be related to the deposition of mercury from the atmosphere. Table 4-1 below illustrates the percent reduction in mercury deposition anticipated to occur in Virginia and in individual river basins as a result of implementation of CAIR and CAMR. All river basins within Virginia are predicted to see decreases in mercury deposition by 2018.

Because each of the source regions and categories contribute different amounts to the total mercury deposition, it also is interesting to attribute the overall change in total deposition to the change in contribution from each geographic region or category. This information is summarized in Table 4-1.

Table 4-1. Portion of Overall Percent Reduction in Mercury Deposition for 2018 Attributable to Each Source Region and Category, for Virginia and the Ten Major River Basins.

Region	Virginia (EGU) (%)	Virginia (Non-EGU) (%)	Remaining 12-km (EGU) (%)	Remaining 12-km (Non-EGU) (%)	Remaining US (%)	Canada & Mexico (%)	IC/BCs (%)	Natural Sources (%)
Virginia	7.2	5.7	61.0	4.6	2.8	0.0	18.0	0.8
Chesapeake Bay	7.4	1.4	62.7	3.1	2.6	0.1	20.0	0.7
Chowan River Basin & Dismal Swamp	9.2	13.9	45.1	10.4	2.3	0.0	16.6	0.7
James River Basin	8.4	8.5	54.9	3.5	2.7	0.1	20.4	0.8
New River Basin	0.6	2.4	55.6	5.0	5.4	0.1	28.9	1.2
Potomac River Basin	14.8	4.2	68.8	0.8	1.1	0.0	9.0	0.4
Rappahannock River Basin	5.1	3.3	72.1	1.2	1.9	0.0	15.1	0.7
Roanoke River Basin	0.6	5.2	68.7	2.5	2.8	0.0	18.8	0.8
Shenandoah River Basin	0.9	3.4	73.6	3.7	2.0	0.0	15.2	0.7
Tennessee & Big Sandy River Basins	12.2	1.2	44.3	9.9	6.4	0.1	23.8	1.0
York River Basin	11.1	5.1	62.3	1.0	2.0	0.0	16.6	0.7

Table 4-1 provided by ICF

The reductions to mercury deposition listed above are mainly predicted to be achieved from control technology installed as a result of CAIR and CAMR. There are some reductions that may be achieved from non-EGUs as a result of other requirements that were not included in the air quality modeling. For example, sources that are electric arc furnaces that melt scrap metal for recycling now may only process scrap metal free of mercury switches. More information on this federal requirement is available at: http://www.epa.gov/ttn/oarpg/t3/fact_sheets/eaf_fs_121707.html. Prior to this federal requirement, Virginia adopted a vehicle mercury switch removal program in 2006, which requires a good faith effort to be made to remove mercury switches from end-of-life vehicles. To date, removal and recycling of mercury switches from vehicles in Virginia has prevented over 35 pounds of mercury from being released into the environment. Automakers have ceased using mercury switches in new vehicles and as newer cars replace older vehicles, the number of vehicles in operation with mercury switches is decreasing, which will reduce the amount of mercury that potentially could be released into the environment from the recycling of old automobiles.

Local-Scale Mercury Deposition Attributable To Individual Facilities
As part of the mercury modeling conducted by ICF, emissions and deposition from the 15 largest mercury emitters in the state were modeled using the AERMOD model to examine the direct impact these facilities have on the area within a three-km area surrounding each source. This analysis yielded three key findings: (1) dry deposition is greater than wet deposition for all facilities, (2) maximum wet deposition tends to occur at locations closest to the facility, and (3) maximum dry deposition tends to occur farther away from the facility location.

Through working with facilities, ICF obtained information on future controls that these facilities plan to install and then modeled the associated changes in mercury emissions and average annual deposition occurring as a result of operation of these facilities. For all facilities, the changes in simulated deposition track the changes in emissions quite closely. As with the regional-scale modeling results, the largest reductions in both emissions and deposition tend to occur between the base year and 2010, with some variability between facilities. Emission increases are associated with some of the facilities in 2015 and 2018, and these changes result in corresponding local deposition increases for the future years.

The type of mercury emitted was also examined as part of this modeling exercise, and the modeling results indicate that most of the local-scale mercury deposition is in the form of reactive gaseous mercury (HG2).

Detailed information on the baseline and projected future mercury emissions for the 15 largest mercury emitters and the corresponding predicted mercury deposition is provided in Section 6 of Appendix A of this report.

Summary of Modeling Results
The modeling conducted by ICF indicates the following:

- Mercury sources located outside of Virginia contribute to the mercury deposition occurring within the state. Global sources are responsible for the largest amount of mercury being deposited within the state.

- Mercury deposition is predicted to decrease statewide in future years as a result of implementation of emission controls in use to meet requirements of the CAIR and the CAMR. Virginia benefits from mercury reductions occurring in surrounding states, particularly emissions reductions from EGUs.

- Emission sources located in Virginia contribute to mercury deposition within the state, and the greatest impacts from the in-state sources are simulated near the source locations. This includes EGU sources and non-EGU sources.

- Examining deposition patterns for EGU and non-EGU sources indicates that, in general, EGU sources tend to impact a larger area, compared to non-EGU sources. This is likely due to shorter stack heights and lower exit velocities at non-EGU sources, which result in less dispersion of mercury.

- The modeling results were calculated by using requirements that must be met under the CAIR and the CAMR. The Washington, D.C. Circuit Court of Appeals has recently issued opinions vacating both of these rules.

Chapter 5- Analysis of Mercury Deposition Modeling – Impact on Fish Tissue Concentrations

DEQ used the information provided by the ICF model about projected reductions in mercury deposition rates to estimate the potential for reductions in fish mercury concentrations in the future, once these reductions in mercury had occurred. In order to do this, information available from the scientific literature as well as experiences in other parts of the country were reviewed to determine what effect might be expected from reductions in mercury deposition into the waterbodies with current fish consumption advisories due to mercury contamination. The differences in mercury deposition rates estimated for 2010 and 2018 were compared to the estimates for the base year utilized in ICF's modeling. Relative proportional reduction factors were calculated for each of the watersheds with fish consumption advisories. These reduction factors were used to estimate the potential for lowered concentrations of mercury in fish from these waterbodies, after the projected reductions in air deposition of mercury have occurred. These estimated, future fish mercury contamination levels were reviewed to assess the potential for removal or relaxations of the existing fish consumption advisories, should future monitoring show that the fish contamination has been reduced to below levels of concern.

Literature Review

Scientific literature was reviewed to gather information to help estimate future fish mercury concentrations, given the reductions in mercury air deposition rates projected by the ICF model.

A large amount of information has been generated in the last 15 years on mercury contamination of fish and the linkages between air emissions of mercury, its cycling in the environment, conversion to methylmercury and eventual bio-accumulation in fish tissue where it can pose a potential risk to humans and wildlife who consume it. Some of the more important and most recent information is briefly discussed below. The emphasis on this summary review is to provide information that will help answer the question, "If we reduce the rates of mercury deposited by air sources into a waterbody that has mercury-contaminated fish, can we expect to see the contamination levels of the fish decrease in response to the decreased rates of air deposition?"

A considerable amount of sophisticated research has been conducted in the Florida Everglades and in experimental lakes in Ontario, Canada, where mercury was added to the waterbody and then traced as it was cycled in the environment to become accumulated in fish tissue. Actual field experiences in Florida and in Massachusetts also provide important information.

Summary of Findings of Literature Search

- Mercury emitted into the air from combustion sources is present in a variety of chemical forms, some of which can be deposited within miles of the emission site, while other forms of mercury can be transported tens to hundreds of miles away from the original source.

- Once deposited in a waterbody, mercury can be transformed into methylmercury by certain bacteria species commonly found in soil or sediments.

- Once converted into methylmercury, it quickly enters the food chain, and concentrations of methylmercury increase in fish, often reaching the highest concentrations in fish species that eat other fish.

- Methylmercury is the most toxic form of mercury and can pose potential risks to human consumers of those fish.

- The amount of mercury being added to an ecosystem and the rate at which this mercury is converted into methylmercury in the ecosystem are the most important factors that determine whether or not fish in a waterbody will accumulate mercury to high levels in any particular waterbody.

- Environmental conditions that favor the bacteria communities that produce methylmercury are known to include waterbodies with low dissolved oxygen, low pH (slightly acid conditions), high organic matter and moderate concentrations of sulfates. These conditions are common to swamps, wetlands and some lakes or reservoirs.

- Newly added mercury appears to be most active in an ecosystem and is quickly converted into methylmercury under favorable environmental conditions.

- Mercury added to lakes can be expected to be converted into methylmercury and begin to enter the food chain relatively quickly, being found in fish within a few months or years of being deposited into the waterbody.

- Mercury deposited onto forested uplands is thought to be relatively unavailable to the aquatic ecosystem. This mercury will enter the waterbody slowly, only after many years of cycling through vegetative decay and erosion of the soils, probably taking many decades to centuries to be transported into the waterbody where it can be accumulated by fish.

- Wetlands appear to respond to changes in mercury deposition and accumulation into the fish in an intermediate time frame involving years to decades.

- Available evidence from both experiments and actual field experiences indicate that although each waterbody will react to changes in mercury inputs differently, it is reasonable to anticipate that if mercury inputs into an ecosystem are decreased, there will be a proportional decrease in the fish contamination levels.

- It is reasonable to accept an assumption of an equal proportional decrease (1:1) in fish concentrations after a reduction in mercury deposition into the waterbody has been achieved; that is, if mercury input is lowered by 20 percent%, we can expect to see the fish mercury concentrations lowered by 20 percent after the ecosystem equilibrates to the new, lower amounts of mercury available in the ecosystem.

- The time frame for the ecosystem to come into equilibrium after the reductions in mercury deposition takes place will be variable and different for each waterbody.

- Lakes will be expected to react most quickly to changes in mercury deposition reduction, showing reduced mercury in fish tissue within a few years to decades.

- Wetlands will be expected to react in an intermediate time frame to changes in mercury deposition reduction, showing reduced mercury in fish tissue possibly within several years to several decades, and probably dependent on how well connected the shallow wetlands are to the nearby river channel.

More detailed summaries of information reviewed as part of the literature review are provided below.

Mercury-Fish Contamination Field Experiments, Everglades

The mercury contamination of fish in the Florida Everglades has been subject to intense studies since the 1980's when elevated levels of mercury were found in fish there. This prompted widespread research and mercury reduction efforts and a development of a Total Maximum Daily Load (TMDL) to try to identify and control the sources of mercury to this area. One of the key findings of the Everglades TMDL study (Florida DEP, 2003) was that there is a linear relationship between mercury deposition and levels of mercury in fish, and when atmospheric deposition of mercury is reduced, levels of mercury in fish also show a decline with a relationship of almost 1:1. Local air emission rates of mercury, primarily from medical waste incinerators and municipal waste incinerators, have declined by over 90 percent since the late 1980s to early 1990s. This has resulted in a corresponding decline of about 80 percent in mercury in largemouth bass and fish-eating birds in the affected area of the Everglades. The changes in fish mercury concentrations occurred relatively rapidly after reduction in local emissions. Fish mercury concentrations were reduced by about 50 percent in about 10 years and by 90 percent within 25 years.

Also, along with the reductions in local air emissions of mercury, reductions of sulfates into the area's waters were achieved, which also could have contributed to the corresponding decreases in mercury levels in the local fish (Gilmore, etal., 2003). Decreases in sulfates in a waterbody have been shown to lessen the methylation efficiency rates of the bacterial community responsible for the mercury methylation cycle, which reduces the potential for fish to accumulate methylmercury. The TMDL report notes that the Everglades is a unique ecosystem, and that other waterbodies may not react the same way, but this experience does demonstrate the potential for linkage between deposition rates and corresponding reductions in fish contamination. The report notes that even after reductions in mercury air-deposition rates, the fish will have some remaining mercury due to remaining mercury in the sediments and continuing, but lower levels of air-deposited mercury.

Mercury-Fish Contamination Field Experiments, Canadian Lakes

A series of long-term experiments (Harris, R. et al.,2004), (Branfireun, et al., 2005), (Patterson, et al., 2006) in experimental lakes in Northwest Ontario, Canada were conducted in 2001-2003, where lakes were dosed with specific isotopes of mercury, and the fate and transport of this mercury was followed. This allowed the researchers to distinguish between mercury already in the water system and the "new" mercury. The mercury isotopes were added to the lake itself, nearby wetlands and an upland forested area. An extensive series of papers has been published on these experiments. A recent publication in the Proceedings of the National Academy of Science in October 2007 titled, "Whole-ecosystem study shows rapid fish mercury response to changes in mercury deposition" (Harris et al., 2007) provides a good synopsis of this work. This 2007 paper concluded that concentrations of methylmercury in fish in the experimental lake rapidly increased as mercury deposition rates were increased over the first 3 years of the study. Mercury added to the lake showed the most rapid conversion into methylmercury and was detected in the fish within months of deposition; continued to increase in the fish tissue during the three years of the experiment; and had not yet reached a steady state. Mercury deposited to a nearby wetland took much longer to appear in the lake waters, reflecting a lag time as the mercury was bound up in the vegetation and cycled through the wetland's vegetation growth and decay cycles and slowly found its away into the lake water. Mercury added to the forested upland area took even longer to be detected in the lake water. The authors concluded that as mercury emission controls are instituted and atmospheric deposition of mercury decreases, there is the expectation that a decrease in atmospheric mercury deposition will result in lower fish mercury concentrations. There will be some lag time before the ecosystem and fish concentrations of mercury become equilibrated to the lower mercury inputs. The effects are expected to occur in two phases, an initial rapid decline in fish mercury concentrations after reductions in direct deposits into the waterbody occur, followed by a more prolonged reaction as mercury previously deposited in wetlands or on the upland ecosystems become re-equilibrated. Lakes that receive most of their mercury from the atmosphere could be expected to respond within years to approximately a decade, while wetlands may respond less rapidly, and waterbodies that receive mercury after being deposited to forested, upland ecosystems would take longer (decades and possibly up to centuries).

Although this experiment found a long lag time in transport of the mercury from the wetlands to the lake, the report also noted that other types of wetlands could export newly deposited mercury and impact fish mercury concentrations on a much shorter time scale than what was seen in this particular lake. Much depends on the connectivity of the wetland to the waterbody where the fish reside. Other related experiments, in another lake and wetland, have shown the mercury deposited in wetlands is rapidly methylated and can be transported by shallow flow to the nearby lake within a relatively short time. The northern wetland in this experiment may not act the same as other wetlands because of differences in hydrologic connectivity, the type of moss vegetation and the colder climate with a short warm season. When wetlands are hydrologically well-connected to nearby lakes or rivers, as is often the case in southern coastal plain swamps as in Virginia, it can be expected that the shallow wetlands bordering the channel of the river flowing through the swamp will act as a site of increased methylation, and the methylmercury can be readily transported via the water flow through the system.

Additional experiments in the Florida Everglades and the group of experimental lakes in Canada (Hintelmann et al., 2002), have provided evidence that "new" mercury that has been recently added to an ecosystem is much more likely to be converted into methylmercury and bio-accumulated into the local fish as compared to "older "mercury that may already be in the local environment from previous deposits. The newly added mercury appears to be more environmentally active than the older mercury, possibly due to the mercury becoming bound with sulfates in the sediments over time. It has been shown that even with previously contaminated ecosystems, newly added mercury is even more active than previously existing, "older" mercury. Recently-added mercury shows up in fish tissue in a relatively short period of time. Mercury deposited into waterbodies or wetlands is most active and quickly finds its way into fish tissue, while mercury added to forests or upland sites did not show up in fish tissue during the course of the experiments. This information suggests that "new" mercury deposited into the water or wetlands is most important to methylation and resulting fish contamination. The bioaccumulation of the new mercury takes place relatively quickly, showing up in the fish tissue within months of adding it to the lakes or wetlands. After time, months to years, mercury in sediments appears to be stabilized, possibly bound up with reduced sulfur compounds in the sediments and is not as available to the biota as newly added mercury. This has implications that suggest that if the ecosystem is capable of responding relatively quickly to increases in inputs of mercury, then reductions in the amount of mercury deposited into the ecosystem should result in lowered fish contamination levels within a relatively short time frame, too. If a way can be found to decrease the amount of "new mercury" being added to the ecosystem, then a decrease in fish mercury contamination levels may be observed.

Findings of the International Conference on Mercury as a Global Pollutant

A recent international meeting of mercury specialists, the 8th International Conference on Mercury as a Global Pollutant, was held in Madison, Wisconsin, in 2006. Panels of mercury experts were charged with addressing several important questions regarding mercury fate and transport issues. One panel was given the question, "How would methylmercury levels in fish respond to reduced anthropogenic emissions of mercury?"

The panel concluded (ICMGP 2006) that the concentrations in methylmercury in fish will decrease in response to mercury-load reductions. The magnitude, rate and lag time of that reduction will vary significantly, depending on site-specific factors that affect the amount of methylmercury available to the food web. The most mercury-sensitive ecosystems have several characteristics in common: efficient delivery of mercury to zones of methylation, high rates of methylation of mercury in these zones, and efficient uptake of the methylmercury into the food web.

The rate of recovery of a fishery in a specific waterbody depends, in part, on the transport of mercury that has accumulated in the watershed area. Increased transport of mercury from the terrestrial zone to the waterbody is associated with shallow surface deposits of mercury, decomposition rates in the soil, high organic content of the soil and land disturbances and soil erosion that lead to a washing of the mercury into the waterbody.

Very similar conclusions were reached in a recent publication that reviewed the available information on recovery of mercury contaminated fisheries (Munthe, R.A. et al., 2007).

EPA Total Maximum Daily Load Guidance for Mercury Impaired Waters

The EPA has recognized that the primary potential risk posed to humans by mercury released to the environment via air emissions involves the complex events that lead to deposition of the mercury onto a waterbody, the conversion of the mercury into methylmercury and the uptake and bioaccumulation of methylmercury into fish tissue, where it can pose a risk to the human consumers. Once a problem is identified with mercury contamination of fish, a waterbody is classified as impaired by a state and plans are made to identify the sources of the mercury and control them by developing a Total Maximum Daily Load (TMDL) that apportions allowable releases of mercury so that the fishery in the waterbody can recover. EPA recognizes the difficulties involved with trying to control mercury deposition when some sources may be outside the jurisdiction of the state where the contamination occurs. EPA has developed guidance for dealing with these issues (EPA 2007).

In this mercury-TMDL guidance, EPA recommends that states estimate the range of percent-reductions in air deposition needed to achieve the acceptable fish-tissue mercury concentration. EPA does not expect complex modeling is needed to develop these estimates, and that the estimates can be based on steady-state assumptions such as a 1:1 linear relationship between reductions in air loadings and reductions in methylmercury in fish tissue. Such a linear relationship has been used in EPA-approved TMDLs for Georgia.

The Massachusetts Experience

New England states also have discovered elevated levels of mercury in fish, especially in lakes and ponds. In response to these mercury levels, the states have entered into regional agreements that have resulted in increased controls on mercury emissions and decreased mercury emissions in the region. Expanded fish monitoring was conducted to evaluate the initial effectiveness of these efforts. The Massachusetts Department of Environmental Protection published a report in 2006 entitled, "Massachusetts Fish Tissue Mercury Studies: Long-Term Monitoring Results, 1999-2004" (Mass DEP, 2006). This report describes long-term monitoring of changes in mercury concentrations in edible tissues of two species of freshwater fish in a series of lakes and provides data to help evaluate the effectiveness of state and regional mercury reduction programs in Massachusetts lakes and especially in an area in northeastern Massachusetts with modeled, higher mercury deposition. This area of higher modeled deposition was caused by local and regional air emissions of mercury, mainly from incinerators. Controls on these local and regional sources of mercury emissions had been implemented beginning in the late 1990s and during the course of the fish monitoring (1999-2004). Massachusetts reported that mercury emissions in New England and the Eastern Canadian Provinces decreased by about 54 percent between 1998 and 2003. During this period, emissions in Massachusetts decreased by about 70 percent, and those in the study area by about 87 percent.

Massachusetts also reported that during the period of the monitoring (1999-2004), consistent and substantial, statistically significant decreases in yellow perch and largemouth bass fish tissue mercury concentrations occurred in most lakes sampled. For yellow perch, of 17 lakes monitored, mean mercury concentrations in this species decreased significantly in 13 of the waterbodies between the earliest and latest dates sampled. Nine of the lakes were located in the area in northeastern Massachusetts with higher modeled mercury deposition and in eight of these lakes, significant decreases in mercury concentrations in yellow perch were observed, ranging from -26.0 to -61.9percent. The mean change for all nine lakes was -32.4 percent. Five of the remaining eight lakes around the rest of the state also had statistically significant decreases in mercury in yellow perch ranging from 20.1 to 28.0 percent, with an overall mean change for all eight lakes of -15.4 percent.

The situation was similar for large mouth bass with mercury concentrations declining in 11 of 17 lakes throughout the state. Eleven of the lakes sampled were in the area in northeastern Massachusetts with the higher modeled mercury deposition, and mercury levels in largemouth bass from seven of those decreased significantly, ranging from -16.0 to -55.2 percent. Mercury levels in three of the four other lakes also decreased, but the changes were not statistically significant. The mean change in mercury concentrations in largemouth bass among all 11 of these lakes was -24.8 percent. Four of the remaining six lakes located around the rest of the state also had statistically significant, but smaller, decreases in largemouth bass tissue-mercury concentrations. The range of these changes was -15.9 to -36.4 percent, with an overall mean for all six lakes of -19.0 percent.

The Massachusetts report indicates that, given a reduction of air emissions of mercury of about 70-87 percent in the local area, the fish concentrations of mercury declined an average of 24.8 percent to 32.4 percent in a five-year period. This indicates that reductions in local emissions of mercury can have a direct and rapid effect in corresponding fish uptake of mercury in the local area. The ratio between mean declines in fish mercury concentrations and the mercury emissions declines range between 0.22 and 0.27 on a regional basis and 0.29 and 0.37 in the area with higher deposition. It is important to recognize this is based on declines in mercury <u>emissions</u> and <u>not deposition</u> estimates (which are not available). Typically, local deposition of mercury is a fraction of the mercury emitted to the air, so the ratios for declines in fish mercury compared to deposited mercury would be expected to be higher than the 0.22 to 0.37 observed based on emissions data only. Also, the period of investigation is only a few years, and it is expected that the ecosystem will take some period of time to re-equilibrate to the new, reduced mercury deposition rates.

Overall, this information from the Massachusetts study is very encouraging and indicates that a decline in deposited mercury to a waterbody will result in a corresponding decline in fish contamination, and that such a decline in fish mercury contamination can begin to occur within a few years of the changes in mercury deposition.

Conclusions of the literature review

The experiments in the Everglades and in the Canadian lakes where mercury was added to the test water demonstrated that mercury deposited from the air is quickly converted into methylmercury in these environments and can be found in fish tissue within a few months to years. This demonstrates a fairly rapid response to added mercury. The time between addition of the new mercury to the waterbody and when it is found in fish tissue is quickest for lakes (months to years) and longest for mercury deposited to forested uplands (years to many decades or to maybe even centuries). Wetlands are expected to respond in an intermediate timeframe, depending on a variety of site-specific factors. Actual experience of the start of recoveries of fisheries in the Everglades and in Massachusetts demonstrated that, following reductions in air emissions of mercury in local and regional sources, within a few years the local fish also showed a corresponding decrease in mercury uptake.

In each waterbody, site-specific physical, chemical and biological factors affect the rate of conversion of mercury into methylmercury and its uptake into the food web. High rates of methylation are associated with sources of mercury in areas with high organic matter, low pH, and moderate concentrations of sulfates and sulfur, along with the presence or abundance of bacterial communities capable of methylation of mercury (Munthe, R.A. etal., 2007). Once methylmercury is formed, each waterbody will have a different food-web structure that also can influence the rate of bioaccumulation of mercury into fish in these waterbodies. While these various factors are understood to have effects on the rate of methylation and uptake on mercury, these processes are not understood well enough to allow for accurate predictions of rates of methylation or mercury bioaccumulation in the various waterbodies. This makes the construction of a reliable model for accurately predicting the effects that changing inputs of mercury will ultimately have on local fish contamination levels unworkable without a great deal of site-specific study and information. Thus, the development of such a model is impractical for all the different swamps, rivers, reservoirs and ponds in Virginia, all of which likely have different mercury cycling efficiencies and different food webs.

On the other hand, each waterbody may be considered as a dynamic system that will respond to changes in mercury input in a consistent manner once the ecosystem equilibrates to the changed conditions. Using this as a basis, it can be predicted that a reduction of any of the factors that has the potential to increase the amount of mercury in the waterbody, or that increases the rate of mercury methylation efficiency; should show a corresponding reduction in methylmercury contamination levels in fish. If the environmental conditions that affect the efficiency of mercury methylation in the soil or sediment are considered to be natural, ecological conditions that remain in some form of dynamic equilibrium, then the amount of change in mercury input can be expected to result in a proportional change in the fish tissue mercury concentrations once the ecosystem has become equilibrated to the changes in available mercury. Thus, it is assumed that if mercury deposition into a waterbody is reduced by a certain amount, a similar and proportional reduction in mercury concentration in fish in that waterbody is to be expected.

The available information indicates that when mercury deposition to a waterbody is reduced, it is reasonable to expect to see a corresponding decrease in fish contamination levels (Mass DEP, 2006), (Munthe, R.A. etal., 2007), (ICMGP, 2006), (Florida DEP, 2003). An assumption of a 1:1 relationship would be appropriate for estimating potential future fish mercury concentrations in relation to percent reductions in mercury deposition rates.

This assumption of a 1:1 relationship of a reduction in mercury input into an ecosystem to a corresponding reduction in fish bioaccumulation of methylmercury will be used to estimate future fish mercury concentrations in Virginia waterbodies that are currently subject to fish consumption advisories and where the primary source of mercury is believed to be air deposition.

<u>Mercury in Virginia Waterways</u>

Two rivers in Virginia have been contaminated with mercury due to past industrial pollution incidents. These are the only known instances where significant discharges of mercury directly into Virginia waterbodies has occurred in the past and resulted in fish consumption advisories. The North Fork of the Holston River in southwest Virginia and the South River and the South Fork Shenandoah River in the Shenandoah Valley have fish with elevated levels of mercury caused by two past industrial pollution incidents. The North Fork of the Holston River became contaminated with mercury from the Olin Corporation's Saltville facility as part of a chlorine production process. Olin has been addressing contamination in the river with assistance from the EPA and DEQ since the 1980s. Mercury was used by a DuPont plant in Waynesboro in fiber production between 1929 and 1950. Mercury contamination in the South River was discovered in the 1970s and now extends to the South Fork Shenandoah River. DEQ, in partnership with the South River Science Team, regularly takes samples of water, fish tissue and sediments in the South River and the South Fork Shenandoah River with money from a trust fund established by DuPont Co. Until 2001, these two industrial sites were the only sites with fish consumption advisories due to mercury in Virginia.

<u>Monitoring of Mercury-Fish Contamination</u>

The DEQ Fish Tissue and Sediment Monitoring Program is used to monitor for fish contamination issues that could pose potential risks to human consumers. DEQ's fish monitoring efforts have always been directed toward investigating waterbodies with the highest probability of chemical contamination, and most of these monitoring efforts have focused on waterbodies that receive permitted discharges from major industrial and municipal facilities. Until about the year 2000, there was little reason to monitor fish in many of Virginia's swamps or wetland-dominated rivers, because most of these waters do not have significant industrial municipal discharges. In the late 1990s, however, many other states and other countries began discovering fish with high levels of mercury in lakes and wetlands in areas without any significant known sources of mercury discharges into the affected waterbodies. An understanding developed that some types of waterbodies, such as lakes and wetlands, might be predisposed to fish mercury contamination issues, even if they were not subject to any significant, direct source of mercury discharges. DEQ began to investigate this possibility by expanding the monitoring of fish in some rivers that are influenced by wetlands. Results of this monitoring showed that several of Virginia's waterbodies do contain fish with elevated levels of mercury, even where there were no known significant industrial or municipal dischargers into the waterbody.

<u>Summary of Mercury-Sensitive Waters</u>

Fish with elevated levels of mercury have been found in some waterbodies, even when there are no known local sources of mercury that discharge into the water. Some aquatic ecosystems have natural environmental conditions that make them more sensitive to even small amounts of mercury, allowing rapid and efficient uptake of mercury into the food chain and accumulation in fish. These aquatic ecosystems have environmental conditions that allow certain bacteria in the sediment to convert mercury into methylmercury in a highly efficient manner. This increases the rate at which added mercury can be converted into methylmercury and accumulated by the fish in these waterbodies. The important environmental conditions that create the right conditions for these types of bacteria include low dissolved oxygen, low pH (slightly acidic waters) and high levels of organic matter. These environmental conditions are common in swamps, wetlands and some lakes or reservoirs. This helps explain why some waterbodies have elevated levels of mercury in fish, even when there are no direct sources of mercury into the waterbody except for low levels of mercury deposited from the air. This phenomenon of some waterbodies being especially sensitive to mercury contamination will be described in more detail below.

Detailed Discussion of Environmental Conditions of Mercury Sensitive Waters

During the 1990s scientists began to better understand the extent of mercury contamination of fish in lakes and other waterbodies in many parts of the world. Many of these waterbodies, including the Everglades in Florida and isolated lakes in the southeastern and northern United States, Canada and Scandinavia had little or no direct discharges of wastewater from industries or wastewater treatment plants, yet the fish in these waterbodies showed elevated levels of mercury. As more research was conducted, it became apparent that some waterbodies have physical and chemical characteristics that promote the uptake of mercury into the food chain and this leads to the accumulation of mercury in some species of fish, especially the top predator fish, such as bass.

In order to become readily taken into the food chain, mercury must be chemically combined with a methyl molecule (CH_3) to form methylmercury ($Hg\text{-}CH_3$). Some species of naturally occurring bacteria commonly found in soil or sediment are capable of absorbing mercury in a variety of forms and converting it to methylmercury, thereby making the mercury more biologically active. This "methylation" by bacteria in soils of mercury into the toxic form methylmercury is a key step in the process that most dramatically influences whether or not mercury may become accumulated in fish to high enough concentrations that it could present a potential risk to consumers if eaten in an unrestricted fashion.

Methylmercury can easily pass through cell membranes and is much more toxic than elemental mercury. Once converted into methylmercury, mercury is much more likely to be easily absorbed by living things and, as these are eaten by other aquatic animals, the methylmercury is accumulated to higher levels in each step up the food chain. The top predators in the ecosystem, generally the fish species that eat other fish, such as bass, often have the highest concentrations of mercury.

As research continued in the 1990s, it became clear that certain environmental conditions were associated with the observed high levels of mercury in fish. In general, high levels of mercury in fish were seen in waterbodies that were more acidic, contained high levels of organic matter and had low levels of dissolved oxygen, all of which are often natural characteristics of some types of lakes, swamps or wetlands. Under these environmental conditions, the types of bacteria that can convert mercury into methylmercury are more likely to be present and active.

These waterbodies are considered “mercury sensitive waters” because their natural environmental conditions [low dissolved oxygen, low pH (a measure of acidity) and high amounts of organic matter] make them more likely to promote the methylation of any mercury that enters these ecosystems. In other words, if the same, small amount of mercury is added to a swamp water and a free-flowing stream or river, the fish in the swamp are more likely to accumulate higher levels of mercury.

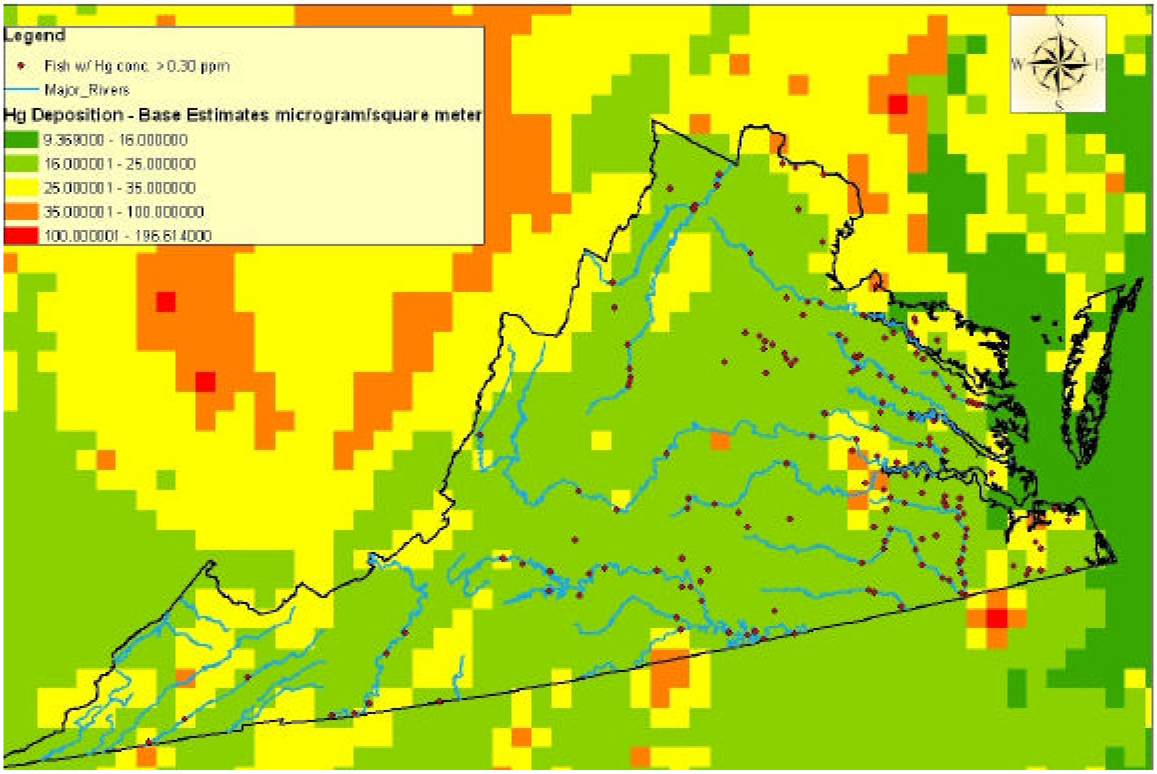
Mercury coming out of combustion stacks can be in three general forms: elemental mercury as a vapor, ionic mercury as inorganic compounds (mostly mercuric chloride) and particulate-bound mercury as organic compounds. Elemental mercury (as a vapor) is generally transported great distances, becoming part of the global air mercury reservoir, while particulate-bound mercury is deposited locally, and ionic mercury is transported and deposited intermediate distances. The ionic forms of mercury are very water-soluble and can quickly become incorporated into the mercury methylation cycle and quickly enter into the food chain.

The journey between air emissions of mercury to fish contamination involves photochemical processes, deposition and conversion of mercury compounds into methylmercury at the water-sediment surface interface. The conversion into methylmercury is performed by a class of bacteria known as sulfur-reducing bacteria, which are very common in soil and sediments. These bacteria are found in soil and in sediments in waterbodies where the environment changes between oxygen-rich to oxygen-poor. As mercury compounds and sulfates are deposited onto the surface of the sediment, they diffuse into the bacteria-rich zone and are converted into methylmercury by the bacteria.

Figure 5-1 illustrates the predictions of air-mercury deposition rates for the base year of 2002 from the ICF study. Superimposed on the map of Virginia are locations in waterbodies where the average concentrations of mercury in recreationally important fish species were greater than 0.30 ppm (the proposed fish criterion for fish tissue in Virginia).

Figure 5-1

Total Atmospheric Hg Deposition Estimates(2002) vs
Avg. Recreational Fish Hg Concentrations > 0.30ppm



DEQ has found that fish in at least 11 waters in eastern Virginia are contaminated with mercury. Sampling results triggered fish consumption advisories in the Great Dismal Swamp Canal (including Lake Drummond), portions of the Blackwater River and Dragon Run Swamp, as well as eight other rivers and small lakes. These waters appear to be mercury-sensitive, meaning that they are more likely than other waters to have natural conditions that are favorable for the conversion of mercury into methylmercury. The waters share three characteristics: low levels of oxygen, high amounts of organic matter and low pH, which indicates that they are acidic. These traits are common in swamps, streams and rivers in Virginia's coastal areas as well as in some lakes or reservoirs. Another chemical constituent that appears to be important to the increased potential for mercury methylation in the environment is sulfate. Moderately elevated levels of sulfate appear to increase the potential for methylation of mercury. Extremely high concentrations of sulfate, however, seem to have a dampening effect on the methylation process. It is thought that sulfate helps to stimulate the bacteria that are responsible for the mercury methylation. Information from the Florida Everglades (Florida DEP, 2003) study indicates that some of the reduction of mercury in fish tissue in those sites is attributable to joint reductions of mercury deposition following control of local air emissions as well as reductions in local inputs of sulfates into the waterbody.

Monitoring of Fish Contamination in Virginia

The DEQ - Office of Water Quality Programs' Fish Tissue and Sediment Contaminants Monitoring Program conducts routine studies of fish tissue and sediment samples in state waters. The fish monitoring program collects fish and sediment samples from selected sites in Virginia waters and has them analyzed for selected toxic contaminants that are likely to be found in fish tissue. These contaminants include a variety of organic chemicals such as pesticides and poly-chlorinated biphenyls (PCBs), as well as metals, including mercury. The sites where the fish and sediment are collected are selected based on a variety of reasons, but these sites are targeted mostly because of a proximity to industrial or municipal discharges into the waterbodies, or other potential sources of toxic chemical contaminants that are likely to bioaccumulate in fish tissue.

The monitoring program is designed to sample sites in the river basins in Virginia, rotating the monitoring around the state in each major river basin every three to five years, depending on the availability of sufficient resources. Depending on available resources (staff and funds for contaminant analysis), between 70 and 100 sites have been monitored each year since 1998. Fish and sediment samples are collected between April and September of each year, the chemical analysis is performed during the winter, results are reported to DEQ beginning in February of the following year, and all data are due no later than June 30. All data are shared with the Virginia VDH and also posted on the DEQ website soon after receipt from the lab.

At each monitored site, five to ten individual fish for each of three to five different species of fish are collected. These fish species are selected to represent different feeding habits and positions in the food chain and will include a bottom feeder like a catfish, an insect-eating fish like the sunfish species and an upper-level predator species like a bass. By collecting these different species, DEQ can determine if a toxic chemical may accumulate in one level of the food chain.

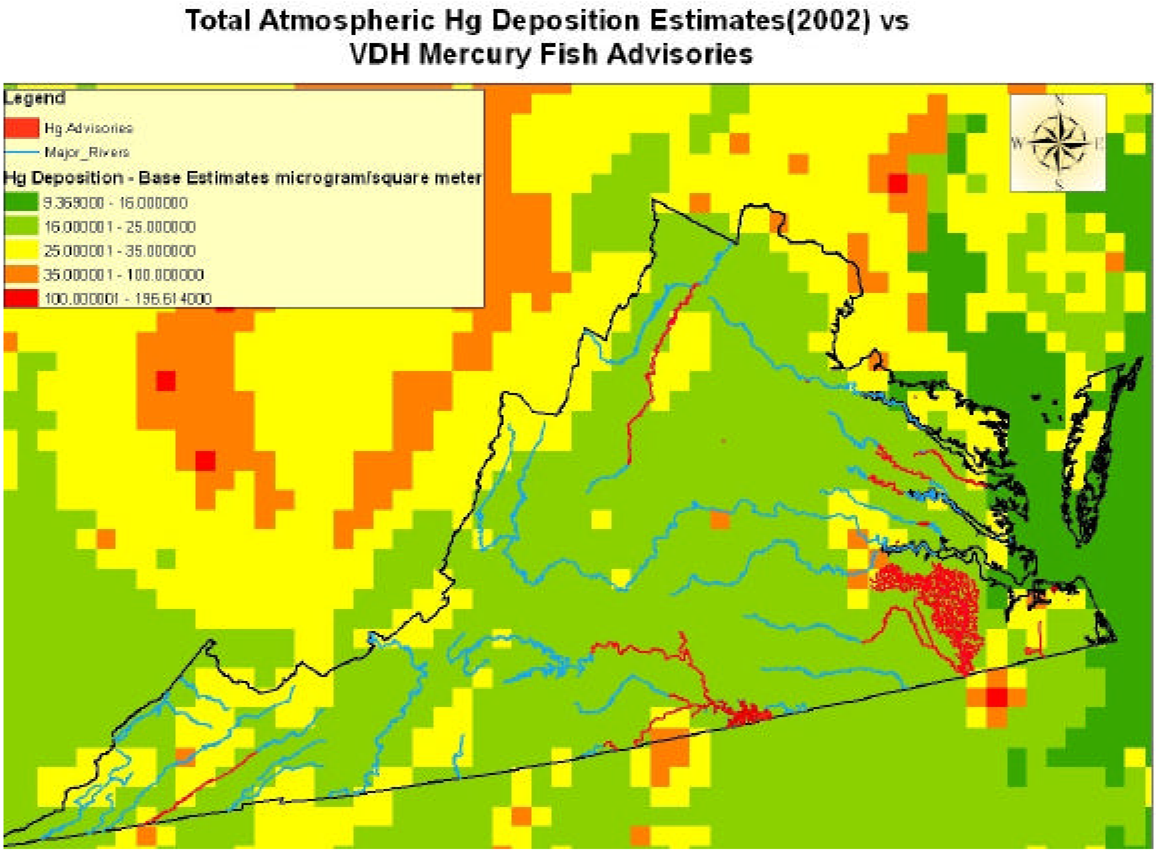
The concentrations of toxic contaminants detected in the fish are assessed to determine the potential for human health risks for individuals who may consume fish from state waters and to identify impaired aquatic ecosystems. The VDH uses the data generated by the program to determine the need for issuing fish consumption advisories. DEQ and other state and federal agencies also use the data to assess the environmental quality of Virginia's waters. Along with the fish, at least one sediment sample is collected at each station where fish tissue are sampled and analyzed for a suite of bioaccumulative chemical contaminants.

Fish Consumption Advisories Due To Mercury-

In Virginia, DEQ is responsible for monitoring fish for bio-accumulative chemicals and assessing if a waterbody is impaired due to elevated levels of toxic contaminants. DEQ shares all these data with the VDH staff who review the fish contamination data to determine whether a fish consumption advisory is warranted and, if so, VDH issues the advisory. For each waterbody, all available data on the contamination levels of each toxic contaminant are reviewed and the different species of fish are assessed separately.

Figure 5-2 displays the current (as of 2007) fish consumption advisories for mercury issued by VDH and the corresponding modeled mercury deposition for the base year.

Figure 5-2



The VDH uses 0.5 mg/kg or 0.5 ppm of methylmercury in fish filet tissue as a trigger level for the issuance of a fish consumption advisory. If average tissue concentrations of mercury are below 0.5 ppm, the VDH will conclude that a fish consumption advisory is not warranted. When a fish species' tissue average concentration of mercury is between 0.5 and 1.0 ppm, VDH will recommend limiting consumption of the contaminated species to two, eight-ounce meals per month and that young children, pregnant women and nursing mothers should not consume the contaminated species of fish. If the average concentration of mercury in a species of fish is between 1.0 and 2.0 ppm, the VDH will recommend limiting consumption to one, eight-ounce meal per month. If the average mercury concentration in fish exceeds 2.0 ppm, the VDH will recommend that the contaminated species of fish not be consumed.

Based on these VDH guidelines for issuing fish consumption advisories because of mercury, a fish consumption advisory that has been issued by the VDH can be expected to remain in place until the average concentration of mercury in the affected species has been reduced below 0.5 ppm. It is expected that at least two years of monitoring data that show average fish mercury concentrations below 0.5 ppm in the species of fish previously known to be contaminated will be needed to show that such a reduction in fish mercury contamination has occurred and a removal or relaxation of the fish consumption advisory is warranted.

The VDH trigger value of 0.5 ppm applies to methylmercury in edible fish filet tissue. The analytical lab used by DEQ to analyze fish contaminants reports concentrations of total mercury in fish tissue rather than methylmercury. This is a cost-saving issue as methylmercury analysis is more expensive. This is standard practice for analyzing mercury in fish tissue and most of the mercury in fish tissue is, in fact, methylmercury. It has been shown in numerous studies that in larger, predator fish (the species most likely to bioaccumulate mercury to higher levels), approximately 90 percent to more than 95 percent of the total mercury detected is methylmercury. Risk assessments on total mercury concentrations in fish is conducted with recognition that this may involve a potential 5 to 10 percent overestimation of the methylmercury included in the total mercury concentration in fish tissue. The use of this methodology is a conservative approach that is utilized to account for variability in the amount of mercury that may bioaccumulate within a fish. This potential difference of 5 to 10 percent between measured total mercury and methylmercury is rarely an issue except in a few cases where the concentration of total mercury in fish sample is just above 0.5 ppm. In such borderline cases, VDH may postpone issuing a fish consumption advisory until additional monitoring is conducted to better confirm whether the average concentrations of methylmercury in the affected species of fish are above the level of concern.

Summary of Calculation of Waterbody Specific Mercury Reduction Factors Used to Estimate Changes in Future Fish Contamination

One of the important issues investigated in this report is the potential for reductions in mercury concentrations in fish after the projected reductions in mercury deposited by air into the watershed has occurred. In order to do this, estimates were needed of the reductions in air-deposited mercury that were projected by the air-mercury deposition model for the watersheds of the mercury sensitive waterbodies. The ICF model produced estimates of mercury deposition rates for the base year as well as projected estimates of deposition rates for 2010, 2015 and 2018. These estimates of past and future mercury deposition rates were used to predict the proportional reductions of inputs of mercury into the watersheds of the mercury sensitive waterbodies in Virginia after the years 2010 and 2018.

These estimated reductions in deposited mercury were used to estimate the proportional amount of reduction in mercury in fish that might be expected after the reductions in air deposition had taken effect. These reductions in air deposition rates were averaged across the watershed of each affected waterbody to produce a “reduction factor” that could be used to estimate potential future fish mercury levels in that waterbody. It was assumed that a reduction in mercury deposited into the watershed would result in an equal amount of reduction in fish tissue mercury.

Details of Method of Calculation of Reduction Factors

The ICF deposition model projected mercury deposition rates after the projected reductions in air deposition into the watershed will have occurred. The ICF deposition model produced estimated mercury-air deposition rates for the entire state of Virginia and surrounding areas for the base year and projected mercury deposition rates for the years 2010, 2015 and 2018. These mercury deposition rates were estimated for wet deposition (deposited in rainfall), dry deposition (particulate) and total mercury deposition rates. These estimates were supplied for cells overlaid on a map of Virginia and the surrounding states. The square cells are 12 kilometers (7.4564 miles) on each side, and cover 144 square kilometers, or about 55.6 square miles. The model predicted a total mercury deposition rate for the base year for individual cells which was considered to be representative of the atmospheric deposition rate that contributed to the mercury fish tissue concentrations detected in DEQ's fish monitoring program between the years 2002 and 2006, which is the period during which DEQ expanded fish monitoring to more extensively sample swamp waters unrelated to known potential human impacts.

The rate of total mercury deposition predicted for 2010 by the model for a cell was divided by the deposition rate in the base year to get an estimate of the relative proportion of the 2002 mercury deposition that would remain in 2010. For example, if the total mercury deposition rate in 2002 was estimated by the model to be 20 micrograms per square meter (ug/m^2), and the model's estimate for 2010 was 16 ug/m^2, then the total mercury projected to be deposited in that cell in 2010 is 16/20 = 0.80. That is, 80 percent of the mercury that was estimated by the model to have been deposited in the base year of 2002 is expected to be deposited into that cell in 2010, representing a 20 percent decrease in mercury input to that cell.

This example calculation produces a "reduction factor" of 0.80 that, when multiplied by the average concentration of mercury of a species of fish collected in the past from that waterbody, can be used to estimate the potential fish mercury concentrations in the future after the ecosystem responded to the reduced mercury deposition rates predicted by the model for 2010. The same calculations were performed for the projected 2018 reductions in total mercury deposition rates. In general, the major projected reductions in mercury deposition rates were predicted by the model for 2010, with an additional reduction of only one to three percent by 2018. The projected reductions for 2015 were intermediate between the estimates for 2010 and 2018, but were not calculated in every case because they were within approximately one percent of the 2018 model predictions. The reduction factors calculated for 2010 and 2018 were used to assess potential, future fish mercury concentrations in the mercury-sensitive waters where fish consumption advisories are currently in effect in Virginia. These predictions were made using the results of ICF's deposition modeling which provided the mercury deposition to occur as a result of emission reductions required by CAIR and CAMR.

Comparisons were made between the ICF model's estimates of total mercury deposition rates for the base year of 2002 and for future deposition rates for 2010 and 2018 for each model cell that overlaid the Virginia river basins that are considered to be mercury-sensitive due to environmental conditions and where a current fish consumption advisory exists due to elevated levels of mercury in fish. These are the Dragon Run Swamp, Mattaponi River, Herring Creek, Pamunkey River, Chickahominy Lake, Blackwater River, Nottoway River, Meherrin River, and the Dismal Swamp Canal and Lake Drummond, the Kerr Reservoir, Lake Gordonsville, Harrison Lake, Motts Run Reservoir and Chandler's Mill Pond. All of these waterbodies are thought to be mercury-sensitive because they are either isolated lakes or are river systems that are significantly influenced by connected swamps or wetlands, and they generally do not have any significant sources of human discharges into the waterbody that are a likely source of mercury. A few other rivers or lakes also have fish with levels above 0.30 or 0.50 ppm mercury, but these have significant human activity within their watersheds which could provide other sources of mercury, and these waterbodies are not connected to wetlands or other zones of increased mercury methylation.

For each cell that overlaid these waterbodies, proportional estimated reductions in total mercury deposition rates were calculated for 2010 and 2018 as described above. Because the model's predictions of deposition rates are not considered to be exactly delineated along the borders of the 12 kilometer squares, the cells surrounding the actual cells overlaying the river basins were also reviewed to determine if any of these border cells showed significantly different deposition rates. This was done to evaluate if a nearby area with predicted higher mercury deposition was in close enough proximity to the river basin to possibly influence the river's drainage area. If any of these border cells showed a difference in total mercury deposition rates of greater than 10 percent compared to the cells actually overlaying the waters in the river basin, projected proportional reductions were calculated for the border cells as well as the cells actually overlaying the river system and average reduction rates were calculated including the border cells' data.

These potential areas of higher mercury deposition were evaluated separately to see if this could be a potential for significant, different estimates of effects on future changes in fish mercury contamination levels. In general, none of these potential areas of higher mercury deposition showed a difference in mercury deposition reduction factors of greater than 10 percent of the average reduction factor for the entire river basin's watershed. One of the greatest differences was at the headwaters of the Blackwater River, with a reduction factor of 0.7492 for the three headwater streams compared to the average of 0.8296 (a relative difference of 9.7 percent) for the rest of the Blackwater watershed. The other greatest difference in deposition rates occurred at the Virginia border with North Carolina at the confluence of the Blackwater River and the Nottoway River, where the overall average reduction factor for the Blackwater River basin was 0.8296 and the reduction factor for the downstream border cells in North Carolina was 0.6745, for a relative difference of 19 percent.

In most cases, the proportional reduction factors for the cells along a river system were fairly uniform in value, generally differing by only a few percentage points, and an average reduction rate was calculated for the entire river basin. These reduction factors were used to estimate the potential for changes in fish mercury concentrations by multiplying the average mercury concentration in a species of fish from that river by the projected reductions in mercury deposition for the river basin for both 2010 and 2018.

The modeled reductions in total mercury deposited into the individual rivers' watersheds were used to calculate the relative amount of mercury deposition that was projected to continue to occur in future years in comparison with the baseline mercury deposition rates estimated for the base year. The modeled deposition rates for the base year are considered representative of the conditions that were responsible for the fish mercury concentrations that were detected during the DEQ fish monitoring between 1998-2006. This information was used to calculate a "reduction factor" for future years representing the remaining air-deposited mercury compared to the rates of deposition in the base year. For example, the air model predicted that after the 2010 anticipated emissions reductions had taken effect, the average air deposition rate of total mercury onto the watershed of the Dragon Run Swamp would be 82.01 percent of the mercury deposition rate in the base year. This represents an estimated 17.9 percent reduction in the air deposition rate for total mercury after 2010, compared to the deposition rate of the base year. This produces a "reduction factor" of 0.8201 estimated for this watershed based on projected 2010 deposition levels. The reduction factor for the river basin can be used to estimate future fish mercury concentrations levels in response to reduced mercury deposition.

It was assumed by DEQ that the fish mercury concentrations in an ecosystem are in dynamic equilibrium with mercury inputs to that watershed and that a reduction in mercury deposition will result in a proportional reduction in fish mercury concentrations after the ecosystem re-equilibrates to the lowered inputs of mercury. Under this scenario, the reduction factor for the watershed can be multiplied times the fish mercury concentrations observed in previous monitoring (which are assumed to be a result of deposition rates represented by the base year) to estimate future mercury fish concentrations after the projected reductions in mercury deposition rates have occurred. For example, if previous samples of largemouth bass from the Dragon Run Swamp contained an average concentration of mercury of 1.0 ppm, then after the projected 2010 reductions in air deposition rates take effect, future concentrations in this species may be estimated to average 1.0 ppm mercury x 0.8201 (the river-specific reduction factor based on 2010 estimated remaining mercury deposition) = 0.8201 ppm mercury.

The reduction factors represent the proportional amount of mercury deposition to the watershed based on the estimated deposition rates for the base year that the model estimated will continue to occur after the 2010 and 2018 anticipated reductions have taken effect in mercury-air deposition for the modeled years 2010 and 2018. The reduction factors generally decrease slightly numerically between 2010 and 2018, which reflects slight additional reductions in the air deposition rates. For comparison purposes, a lower value of a reduction factor indicates that a greater amount of mercury from air deposition is expected to occur in the watershed, i.e., a greater percent reduction was estimated by the model.

The average projected reduction factors in total mercury air deposition estimated for 2010 and 2018 for the mercury-sensitive river basins important to this fish consumption and risk assessment study are shown in Table 5-1.

Table 5-1 Mercury Deposition Reduction Factors for Advisory Waterbodies(compared to base year)

		2010	**2018**
		Reduction Factor	**Reduction Factor**
River Basin		**Year 2010**	**Year 2018**
Dragon Run Swamp		0.8201	0.7972
Mattaponi River		0.8120	0.7853
Herring Creek		0.8120	0.7972
Pamunkey River		0.8063	0.7830
Chickahominy Lake		0.8096	0.7885
Harrison Lake		0.7647	0.7635
Blackwater River		0.8296	0.8145
Nottoway River		0.8332	0.8079
Dismal Swamp Area		0.7808	0.7711
(potential alternate for canal)			0.7332 (see text)
Kerr Reservoir (Roanoke River)		0.8110	0.7765
Chandler's Mill Pond		0.7215	0.6995
Motts Run Reservoir		0.7910	0.7700
Lake Gordonsville		0.8433	0.8289

The ICF air deposition model's projected future changes in mercury deposition rates were used to estimate the potential for changes in fish concentrations of mercury in response to the projected reductions in mercury input into the ecosystem via reduced air emissions and corresponding reductions in air deposition of mercury into the watersheds.

Assumptions Used in Analysis

It was assumed that, given a reduction in mercury deposition into the waterbody system, there would be a corresponding and proportional reduction in mercury in the ecosystem available to be methylated and taken up into the food chain. It was assumed that there would be a one-to-one relationship between reduced mercury deposition and the resulting fish concentrations in that waterbody; that is, if the amount of mercury deposited into the ecosystem is reduced by 20 percent, a potential reduction of 20 percent in the concentration of mercury in the local fish tissue would result. This assumes that, once there is a reduction in mercury input, the ecosystem will have less mercury to process by methylation in the sediment into methylmercury, and less uptake of methylmercury into the food chain and magnification of the mercury concentrations in fish tissue as it moves up the food chain. All these processes within an ecosystem are assumed to be in balance and, if the initial key amount of mercury is reduced, then correspondingly lower concentration in fish tissue will eventually result.

As discussed previously, available evidence from a variety of sources suggests that this is a reasonable assumption, after the ecosystem processes this mercury and the methylation process and food-chain uptake occurs. The time frame necessary for the ecosystem to readjust to the reduced mercury inputs and come to equilibrium, however, will be site-specific and each waterbody is likely to react somewhat differently. It is unknown what time frame may be necessary for the ecosystem to adjust to the reduced mercury available and when the fish tissue concentrations of mercury may be lowered to correspond to the reduced mercury inputs. The process may vary from a few years to several decades or longer.

Summary of Estimated Changes in Fish Mercury Concentrations in Response to Decreased Mercury Deposition Rates in 2010 and 2018

The reduction factors described in the previous section were used to predict the potential for reduced fish mercury concentrations in the future. These estimates of future fish mercury concentrations are based on the estimates of reduced air-mercury deposition rates predicted for 2010 and 2018. After these projected future reductions in mercury depositions have been achieved, the ecosystems are expected to equilibrate to the lowered inputs of mercury and this is expected to result in a proportional lowering of fish mercury concentrations in the future.

The timeframe for the ecosystem to adjust to the lowered mercury levels and for the fish to reach the predicted lower mercury concentrations will depend on how quickly the specific waterbody will equilibrate to the new, lower mercury levels. This will probably be on the order of a few years to decades, with lakes responding more quickly and wetlands requiring some additional time. The fish already contaminated will continue to show mercury levels due to earlier mercury deposition levels until they die. Many of these fish species may live five or more years, so significant changes in adult fish in these waterbodies may not be detectable for at least that time period. Changes in fish mercury contamination levels might be more readily detected in younger fish at one to two years of age, after the predicted changes in mercury deposition have had a chance to occur.

Use of Reduction Factors to Estimate Future Fish Mercury Concentrations

The DEQ data set of fish tissue mercury concentrations reported for fish from selected waterbodies was reviewed to determine if the reductions in mercury deposition projected for 2010 and 2018 by the air deposition model could be expected to result in reduced fish tissue concentrations in these waterbodies and especially to evaluate whether these reductions might result in a relaxation or removal of the fish consumption advisories.

Two "screening values" of mercury concentration in fish tissue were evaluated. The level of concern used by the VDH to issue a fish consumption advisory is 0.50 ppm. The data were examined to evaluate whether or not the levels of mercury could be expected to decrease to a level below this 0.50 ppm level, and the possibility of relaxing or lifting the current fish consumption advisories. The data were also examined using 0.30 ppm as a criterion. This is the fish methylmercury criterion recommended by the EPA, and this has been proposed for adoption in Virginia during the current triennial review of water quality criteria.

The historical fish mercury concentration data were collected for all the fish collected by DEQ's fish monitoring program between 2002 and 2006, which is the period of time when DEQ expanded the monitoring of fish into these swamp waters. The data were separated for each waterbody affected by current mercury-caused fish consumption advisories and the average concentration of mercury was calculated for each fish species collected in the waterbody. These average mercury concentrations were compared to the 0.50 advisory thresholds and to the potential future 0.30 ppm water quality criterion. The results of the analysis are presented below for the mercury-sensitive waters listed in Table 5-2.

Summary of Predictions of Changes in Fish Contamination Levels

As of 2007, there are thirteen waterbodies with fish consumption advisories that are considered mercury-sensitive waters and which have very little direct human impact attributable to the mercury-related fish consumption advisories. The estimates for reduced deposition rates of mercury after 2010 and potential effects on future fish contamination levels suggest that there is a possibility that three to four of the thirteen fish consumption advisories might become unnecessary and at least one fish species might be removed from the advisories in all but two of the advisory waterbodies.

A summary of the important findings of this analysis of the potential for reduced levels of mercury fish contamination following reduced rates of mercury-air deposition rates includes:

- Most of the expected reductions in mercury deposition will occur due to the emissions reductions projected for 2010. The additional reductions projected for 2018 are only an additional one to three percent.

- Estimated reductions in mercury deposited into the affected waterbodies and consequently into fish tissue vary from about 17 to 30 percent.

- Applying the reductions in air deposited mercury projected for 2010 and 2018 to the average fish mercury concentrations in the fish consumption areas, there is a possibility of the affected fish species' containing less than the concentration of mercury necessary to issue a fish consumption advisory. It was estimated that the average mercury concentration in the affected fish species could drop below the VDH trigger value (0.50

ppm) for issuing a fish consumption advisory for all species of fish included in the advisory in 3 of the 13 advisory waterbodies, and that this is a borderline possibility in one other waterbody. If this were to be the case, the current advisories may be removed from these three or four waterbodies. In addition, the Dismal Swamp Canal and Lake Drummond may be affected such that one of the two contaminated fish species can be removed from the advisory and the advisory area may also be reduced in size.

- In 11 of the 13 advisory waterbodies, at least one species of fish was estimated to have a potential for containing mercury concentrations less than 0.50 ppm in the future, after the 2010 reductions take effect. If this were to prove true, then these fish species may be removed from the advisories in the future.

- Almost all fish species currently included in the various fish consumption advisories will remain above the Proposed Virginia Fish Tissue Criterion of 0.30 ppm, with only one exception in one waterbody.

- The time frame necessary for the waterbodies' ecosystems to respond to the reduced mercury inputs and the resulting expected reduction in fish tissue mercury concentrations will vary for each waterbody. Reservoirs and lakes will likely respond within a few years to decades, while wetlands will likely respond more slowly, but possibly within years to decades, or longer.

This analysis suggests that, after the expected controls on mercury air emissions required by CAIR and CAMR projected for 2010 and 2018 have taken effect and the ecosystems respond to the reduced mercury deposited into them as a result, several fish consumption advisories will still be considered warranted.

The results of the assessment for potential changes to existing fish consumption advisories for these waterbodies due to the effects of the estimated lower mercury deposition rates are summarized in Table 5-2.

Table 5-2. Potential for Future Changes in Fish Consumption Advisories

Waterbody	# Fish Species Affected by Advisory	# Fish Species < 0.30 ppm	# Fish Species < 0.50 ppm	Potential for Removal of Species	Potential for Removal of Advisory
Dragon Run Swamp	**1**	**None**	**1**	**Yes**	**Yes**
Mattaponi River	**1**	**None**	**None**	**No**	**No**
Herring Creek	**2**	**None**	**1 of 2**	**Yes**	**No**
Pamunkey River	**1**	**None**	**None**	**No**	**No**
Chickahominy Lake	**3**	**None**	**1 of 3**	**Yes**	**No**
Harrison Lake	**4**	**None**	**2 of 4**	**Yes**	**No**
Blackwater River	**7**	**None**	**3 of 7**	**Yes**	**No**
Nottoway River	**8**	**None**	**4 of 8**	**Yes**	**No**
Dismal Swamp Canal **& Lake Drummond**	**2** **2**	**1 of 2** **1 of 2**	**2 of 2** **1 of 2**	**Yes** **Yes**	**Possible reduced advisory area (see text)**
Kerr Reservoir	**2**	**None**	**1 of 2**	**Yes**	**No**
Chandler's Mill Pond	**1**	**None**	**1 of 1**	**Yes**	**Yes**
Motts Run Reservoir	**1**	**None**	**1 of 1**	**Yes**	**Yes**
Lake Gordonsville	**1**	**None**	**1 possible**	**Yes**	**Possible (see text)**

Details of Estimated Changes in Fish Mercury Levels in Individual Waterbodies

The following section provides the details of the review of each of the fish consumption advisory waters in mercury-sensitive waters.

Dragon Run Swamp

The current fish consumption advisory for the Dragon Run Swamp applies to largemouth bass only. Mercury deposition rates for the watershed of the Dragon Run Swamp were similar in all cells along its length, with projected reduction factors varying by less than 5 percent. The average projected reduction factor estimated for 2010 was 0.8201. That is, 82.01 percent of the mercury estimated to have been deposited in 2002 was estimated to be still deposited in 2010. This is the same as an estimated reduction of 17.99 percent. The projected reduction factor for 2018 is 0.7972.

These reduction factors for 2010 and 2018 were multiplied by the average mercury concentrations for largemouth bass collected from the Dragon Run Swamp and contained in the DEQ's fish contamination data set. The results are shown in the table below:

Dragon Run Swamp	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.49	0.4018 ppm	0.3906

These estimated concentrations are below the 0.50 ppm trigger value used by the VDH to issue fish consumption advisories. If future monitoring of largemouth bass from the Dragon Run Swamp show mercury levels this low, the removal of the current fish consumption advisory for this waterbody could result. However, these estimated mercury concentrations are still above the fish tissue target value of 0.30 ppm that is recommended by EPA and which DEQ has proposed for adoption in 2008 as a fish tissue quality criterion, as part of Virginia’s water quality standards regulation.

Mattaponi River

The current fish consumption advisory for the Mattaponi River applies to largemouth bass. Mercury deposition rates for the watershed were similar in all cells along its length, with projected reduction factors among the cells varying by less than 5 percent. The average projected reduction factor estimated for 2010 was 0.8120, and the projected reduction factor for 2018 is 0.7853.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species, estimated mercury concentrations in largemouth bass from the Mattaponi River are estimated as shown below.

Mattaponi River	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.856	0.6953 ppm	0.6722 ppm

Under this scenario, the estimated reductions in mercury deposition in the Mattaponi River basin are not expected to result in sufficiently reduced contamination in the largemouth bass to allow for a removal of the current fish consumption advisory.

Herring Creek (tributary to the Mattaponi River)

The current fish consumption advisory for Herring Creek applies to bluegill sunfish and yellow bullhead catfish. Projected total mercury deposition rates for the watershed were similar in all cells along its length, with projected reduction factors varying by less than five percent. The average projected reduction factor estimated for 2010 was 0.8120, and the projected reduction factor for 2018 is 0.7972

Applying these reduction factors to the average concentrations of mercury found in the affected fish species, the projected future mercury concentrations in bluegill sunfish and the yellow bullhead catfish are shown below:

Herring Creek	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep. Reductions**	**After 2018 Air-Dep. Reductions**
Bluegill Sunfish	0.591 ppm	0.4798 ppm	0.4711 ppm
Yellow Bullhead Catfish	1.017 ppm	0.8255 ppm	0.8108 ppm

These estimates for the sunfish are below the VDH fish consumption advisory trigger value and could result in a relaxation of the current advisory by removing bluegill sunfish from the consumption advisory. The estimated future concentration in the catfish species, however, is still above the trigger value for a fish advisory, so it is probable that this catfish species will continue to warrant the advisory. Also, both species are projected to remain contaminated at levels greater than the proposed Virginia fish tissue criterion of 0.30 ppm.

Pamunkey River

The current fish consumption advisory for the Pamunkey River applies to blue catfish. Mercury deposition rates for the watershed of the Pamunkey River were similar in all cells along its length, with projected reduction factors among the cells varying by less than 5 percent. The average projected reduction factor estimated for 2010 was 0.8063, and the projected reduction factor for 2018 is 0.7830.

These reduction factors for 2010 and 2018 were multiplied by the average mercury concentration for blue catfish collected from the Pamunkey River, and the resulting projected concentrations are shown below.

Pamunkey River	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Blue Catfish	0.730	0.5886 ppm	0.5716 ppm

These estimated future mercury concentrations in blue catfish remain above the 0.50 ppm trigger value used by VDH to issue fish consumption advisories. Under this scenario, the estimated reductions in mercury deposition in the Pamunkey River basin are not expected to result in sufficiently reduced contamination in the blue catfish to allow for a removal of the current fish consumption advisory.

Chickahominy Lake

The current fish consumption advisory for the Chickahominy Lake applies to largemouth bass, chain pickerel and bowfin. Mercury deposition rates for the watershed of the Chickahominy Lake were similar in all cells along its length, with projected reduction factors among the cells varying by less than 5 percent. The average projected reduction factor estimated for 2010 was 0.8096, and the projected reduction factor for 2018 is 0.7885.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Chickahominy Lake, estimated mercury concentrations are estimated as shown below.

Chickahominy Lake:	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.67	0.5424	0.5283
Chain Pickerel	0.63	0.51	0.4968
Bowfin	1.15	0.931	0.9066

Under this scenario, the estimated reductions in mercury deposition in the Chickahominy Lake basin are not expected to result in sufficiently reduced contamination in the bowfin to allow for a removal of the current fish consumption advisory. However, the projected reduced concentrations in the largemouth bass and chain pickerel are less than 10 percent above the fish consumption trigger value, so there appears to be some potential for possible changes for these species.

Harrison Lake

The current fish consumption advisory for Harrison Lake (Charles City County) applies to redear sunfish, largemouth bass, chain pickerel and bowfin. Mercury deposition rates for the watershed of Harrison Lake produced a projected reduction factor estimated for 2010 of 0.7647, and the projected reduction factor for 2018 is 0.7635.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Harrison Lake, estimated mercury concentrations are shown below.

Harrison Lake	**Average Fish Concentration of Mercury (ppm)**	**Projected Fish Mercury (ppm) Concentration**	**Projected Mercury (ppm) Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Redear Sunfish	0.53	0.4053	0.4047
Largemouth Bass	0.93	0.7112	0.7101
Chain Pickerel	0.61	0.4665	0.4657
Bowfin	1.02	0.78	0.7788

Under this situation, the estimated reductions in mercury deposition in the Harrison Lake basin could be expected to result in sufficiently reduced contamination in the redear sunfish and chain pickerel to potentially allow for a removal of these two fish species from the current fish consumption advisory. However, the projected reduced concentrations in the largemouth bass and bowfin remain above the fish consumption trigger value, so these two species are predicted to continue to warrant a fish consumption advisory, and all four species are predicted to remain above the 0.30 ppm proposed fish tissue criterion.

Blackwater River System

The current fish consumption advisory for the Blackwater River applies to largemouth bass, redear sunfish, bowfin, chain pickerel, white catfish, redhorse sucker and longnose gar.

Mercury deposition rates for the watershed of the Blackwater River were similar in most cells along its length, with projected reduction factors among the cells varying by less than 5 percent with the following exceptions. There is a modeled zone of slightly elevated mercury deposition for 2002 baseline deposition rates in a few cells that overlay or surround the headwaters of the Blackwater River system, just to the east and south of Petersburg. The cells surrounding the headwaters of the Blackwater River in this area show modeled elevated total mercury deposition rates for the baseline year of between 26.057 and 52.81ug/square meter (mean of 33.05), which are slightly higher than the average deposition rates that are estimated for cells along the main portion of the Blackwater River, which range from 24.427 to 19.48 with a mean of 22.029 ug/square meter. There is also another zone of slightly elevated mercury deposition that coincides with the mouth of the Blackwater River. The reductions in deposition rates for 2010 and 2018 estimated by the model for this local area of elevated baseline deposition rates consequently results in calculating a lower reduction factor for the area of the small headwaters; that is, the model predicts a greater percent reduction in mercury deposited into this headwater area in comparison with the majority of the watershed. This small area of elevated total mercury was assessed and a localized reduction factor of 0.7492 was calculated for the uppermost headwaters of the Blackwater River system. However, this was not assessed separately from the rest of the Blackwater River system because the potential area of local influence on these small headwater streams is very small compared to the rest of the Blackwater River watershed, which was relatively homogeneous in modeled deposition rates. Calculated reduction factors for the other cells that overlay the Blackwater River are also homogeneous and range between 0.8108 and 0.8407 (based on 2010), with a mean of 0.8296, which was used to assess the Blackwater River system in its entirety. If this local area at the headwaters with estimated elevated baseline deposition rates and the subsequent lower reduction factor is considered to potentially affect the entire Blackwater River system (approximately 100 miles in length), it could have a potential effect of approximately an additional 1 to 2 percent reduction at most in fish tissue mercury in the future. This would not significantly change the conclusions reached by the analysis shown below, which are based on the assumption that this small, local area would not influence the entire Blackwater River system.

Using the deposition rates for the cells that directly overlaid the watershed for the Blackwater River system, the average projected reduction factor estimated for 2010 was 0.8296, and the projected reduction factor for 2018 is 0.8145. Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Blackwater River, estimated mercury concentrations are estimated as shown below.

Blackwater River and Tributaries	**Average Mercury Concentration in Affected Species**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.676 ppm	0.561 ppm	0.5506 ppm
Redear Sunfish	0.524 ppm	0.4347 ppm	0.4268 ppm
Bowfin	1.090 ppm	0.904 ppm	0.8878 ppm
Chain Pickerel	0.510 ppm	0.4129 ppm	0.4154 ppm
White Catfish	0.651 ppm	0.540 ppm	0.5302 ppm
Redhorse Sucker	0.579 ppm	0.4688 ppm	0.4716 ppm
Longnose Gar	0.705 ppm	0.585 ppm	0.5742 ppm

Based on this analysis, the estimated reductions in mercury deposition in the Blackwater River basin are not expected to result in sufficiently reduced contamination in the various species of fish to allow for the removal of the current fish consumption advisory. This analysis does suggest that the mercury contamination levels in redear sunfish, chain pickerel and sucker species could be expected to diminish over time, possibly to levels lower than the trigger value for fish consumption advisories. This presents the possibility that these species might be removed from the current advisory in the future. However, bass, bowfin, white catfish and gar are expected to remain at mercury levels where a fish consumption advisory is warranted. Also, all of the estimated fish mercury concentrations are projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion.

Nottoway River
The current fish consumption advisory for the Nottoway River applies to largemouth bass, smallmouth bass, sunfish species, bowfin, chain pickerel, channel catfish, redhorse sucker species and longnose gar.

Mercury deposition rates and projected reduction factors among the cells for the watershed of the Nottoway River were similar in most cells along its length; however, similar to the Blackwater, the Nottoway River is intersected with an area of slightly elevated mercury deposition rates at the conjunction of the Nottoway River with the Blackwater River, at the North Carolina border.

Using the deposition rates for the cells that directly overlaid the watershed for the Nottoway River system the average projected reduction factor estimated for 2010 was 0.8332, and the projected reduction factor for 2018 is 0.8079.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Nottoway River, estimated mercury concentrations are shown below.

Nottoway River	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.724	0.6093	0.5849
Smallmouth Bass	0.579	0.4824	0.4678
Sunfish species	0.503	0.4191	0.4059
Channel Catfish	0.572	0.4766	0.4621
Bowfin	0.946	0.7882	0.7575
Chain Pickerel	0.920	0.7665	0.7433
Longnose Gar	0.888	0.7399	0.7174
Redhorse Sucker species	0.545	0.4541	0.4403

Based on this analysis, the estimated reductions in mercury deposition in the Nottoway River basin are not expected to result in sufficiently reduced contamination in the various species of fish to allow for the removal of the current fish consumption advisory. This analysis does suggest that the mercury contamination levels in sunfish, smallmouth bass, channel catfish and sucker species could be expected to diminish over time, possibly to levels lower than the trigger value for fish consumption advisories. This presents the possibility that these species might be removed from the current advisory in the future. However, largemouth bass, bowfin, chain pickerel, and longnose gar are expected to remain at mercury levels where a fish consumption advisory is warranted. Also, all of the estimated fish mercury concentrations are projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion.

Dismal Swamp Canal and Lake Drummond

The current fish consumption advisory for the Dismal Swamp Canal and Lake Drummond applies to bowfin and chain pickerel.

Mercury deposition rates for the watershed of the Dismal Swamp were similar in most cells overlaying the swamp area and the length of the Dismal Swamp Canal. Using the deposition rates for only the cells that directly overlaid the watershed for the Dismal Swamp Canal system, the average projected reduction factor estimated for 2010 was 0.7808, and the projected reduction factor for 2018 is 0.7711. However, there are areas at the north end of the canal near Portsmouth, and also at the south end along the North Carolina border that the air-deposition model projected as areas of slightly elevated mercury deposition rates for the base year of 2002. These higher deposition rates for 2002 in these areas, combined with the projected reductions in future mercury deposition rates for 2010 and 2018, suggest that a relatively greater reduction in total mercury deposited into these areas could occur and result in slightly greater reductions in fish concentrations in these areas. These areas are within the drainage area of the canal and could influence the amount of mercury in the canal system and available to bioaccumulate in the fish. If the changes in deposition along the canal were averaged to include these neighboring cells (the areas with estimated greater mercury deposition rates for 2002), the projected reduction factors for future years would be lower, and the potential for reduced mercury loads in the fish could be greater in this area. To evaluate this possibility, a third reduction factor was calculated using the 2018 estimated reductions in air deposition rates of mercury by averaging the mercury depositions predicted along the length of the canal as well as the neighboring cells at both ends of the canal, where higher mercury base year deposition rates were indicated by the model. This third reduction factor was calculated to be 0.7332 for 2018 (compared to 0.7711 without including neighboring cells); would represent a more optimistic estimate of the amount of reduced mercury deposition in the watershed of the Dismal Swamp Canal; and, subsequently, could result in greater reductions in fish mercury concentrations.

Applying these three different reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from the Dismal Swamp Canal and Lake Drummond, estimated mercury concentrations are shown below.

Dismal Swamp Canal & Lake Drummond	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration (reduction factor 0.7808)**	**Projected Mercury Fish concentration (reduction factor 0.7711)**	**Most Optimistic Estimated Reduction Factor (0.7332)**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Bowfin (Canal)	0.49	0.38	0.38	0.36
Bowfin (Lake)	0.97	0.75	0.74	0.71
Chain Pickerel	0.32	0.25	0.25	0.23

Lake Drummond is connected to the Great Dismal Swamp Canal system by a dam which separates the fish populations. Available data indicate average concentrations of mercury detected in chain pickerel collected in the Canal, the Lake and other areas of the Dismal Swamp National Wildlife Refuge had the same average mercury concentration, so this fish species was assessed for all areas. The data indicated that the bowfin collected from Lake Drummond contain higher average concentrations of mercury than the bowfin in the Canal. Hence, the bowfin collected from the Lake and the Canal were assessed separately. Based on this analysis, the estimated reductions in mercury deposition in the Dismal Swamp Canal and Lake Drummond are not expected to result in sufficiently reduced mercury contaminations in bowfin in Lake Drummond to allow for the removal of the current fish consumption advisory for the Lake, even under the most optimistic levels of reductions in air deposition of mercury.

This analysis does suggest, however, that after projected reductions in mercury deposition rates occur, the mercury contamination levels in bowfin from the Great Dismal Swamp Canal and in chain pickerel throughout the lake, swamp and canal system could be expected to diminish over time to levels lower than the trigger value for fish consumption advisories. This is because the average concentrations of mercury in these two fish species were on the borderline with consumption advisory thresholds to begin with. In fact, by including the most recent mercury monitoring data, the average mercury concentration for the chain pickerel is now below the advisory threshold. This presents the possibility that these species might be removed from the current advisory in the future, at least for the Dismal Swamp Canal. In this case, the Dismal Swamp Canal may no longer meet the criteria for a fish consumption advisory and the Canal may be dropped from the advisory area. However, in Lake Drummond, the bowfin is expected to remain at mercury levels where a fish consumption advisory is warranted. This could result in removing the chain pickerel from the advisory and dropping the Dismal Swamp Canal from the advisory area, retaining only the advisory for the bowfin in Lake Drummond. However, the estimated fish mercury concentrations for bowfin in the Canal are projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion.

Kerr Reservoir, Dan River and Roanoke River

The current fish consumption advisories for the Kerr Reservoir, Dan River and the Roanoke River apply to striped bass and white bass. Both of these fish species spend most of their life in the Kerr Reservoir, but migrate in the spring up the Roanoke River and Dan River to spawn and then return to the reservoir for the rest of the year. It is presumed that these fish species concentrate most of their mercury load during their lengthy time spent in the Kerr Reservoir and were only caught in the Roanoke and Dan Rivers during spring spawning migrations. However, several significant industrial and municipal dischargers exist or have existed along the Roanoke River and Dan River, and these could represent other potential sources of mercury to the Roanoke River or Dan River in addition to air deposition.

Projected total mercury deposition rates for the watershed were similar in all cells along its length, with projected reduction factors among the cells varying by less than five percent. The average projected reduction factor estimated for 2010 was 0.8110, and the projected reduction factor for 2018 is 0.7765.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species, the projected future mercury concentrations in striped bass and white bass are shown below:

Kerr Reservoir (Roanoke and Dan River)	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Stripped Bass	0.7170	0.5815	0.5568
White Bass	0.6040	0.4898	0.4890

This analysis suggests that the mercury contamination levels in white bass in the Kerr Reservoir River basin could be expected to diminish over time, possibly to levels lower than the trigger value for fish consumption advisories. This presents the possibility that the white bass might be removed from the current advisory in the future. This analysis estimated future total mercury concentrations in the striped bass could be only 11 percent and 16 percent above the methylmercury consumption advisory threshold of 0.50 ppm methylmercury. This, along with the assumption that 90 to 95 percent of the total mercury in fish is methylmercury, suggests that striped bass may become close to mercury concentrations levels that are very near the threshold for requiring a fish consumption advisory due to mercury contamination. However, all of the estimated fish mercury concentrations are projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion.

Chandler's Mill Pond

The current fish consumption advisory for Chandler's Mill Pond in Westmoreland County applies only to largemouth bass. Mercury deposition rates for the watershed of Chandler's Mill Pond produced a projected reduction factor estimated for 2010 of 0.7215, and the projected reduction factor for 2018 is 0.6995.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from Chandler's Mill Pond, the estimated mercury concentrations are shown below.

Chandler's Mill Pond	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.591	0.4264	0.4134

This analysis estimated future total mercury concentrations in the largemouth bass from Chandler's Mill Pond could be below the methylmercury consumption advisory threshold of

0.50 ppm, raising the possibility that this advisory could be lifted in the future. However, the estimated fish mercury concentration is still projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion for assessment purposes.

Motts Run Reservoir

The current fish consumption advisory for Motts Run Reservoir applies to largemouth bass only. Mercury deposition rates for the watershed of Motts Run produced a projected reduction factor estimated for 2010 of 0.791, and the projected reduction factor for 2018 is 0.77.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from Motts Run Reservoir, the estimated mercury concentrations are shown below.

Motts Run Reservoir	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.557	0.4406	0.4289

This analysis estimated future total mercury concentrations in the largemouth bass from Motts Run Reservoir could be below the methylmercury consumption advisory threshold of 0.50 ppm, raising the possibility that this advisory could be lifted in the future. However, the estimated fish mercury concentration is still projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion for assessment purposes.

Lake Gordonsville

The current fish consumption advisory for Lake Gordonsville applies to largemouth bass only. Mercury deposition rates for the watershed of Lake Gordonsville produced a projected reduction factor estimated for 2010 of 0.8433, and the projected reduction factor for 2018 is 0.8289.

Applying these reduction factors to the average concentrations of mercury found in the affected fish species (as contained in the DEQ fish contamination data set from 2002-2006) from Lake Gordonsville, the estimated mercury concentrations are shown below.

Lake Gordonsville	**Average Fish Concentration of Mercury**	**Projected Mercury Fish concentration**	**Projected Mercury Fish concentration**
Fish Species	**2002-2006 dataset**	**After 2010 Air-Dep Reductions**	**After 2018 Air-Dep Reductions**
Largemouth Bass	0.609	0.5136	0.5048

This analysis estimated future total mercury concentrations in the largemouth bass could be only 1 to 3 percent above the methylmercury consumption advisory threshold of 0.50 ppm methylmercury. With the assumption that 90 to 95 percent of the total mercury in fish is methylmercury, this suggests that after the predicted future reductions in air deposition of mercury, it is possible that largemouth bass from Lake Gordonsville may become eligible for consideration of a removal of the current fish consumption advisory. However, the estimated fish mercury concentration is still projected to remain above 0.30 ppm, which is currently proposed as a fish tissue criterion for assessment purposes.

<u>Summary of Overall Conclusions of the Review of Potential for Changes in Fish Mercury-Contaminations in Response to Reduced Mercury Air Deposition in Virginia:</u>

- Based on available information from multiple experiments and field experiences, mercury that is air-deposited into aquatic ecosystems can be expected to contaminate fish.

- Lakes and wetlands are especially sensitive to even small amounts of added mercury because these environments are very efficient in transforming the mercury into a form that is readily accumulated by fish.

- Reduction in mercury inputs into a waterbody is expected to result in lowered concentrations of mercury in the fish after the ecosystem readjusts to the lower mercury levels in the environment.

- It is reasonable to expect a proportional lowering of fish tissue mercury concentrations over time in response to decreases in mercury deposition rates from the air.

- The time frame needed before these lowered fish concentrations could occur depends on how efficiently mercury is processed by the aquatic ecosystem and picked up by the fish.

- Each individual waterbody is expected to react slightly differently due to natural variances in the chemical and physical conditions and differences in food-web structure.

- Lakes are expected to respond quickest (within a few years to decades) to reduced mercury deposition, with wetlands requiring more time to equilibrate to the lowered mercury inputs.

- The projected reductions in mercury-air deposition rates after 2010 and 2018 estimated by the ICF model suggests that fish mercury levels may become lower in the future such that some species may no longer warrant a fish consumption advisory.

- The VDH issues fish consumption advisories when average concentrations of mercury in fish exceed 0.50 ppm.

- The DEQ has recently proposed the adoption of a fish tissue criterion for mercury of 0.30 ppm, which is lower than the current threshold concentration used by the VDH to issue fish consumption advisories. If the State Water Control Board adopts this fish tissue criterion for mercury, in the future DEQ may classify some waterbodies as impaired due to elevated mercury contamination in fish before the VDH would find it necessary to issue a fish consumption advisory.

- Of the 13 mercury-sensitive waterbodies in Virginia with current fish consumption advisories due to mercury contamination in fish, the fish mercury levels may be lowered enough in the future to below 0.5 ppm mercury used by the VDH such that three or four of these advisories may no longer be warranted.

- In all but two of the advisory areas, at least one species of fish may have reduced mercury levels in the future that could allow for its removal from the fish consumption advisory and in one case (Dismal Swamp Canal), the advisory area may be reduced.

- Under the projected reduced air deposition rates for the future, nine to ten of the current fish consumption advisories will likely remain in place for at least one species of fish.

- Average mercury concentrations for at least one species of fish could remain higher than 0.30 ppm, so all of these waterbodies could remain classified as impaired by DEQ.

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Chapter 6- Performance and Cost Assessment of Control Technologies at Coal-Fired Power Plants

Summary

This section of the report reviews the performance of mercury (Hg) control technologies and related costs of mercury reduction levels. Virginia coal-fired power plants vary in the amount and type of mercury control equipment installed. Currently, all Virginia coal-fired power plants burn a low sulfur, low mercury, and high chlorine bituminous coal, and most of the plants also burn coal that has been initially washed and processed after mining. Furthermore, some of the plants have technologies already in place to control nitrogen oxide (NO_x), sulfur dioxide (SO_2), and particulate matter (PM). As a result, a certain level of mercury removal is achieved as a co-benefit of these controls; this report attempts to capture the costs of Hg control (costs of control technologies and also possible costs of control levels).

This report provides an overview of commerically available technologies, their performance and their costs. Moreover, the estimated costs of adopting mercury control technologies are based on assumptions in terms of the data collected for the cost assessment and default performance measures, when actual data was lacking or unavailable due to intellectual property right laws. To overcome such data challenges, the Department of Energy's (DOE) approved simulation tool was used and populated with representative, Virginia-specific coal-fired power plants to assess the current versus future costs of adopting mercury control technologies.

This report provides calculated costs for two scenarios: (1) costs of mercury control technologies, if adopted under a mercury control scenario alone and no other control technologies were utilized and (2) costs of a multi-pollutant (NO_x, SO_2, PM) control system that, as appropriately as possible, captures the "net marginal costs" of mercury control alone, under a co-benefit scenario. For the identified Virginia coal-fired utilities, costs of Hg-specific air pollution control equipment was determined to be in the range of $1.50 - $12.14 per MW-hour. Costs of mercury control as part of a multi-pollutant air pollution control scenario was determined to be approximately $1- $7 per MW-hour.

These findings are within the range of estimates from published scientific and federal agency literature and confirm that mercury control through a multi-pollutant control technology scenario is more cost-efficient and feasible than adding mercury-specific controls only. Detailed review of the estimates also confirmed that older (and/or smaller power generating) power plants are less efficient than the newer and/or larger production capacity facilities. The results confirm economies of size and value of co-benefits.

Introduction

The most common characteristics of coal-fired power plants that influence mercury emissions (and thus performance and costs) are:

1. Mercury content of coal
2. Type of burners on the plant
3. Boiler operating conditions

4. Design and operation of particulate devices, and the design and operation of flue gas cleaners (and resulting energy loss associated with adoption of control technologies for emission controls).

Mercury is present in small quantities in coal, usually between 0.02 to 0.8 ppm, with an average of 0.09 ppm (USGS). Mercury in coal occurs in association with pyrite and other sulfide minerals that can be organically bound. Coal mercury is converted to gaseous Hg in the combustion flame; it becomes partially oxidized as the combustion gases cool (Pavlish, 2003). Mercury oxidation in coal boilers is controlled kinetically, homogeneous oxidation reactions are promoted by chlorine, and heterogeneous oxidation is promoted by fly ash and sorbents. Acid gases will have strong influences on the heterogeneous oxidation of mercury, particularly as it affects capture on sorbents (Pavlish, 2003).

The coal used in Virginia primarily is Appalachian bituminous coal with lower sulfur levels, lower mercury levels and higher chlorine levels. Low sulfur levels result in lower sulfur dioxide (SO_2) emissions. Mercury emissions levels are around 9.01 lbs/trillion BTU. These emissions levels are relatively low when compared to emissions from other coal sources; for example, coal burned in Ohio has levels of 17.1 lbs/trillion BTU. The presence of chlorine allows the mercury to more easily adsorb onto particles when entering the flue gas stream after coal combustion. This aids mercury control because the particles in the flue gas that have adsorbed the mercury (aided by the presence of chlorine) are then captured in the particulate control device.

As a result of the mercury found in coal, coal-fired power plants release mercury into the air. The amount released depends on the size of the plant, but a typical 500-MW coal-fired plant may emit up to 250 pounds per year (Change and Offen). In order to control emissions caused by coal combustion, post-combustion control technologies are commonly used. Examples of such control technologies are fabric filters (baghouses) and electrostatic precipitators (ESP) for particulate removal; wet and dry lime scrubbers for sulfur dioxide (SO_2) removal, which are often also described as flue gas desulfurization (FGD); and selective catalytic reduction (SCR) for the removal of nitrogen oxides (NO_X). A mercury-specific control technology is activated carbon injection (ACI), which is being examined for potential installation at various facilities across Virginia. Activated carbon injection is a form of sorbent injection.

Pre-combustion technology such as coal washing and crushing can remove some mercury from the coal before firing. Oxidation of Hg allows for Hg to be more easily adsorbed onto particles that will be removed from the flue gas stream. Post-combustion controls for particulate removal capture these particles, which have adsorbed the mercury from the flue gas stream. Post combustion NO_x and SO_2 controls also help to oxidize the mercury, making it easier to adsorb downstream. Finally, activated carbon injection is a mercury-specific technology that injects carbon particles into the flue gas stream to help collect mercury. These various controls can have mercury removal rates of 90 percent or greater, depending on the site-specific plant configurations.

Coal fired power plants in Virginia currently have a variety of pollution control devices installed to meet standards for sulfur dioxide (SO_2), nitrogen oxide (NO_x), and particulate matter (PM) emissions. These control devices also contribute to the reduction of mercury emissions as a “co-benefit." Pollution controls can be either pre-combustion coal treatment processes or post-combustion flue-gas cleaning devices.

The section below describes how control devices used for bituminous coal, including mercury-specific technologies, contribute to mercury removal. Table 6-1 below shows how power plant technologies affect mercury emissions.

Table 6-1 Power Plant Controls Scenarios and mercury emission controls

POWER PLANT CONFIGURATION AND OPERATIONS STRATEGY	EFFECT ON MERCURY EMISSIONS	EFFECT ON MERCURY EMISSIONS
	Primarily Oxidized Mercury	**Primarily Elemental Mercury**
Coal Cleaning	Decreases emissions (highly coal-specific)	Decreases emissions (highly coal-specific)
Electrostatic Precipitator	Some decrease	Some decrease
Fabric Filter	Some decrease	Larger decrease in emissions
Scrubber	Decrease	No effect
Spray Dryer/fabric filter	Some decrease	Limited decrease
ACI	Decrease	Decrease

Pre-Combustion Controls

Pre-combustion controls decrease the amount of mercury in coal before it even enters the boiler. These types of control technologies consist of pre-cleaning the fuel before it enters the combustion chamber. As previously mentioned, typical bituminous coal used in Virginia power plants has about 9.01 lbs/trillion BTU of mercury, which is relatively low in Hg content. Virginia bituminous coals are well-suited to controlling mercury because the high chlorine content promotes mercury oxidation and results in a higher percentage of mercury capture.

Mercury in flue gas has two different forms, oxidized and elemental. The ability of control devices to capture mercury is dependent on the type of mercury that is in the flue gas. Elemental mercury is more difficult to capture than oxidized mercury. Bituminous coals can have approximately 14 percent of their mercury in elemental form (HG0), 52 percent in ionic form (HG2), and the remaining 34 percent is particulate-bound (HGP) (PADEP, 2006). These estimates are highly variable.

Coal cleaning

Performance:

The purpose of coal cleaning is to remove small particles of unwanted elements in the coal. The coal is finely ground until the small particles of unwanted substances can be removed. For high sulfur fuels, the pyritic compounds can be separated from the less dense coal using gravity. Removal of these compounds reduces SO_2 emissions and also has the added benefit of removing the mercury associated with the pyretic compounds (Luttrell, 2000). This process is most effective with high sulfur coal (Luttrell, 2000). The co-benefit of the mercury removal is not generally included in the removal efficiency for the plant because mercury is removed from the coal prior to its entering the boiler.

Roughly 77 percent of all bituminous coals are washed for removal of pyritic sulfur and ash. Mercury removal for physical washing methods ranges from 0 to 60percent on bituminous coals that are washed (Pavlish, 2003). Advanced cleaning methods and hydrothermal treatment offer a higher percentage of removal but no more than 70 percent (Pavlish, 2003). Froth flotation, selective agglomeration, advanced cyclone design, and several different chemical methods are being researched but are not commercially available yet.

The cost-effectiveness of various types of coal cleaning used on bituminous coals ranges widely. In some cases, additional costs for mercury removal are not incurred since the coal is already washed for sulfur removal. On the other hand, coal cleaning can cost as much as $33,000/lb of mercury removed for washing methods like hydrothermal treatment. Table 6-2 below provides a summary of performance and costs of coal cleaning.

Table 6-2 Performance and cost overview of coal cleaning (Pavlish, 2003)

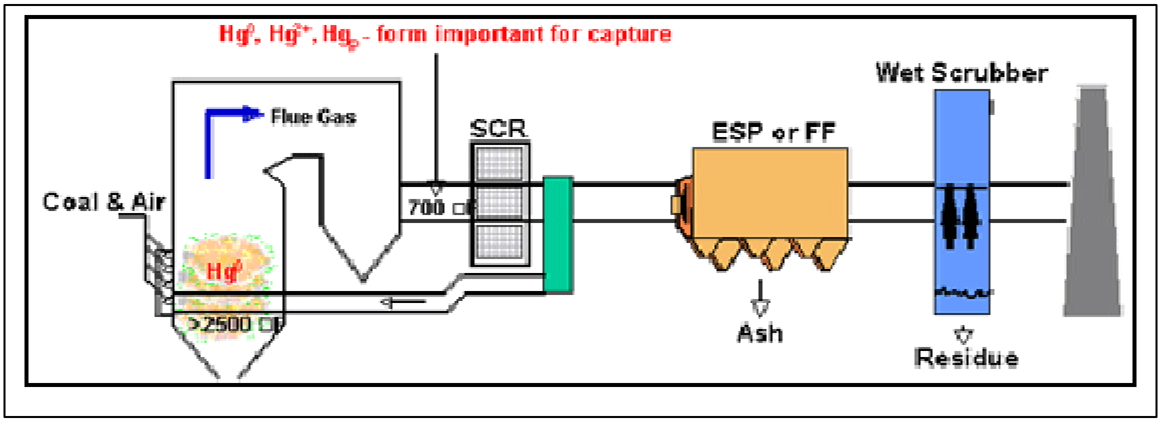
CONTROL TECHNOLOGY OPTION	STATUS	COST	CONTROL POTENTIAL	TECHNICAL IMPLEMENTATION ISSUES
Conventional	Commercial	Low	Low	70% eastern fuels already cleaned
Advanced	Near Commercial	High	Moderate	Not cost-effective
Hydrothermal	Developmental	Moderate	High	Not proven on a commercial level

Post-Combustion Controls

Post-combustion controls occur either within the boiler itself or as the flue gas stream passes from the boiler to the exhaust stack. Post-combustion controls aimed at controlling PM, SO_2 and NO_x also have a co-benefit for Hg control as explained earlier. ACI is a specific mercury control technology and is examined in this cost assessment. The following sections examine these controls, their performance and their costs. Figure 6-1 below shows a control system designed to remove PM, SO_2, and NO_X that also effectively controls mercury emissions. Such a control system can achieve 90 percent or greater mercury reduction.

Figure 6-1 (EPA, 2007).

<u>Particulate Controls</u>

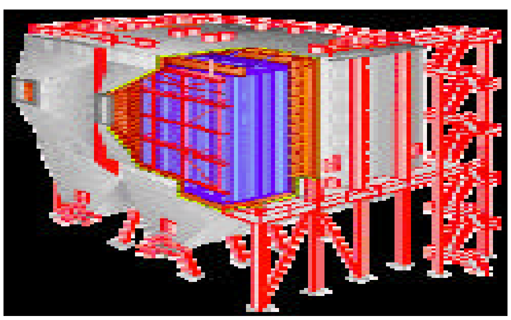


ESP (electrostatic precipitator)

Performance:

Electrostatic precipitators, as shown in Figure 6-2, remove particulate matter from the flue gas stream by charging particles and then collecting them on grounded plates. Electrostatic precipitators can be located either before the preheater at a temperature of 300-450°C (hot-side) or after the preheater at a temperature of 130-180°C (cold-side), with cold-side ESP being the most widely used (Clean Coal Technologies, 2007). U.S. power plants routinely achieve 99 percent or greater particulate removal.

Figure 6-2 (Courtesy of PA DEP)



ESPs aid in mercury capture as a co-benefit technology. In the flue gas, mercury is adsorbed onto the carbon in the fly ash, which is then removed by the ESP. According to Staudt (2003), the amount of mercury adsorbed onto the fly ash is dependent upon:

- the rate of mercury speciation (oxidized mercury adsorbs more readily than elemental mercury),
- the amount of fly ash in the flue gas stream,
- fly ash properties, including carbon content, and
- the temperature of the flue gas in the ESP.

In general, mercury is more easily adsorbed onto the fly ash when temperatures are lower. Mercury becomes gaseous at higher temperatures, and less contact between the mercury and the fly ash is possible in this phase (Air Pollution Prevention and Control Division, 2005). Therefore, cold-side ESPs are much more effective at mercury removal (about 29 percent removal efficiency) than hot-sided ESPs (about 11 percent removal efficiency). Since HG2 adsorbs more easily to carbon in fly ash than does its gaseous form (Staudt, 2003), the high chlorine content of bituminous coal used in Virginia power plants also increases removal efficiencies. Chlorine acts as an oxidizing agent, increasing the amount of HG2, and therefore more mercury can be adsorbed and removed in particulate control devices.

Depending on the conditions of the flue gas, coal type, and specifications of the ESP, mercury capture for an ESP can range from 0 to 89 percent (Staudt, 2003). Mercury removal rates for Virginia utilities burning bituminous coal equipped with only cold-side ESPs are estimated to be about 29 percent. A case study comparing the costs of ESP's with fabric filters can be found at the end of the section on fabric filters.

Cost:

ESP capital costs range from \$30 to \$80/kW. A standard installation of an ESP will be at the lower end of this range. Operating costs range from 0.15 to 0.30 cents/kW-hr (MIT, 2007). ESPs are standard on pulverized coal units so that they are usually considered to be part of the base cost.

Fabric Filter (FF)

Performance:

Fabric filters, sometimes known as baghouses, also remove particulate matter. Particles from the flue gas stream are deposited on filters, usually cylindrical fabric bags arranged in rows. Fabric filters can also use cartridges made of cintered metal or porous ceramic. Many rows make up a compartment, and several compartments make up the entire fabric filter system. The bags usually have internal wire mesh frames to keep them from collapsing (EPA, 2007). Fabric filters generally operate between 120-180°C (Clean Coal Technologies, 2007).

Figure 6-3. A fabric filter retrofit at a coal-fired power plant

Fabric filters remove mercury in the same manner as ESPs, by collecting particles onto which the mercury has adsorbed. As with ESPs, the speciation of the mercury in the flue gas stream will affect the collection of mercury by the fabric filter. However, the close contact between the gas and the collected particulate matter in a fabric filter leads to more mercury adsorption and a higher removal efficiency rate when compared to an ESP (Staudt, 2003).

Fabric filters remove about 99 percent of particulate matter from the flue gas stream (Clean Coal Technologies, 2007). They are also estimated to remove up to 90 percent of mercury when burning bituminous coal, as is used in Virginia (Staudt, 2003).

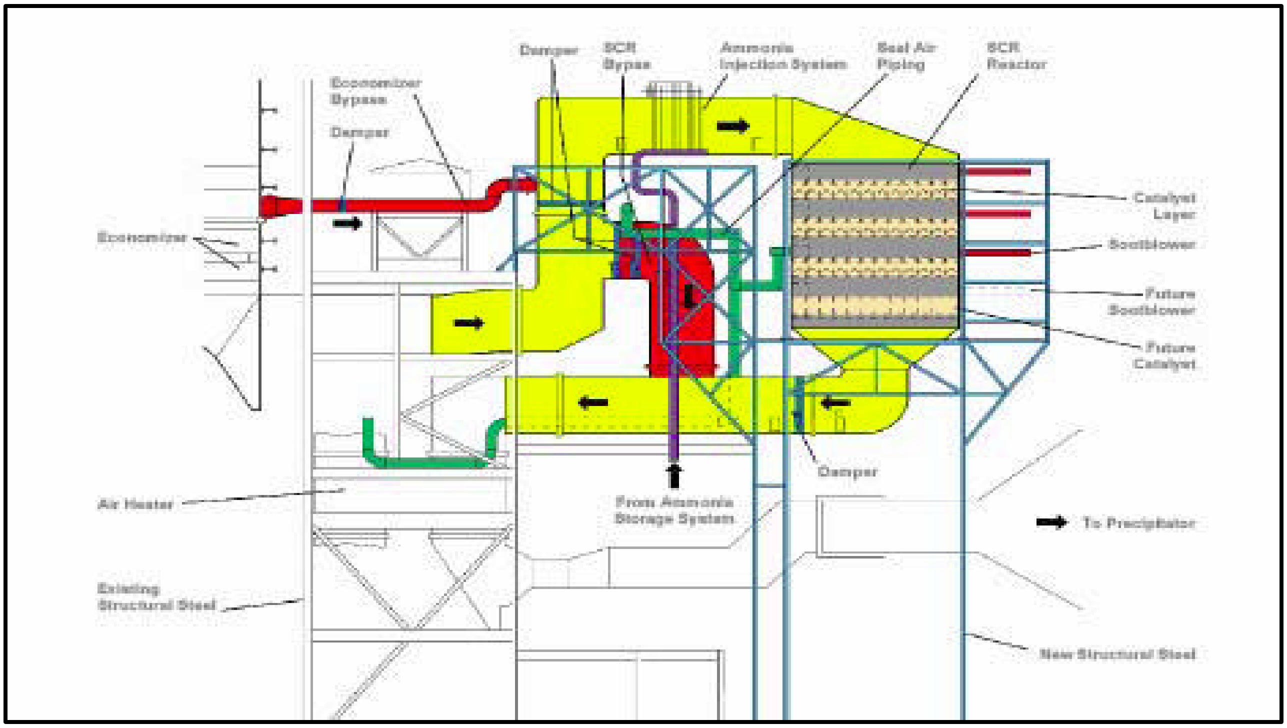
Cost:
Although ESPs and FFs are both used to control particulate matter, they have different capital, maintenance, and operations costs. A case study from a plant in Southeast Asia has compared both devices in terms of U.S. dollars. The installation costs were found to be quite similar for both devices. However, there were significant differences in costs of operation and maintenance. The cost of bags and fan power consumption significantly increased the costs for FFs. In that case study, the ESP was chosen because the yearly accumulated extra cost for operating and maintaining fabric filters amounted to $16 million after 10 years of operation. Though a FF might be a more attractive option for controlling mercury emissions, it is clear that it can be a more expensive solution. Table 6-3 below shows costs from this case study (McIlvaine Company, Precip Newsletter, 2000).

Table 6-3 Cost Comparison between an ESP and a Fabric Filter

Scope of Activities	ESP	Fabric Filter
Capital Costs, Initial Investment (2000 dollars)		
Import Parts	3,309,000	3,750,000
Local Parts	1,044,000	903,000
Installation Costs	1,133,000	1,044,000
Total U.S. $	5,486,000	5,697,000
Maintenance Costs per year ($)		
Normal operation	10,000	10,000
Bags (2 year life)	0	280,000
Total U.S. $	10,000	290,000
Operating Costs per year ($)		
Pressure drop, mmWG	1,136	1,290
Power Consumption, fan, kW	3,535	4,005
Power Consumption, filter, kW	443	581
Total U.S. $	1,909,000	2,201,000
Summary U.S. $		
Installation Costs	5,486,000	5,697,000
Operation & Maintenance Costs / yr	1,919,000	2,491,000

NO_x Controls: **SCR (selective catalytic reduction)**

Figure 6-4 SCR Device, Courtesy of PA DEP



Performance:

Selective Catalytic Reduction (SCR) technology is used to reduce NO_x emissions by injecting ammonia vapor in to the flue gas stream. The ammonia vapor passes over a catalyst and reacts with the NO_x to form nitrogen gas and water. The SCR is usually located between the economizer and the preheater so that it may operate in the ideal temperature range of between 300°C and 400°C. This temperature is maintained in the SCR reactor by mixing the hot flue gas exiting the economizer with the cooler flue gas from the economizer bypass (Clean Coal Technologies, 2007). SCR units can achieve 90 percent NO_x reduction.

SCR technology can increase the mercury removal efficiencies of coal-fired power plants. As stated elsewhere in this document, mercury speciation has a significant impact on the amount of mercury removed. The oxidized form of mercury HG2 can form mercuric sulfide ($HgCl_2$), which is highly water soluble and can be captured in wet FGD systems. The catalysts used in SCR tend to oxidize elemental mercury from HG0 to HG2, making the mercury easier to capture downstream in a wet Flue Gas Desulfurization (FGD) system. The oxidation of mercury by the catalysts is thought to be affected by:

- the space velocity of the catalyst
- the temperature
- the ammonia concentration

- the catalyst age
- the concentration of chlorine in the flue gas stream

These interactions are complex and currently not fully understood. A higher chlorine concentration, a lower temperature, and a newer catalyst have been shown to result in a higher oxidation of mercury. There is still more to learn about the oxidation of mercury with SCR systems (Staudt, 2003).

When using SCR in conjunction with wet FGD and particulate control on a power plant burning bituminous coal, mercury removal efficiencies of 90 percent can be achieved. For plants with no wet FGD system the use of SCR did not affect mercury capture. (Staudt, 2003).

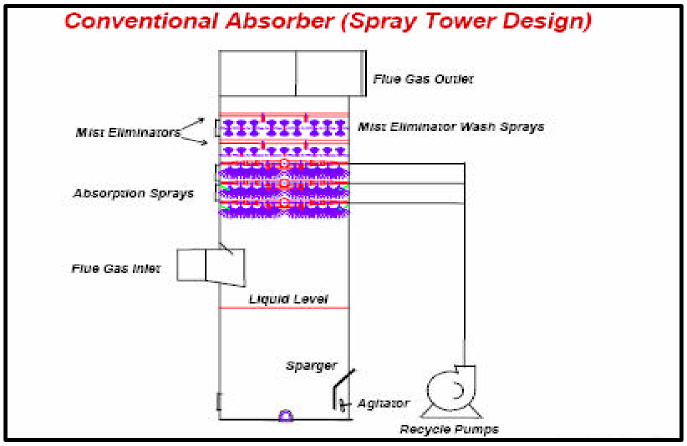
Cost:
One estimate shows that capital costs for SCR devices range from $40.88/kW to $91.51/kW. In this estimate the annual costs of operating and maintaining an SCR device range from $1,300,000 to $2,410,000 (McIlvaine Company, FGD and DeNOx Newsletter, 2000). Another study showed overall estimates of SCR installation to cost in the range of $100 to $200/kW. These estimates include costs for construction labor, equipment and material, project management, engineering and construction management. Construction labor costs were relatively constant for all size plants. However, economies of scale affect the material costs, making larger units cheaper. The average unit size in the study was 644 MW; the retrofit of a unit this size would cost in the range of $100 to $150/kW. Smaller units, around 300 MW, saw increased costs in the $200/kW range. The range continues to increase as unit size decreases (McIlvaine Company, FGD and DeNOx Newsletter, 2006).

A Massachusetts Institute of Technology (MIT) study estimated capital costs for SCR units to be roughly $20 to $40/kW for a new unit installation. For a retrofit unit installation, the capital costs increase in range to $50 to $90/ kW. Operating costs are in the range of 0.05 to 0.15 cents/kW-hr for SCR units according to this study.

SO_2 Controls

Performance:
Flue gas desulfurization controls SO_2 emissions. There are two types most commonly used by power plants in Virginia, wet scrubbers and spray dryers. Worldwide, wet scrubbers are the most commonly used device, followed by spray dry scrubbers and sorbent injection systems. The basic concept behind FGD systems is removal of the SO_2 gas from the flue gas stream by absorbtion into a liquid. These devices can achieve 95 percent success or better in SO_2 removal. Wet FGD units remove nearly 90 percent of HG2 but essentially none of the HG0 (Pavlish, 2003). Mercury removal can be enhanced in scrubbers if HG0 is converted to an oxidized form in or ahead of the scrubber using an SCR (see above).

Figure 6-5 FGD Device Courtesy PADEP



Cost:
As is typical with any control technology, FGD systems are much more costly when installed as retrofits rather than a new installation. Additional costs are incurred because the FGD systems must be fit within the existing site space and must be integrated with the existing plant and its structures. According to one study, retrofit costs for FGD systems can be as much as 20 to 40 percent more expensive than the cost for a new unit of similar size. For example, retrofitting a 170 MW unit averages $230/kW-hr whereas fitting a new 240 MW unit with an FGD system may cost $190/kW-hr. Both of these units use the same sorbent, both have fabric filters, and both have spray dryers, but the retrofit is more expensive. Another example shows the same result: a retrofit for a 180 MW unit costs $320/kW while control technologies on a new 430 MW unit costs only $150/kW (McIlvaine Company, FGD and DeNOx Newsletter, 2004). This large difference could be due to the scale of the units, but nonetheless the retrofits are more expensive.

A Massachusetts Institute of Technology study shows similar estimates. The study estimated capital costs for wet scrubbers range from $100 to $200/kW-hr. Operating costs ranged from $0.20 to $0.30/kW-hr with this estimate being heavily dependent on sulfur levels (MIT, 2007).

Wet FGD
Performance:
Wet flue gas desulfurization, also referred to as wet scrubbing, is the most widely used FGD technology for SO_2 control. The controls are usually installed upstream of some particulate matter control device, like a fabric filter or electrostatic precipitator. In a wet FGD system SO_2 is absorbed into a liquid, sometimes water, but often a chemical solution that absorbs the specific pollutant more readily. Calcium, sodium and ammonium-based solutions are commonly used as sorbents. Limestone and lime are the most common due to their availability and low cost. The lime or limestone and the SO_2 react with the oxygen in the air and eventually become gypsum, a by-product that can be sold to be used by other industries (Clean Coal Technologies, 2007). If gypsum is not produced, then the cost of treating and cleaning the water used in the wet FGD must be considered (EPA, 2007).

Wet FGD systems can achieve mercury removal co-benefits. Gaseous compounds of HG2 are soluble, meaning they can be absorbed in water or, in this case, the lime solution or slurry. However, HG0 is not soluble; therefore, the efficiency of the wet FGD in removing mercury is largely dependent upon which form of mercury is found in the flue gas. Mercury in the form of HG2 can react with the sulfur from the SO_2 already absorbed in the liquid to form mercuric sulfide (HgS) or the chlorides in the liquid to form mercuric chloride ($HgCl_2$), which becomes sludge and can be removed from the system.

Wet scrubbers can achieve a removal efficiency of SO_2 up to 99 percent (Clean Coal Technologies, 2007). The mercury removal efficiency of wet FGD systems can range from around 23 to 97 percent, depending upon the speciation of mercury in the flue gas stream and the type of particulate control used (Staudt, 2003). Virginia plants with both fabric filters and wet FGD controls are estimated to have a removal efficiency of over 90 percent.

Spray Dryer Absorbers

Performance:

Spray dry absorbers (SDAs) are another type of FGD system that requires a particulate control device. SDAs are similar to the wet scrubber in that the pollutant is absorbed into a liquid. Spray dryers use a spray mist of the slurry, however, instead of the bulk liquid. As with the wet FGD system, SO_2 is absorbed into the solution and forms calcium sulfite and calcium sulfate. Instead of becoming sludge, the heat of the flue gas evaporates the liquid and leaves dry particles. The particles are then collected by the particulate control downstream (EPA, 2007).

With respect to mercury removal, spray dryers are generally more efficient than wet scrubbers. Spray dryers can capture both HG2 and HG0, as HG2 can be absorbed in the spray droplets and both can be adsorbed onto the calcium sulfite and calcium sulfate particles. These particles are then collected downstream in the particulate control. If the particulate control is a fabric filter, there is an even greater potential for mercury capture as the flue gas passes through collected fly ash and dried slurry caked on the filter (Staudt, 2003).

In general, spray dryers can achieve SO_2 removal efficiencies of over 90 percent and up to 95 percent (Clean Coal Technologies, 2007) and over 98 percent, according to EPA. Since Virginia utilities burn bituminous coal with lower concentrations of HG0 and appropriate chlorine contents, the mercury removal efficiency for a SDA system followed by a particulate control system can reach 98 percent (Staudt, 2003).

<u>Mercury Specific Controls</u>
Activated Carbon Injection (ACI)

Figure 6-6 ACI before the PM Device (Courtesy PADEP)

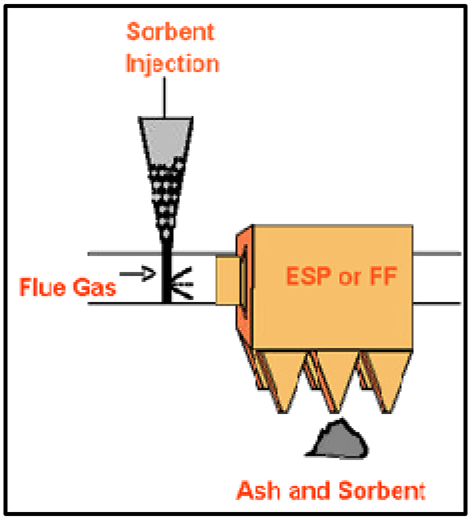
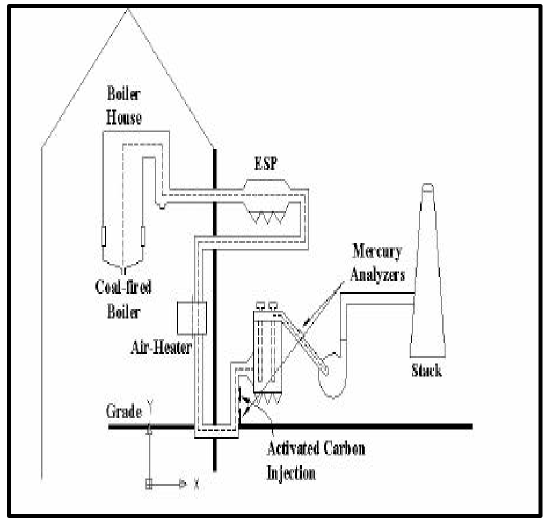


Figure 6-7 ACI after the PM Device (Courtesy PADEP)



Performance:
Activated carbon injection (ACI) is a technology used to specifically target and reduce mercury emissions. This technology is relatively new. It has not been installed in power plants in Virginia, although installation of ACI is planned for the new Virginia City Hybrid Energy Center in Wise County, Virginia. ACI has also been installed in municipal waste combustors for mercury control in the Northern Virginia area. ACI uses a powdered activated carbon sorbent that is injected into the flue gas stream at some point preceding or following the particulate control device. All forms of mercury can be adsorbed onto the carbon particles, which are then carried down the flue gas stream to be captured by the particulate control. As previously mentioned, fabric filters will capture more mercury than ESPs, because the carbon particles already captured by the fabric filter will adsorb additional mercury as the flue gas passes through the bags (EPA, 2007).

The performance of activated carbon injection is directly related to the carbon's physical and chemical characteristics. Important physical properties are surface area, pore size distribution, and particle size distribution. Mercury capture will increase with increasing surface area and pore volume. Properties of activated carbon should be selected to maximize mercury control. The injection of activated carbon ahead of an ESP or FF offers a technically feasible approach for the control of mercury emissions. Much of the cost for this technology depends on the rate of sorbent injection.

Several other sorbents, in addition to activated carbon, are being researched and developed. This research may lead to a reduction in cost and increase in performance of sorbent injection technology for mercury removal (Staudt, 2003). One such sorbent injection technology is a halogenated ACI system. If the flue gas does not contain enough chlorine, a sorbent which also contains a halogen, such as chlorine or bromine, may be used to increase the oxidation of the mercury. As previously explained, this increases the ability of the mercury to adsorb to carbon particles. This technology has been shown to be just as effective as non-halogenated ACI. Less carbon will need to be injected as the oxidized mercury can also adsorb to fly ash particles, making this technology potentially less expensive. The Pennsylvania Department of Environmental Protection (PADEP) found that brominated-ACI along with an ESP device obtained 90 percent mercury removal (PADEP, 2006).

Another promising development for ACI has been developed by Praxair Technology, Inc. They have the technology to allow coal-fired power plants to produce activated carbon on-site. This allows for a secure supply, increased potential for revenue if a surplus is produced, and a reduction in costs against purchased carbon. The technology is best for Powder River Basin (PRB) and lignite coal but it also works for bituminous coal. Bituminous coal, however, does not always produce the best activated carbon. On-site ACI maybe an attractive option for power plants that want to use ACI, since producing the carbon on-site may reduce capital costs per pound of mercury removal. Praxair has estimated a 40 percent savings versus purchasing activated carbon offsite (Praxair, 2008).

A potential problem with ACI is the price of carbon, which is very volatile in today's international commodity markets. The price of carbon could increase and affect how cost-effective ACI technologies are in the market. Currently, standard powered activated carbon costs about $0.50/lb and halogenated powdered activated carbon costs about $1.00/lb (Srivastava, 2006). However, it is possible that carbon could reach $2/lb, resulting in specialty sorbents like brominated carbon becoming more competitive. (McIlvaine, 2008).

Cost:
In comparison to activated carbon, the brominated ACI, estimated by PADEP to result in 90 percent mercury capture, was much more expensive. The capital costs were cheaper at $4.9 to $9.8 million, but annual operating costs were much more expensive, estimated at $14.7 million. Total estimates came to between $15.4 to $15.8 million (PADEP, 2006).

Table 6-5 below shows cost estimates for both a 100 MW power plant and a 975 MW power plant that uses activated carbon injection to control mercury.

Table 6-5 (Pavlish, 2003). ACI design and cost

Carbon Injection System Design and Costs		
Reference power plant size (MW)	**100**	**975**
Bulk Carbon Density, lb/ft3	24	24
Carbon injection rate, lb/ft3	906	8,929
Silo Volume (15 day storage), ft3	13,600	134,000
Mass of Carbon, lb	326,000	3,210,000
Equipment Item Costs	**Thousands US $**	**Thousands US $**
Carbon Silo	143	1,722
Feed bin	6	24
Gravimetric feeder	10	12
Pneumatic conveyor	35	96
Carbon injection ports	25	36
Total equipment	291	2,526
Purchased equipment w/retrofit	379	3,283
Total Capital Costs	**889**	**6,139**

Other Sorbent Injection Technologies

Performance:

Other sorbent injection technologies exist that can be used to control mercury; however, they are typically not as effective as ACI. Development of low-cost, ultrafine sorbents would make injection technology a much more feasible option. Table 6-6 provides an overview of all sorbent injection technologies.

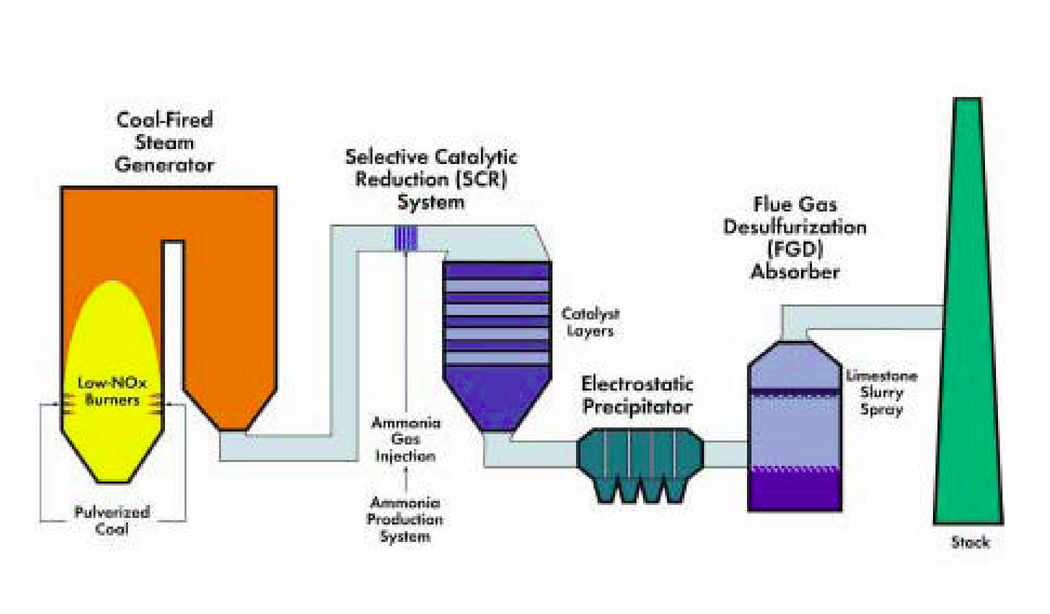
Table 6-6 (Pavlish, 2003). Sorbent Injection Technology

CONTROL TECHNOLOGY OPTION	STATUS	COST	CONTROL POTENTIAL	TECHNICAL IMPLEMENTATION ISSUES
Activated carbon	Commercial	Low-Moderate	Moderate-High	Separate Injection system required. Effectiveness very sensitive to temperature
Calcium-based sorbents	Commercial	Low-moderate	Moderate	Separate injection system required. Prep system may be needed.
Clay-based sorbents	Commercial	Low-moderate	Low	Separate injection system required
Sodium-based sorbents	Developmental-Commercial	Low-moderate	Low-moderate	Limited experience for Mercury Control. Separate injection system required
Metal oxide-based	Developmental-Commercial	Low-moderate	Moderate-high	Limited experience for mercury control. Separate injection system required

Co-Benefit Technologies and their Combinations

Many power plants already have existing mercury capture as a co-benefit of other air pollution control technologies for NO_x, SO_2 and PM. The PM control equipment captures particulate-bound mercury, and the FGD system captures the soluble form of mercury, HG2. As discussed above, the SCR technology used to control NO_x emissions can increase mercury removal efficiencies by oxidizing elemental mercury, making it easier to capture in an FGD system.

Figure 6-8 Typical Co-Benefit Configuration



Performance:
The SCR systems will enhance the oxidation of HG0 to its soluble ionic form of HG2, which results in increased removal by the FGD system (EPA, 2007). An SCR device combined with an ESP then followed by a wet scrubber, as shown in Figure 6-8 above, is an effective option for controlling mercury emissions. The three devices remove mercury with 90 percent efficiency for bituminous coal while maintaining their original primary functions (PADEP, 2006). Though these devices were not designed to remove mercury, their roles can be modified to increase mercury collection without degrading other emission control operations. The mercury removal process can be further aided by increasing the rate of slurry recirculation in scrubbers or injecting additives into the scrubber slurry (PADEP, 2006).

Cost:
Table 6-7 below shows cost estimates for each of the co-benefit technologies if they were to be installed separately; also included is their mercury control potential.

Table 6-7 Co-Benefit Technologies

CONTROL TECHNOLOGY OPTION	STATUS	COST	Hg CONTROL POTENTIAL
ESP	Commercial	Capital Costs – $5,486,000 Maintenance Costs – $10,000 Operation Costs – $1,909,000	36%
SCR	Commercial	Construction - $50/kW Equipment/Material - $100/kW Project Management - $150/kW Average Total Costs - $240-340/kW	0%
FGD	Commercial	Average Total Costs - $150-320/kW	30%
FF	Commercial	Costs included in FGD estimates	

Integrated Gasification Combined Cycle (IGCC)

Integrated Gasification Combined Cycle (IGCC) is a new technology for the production of electricity from coal. IGCC is a two-cycle process in which coal is treated by a gasifier to form 'syngas,' made primarily of hydrogen, carbon monoxide, and methane and other gaseous constituents. Next, the syngas is burned in a combustion turbine, which drives an electric generator (first cycle). Hot air from the combustion turbine is channeled back to the gasifier, while the exhaust is recovered and used to boil water, creating steam for a steam turbine-generator (second cycle).

IGCC has inherent advantages for emissions control because cleanup occurs in the syngas, which has not been diluted with combustion air. Removal of contaminants is more effective and economical than cleaning up large volumes of low-pressure flue gas (MIT, 2007). IGCC will enable the effective control of particulate matter, SO_2, NO_x, and mercury. IGCC systems remove mercury by running the syngas through carbon beds, thus removing as much as 95 percent of mercury. The mercury and other toxics captured in the carbon beds produce a relatively small amount of waste material. The amount is small enough that the waste can be managed to permanently remove mercury from the environment. The cost of this mercury removal has been estimated to be $3,412/lb Hg removed. Removing mercury will translate into an estimated cost increase of $ 0.025/kW-hr if IGCC is used. However, the current capital costs for IGCC systems are significantly higher than for comparably-sized, conventional pulverized coal technology.

Virginia DEQ's Cost Assessment of Control Technologies

This section summarizes DEQ staff's cost assessment of mercury control technologies for Virginia-specific representative coal-fired power plants.

Analytical Procedure and model:

Much literature exists regarding cost assessments for technologies controlling conventional Clean Air Act pollutants; however, not enough literature exists on the costs of Hg control through the Clean Air Interstate Rule (CAIR)- and the Clean Air Mercury Rule (CAMR)-based scenario. To better assess the costs of mercury removal by Virginia-specific, coal-fired power plants, an effort was made to collect the best possible information on existing and future controls (performance and cost) information that is representative of existing facilities in Virginia. This information was collected from Energy Information Administration (EIA) databases, EPA studies, and available permit and compliance data.

Analytical Procedure: The cost assessment was based on two key considerations:

1. **Co-benefits:** As explained above, the co-benefits of mercury control through CAIR-based control technologies is known and empirically measured. This study thus assessed the costs of a mercury controls only (CAMR-based) scenario and a multi-pollutant-based mercury removal scenario (CAIR-CAMR) scenario.
2. **Net marginal costs:** Net marginal costs of mercury control were assessed for emission control levels of 65, 80 and 90 percent. Most facilities in Virginia were achieving 65 percent level controls through the adoption of CAIR-based controls. About 65 percent mercury removal was also required through the passage of the Virginia General Assembly HB 1055. Additional control levels of 80 percent and 90 percent reflect typical mercury control levels as sought or evaluated by other states' model rules.

Model: Integrated Environmental Control Model (IECM)

The cost assessment was done simultaneously using a MS-Excel-based, cost-effectiveness calculation of existing and projected control technologies data (performance, removal efficiencies and costs) and, at the same time, through the use of a simulation tool called the Integrated Environmental Control Model (IECM). IECM is a simulation program that is approved by the DOE and was developed in collaboration with Carnegie Mellon University. IECM provides plant-level performance, emissions and cost estimates for a variety of environmental control options for coal-fired power plants specifically. The fundamental building blocks of IECM are a set of performance and cost sub-modules for individual technologies that can be linked together to configure a user-specified power-generating system. The process models employ mass and energy balances to quantify all system mass flows, including environmental emissions. For each technology module in the IECM, associated cost models are developed for total capital cost, variable operating costs and fixed operating costs. These elements are then combined to calculate a total annualized cost based on a consistent set of user-specified financial and lifetime assumptions. Normalized costresults, such as costs per kilowatt (or kilowatt-hour) of net capacity and cost per ton of pollutant avoided or removed, can also be computed.

Taking into consideration Virginia-specific bituminous coal and plant specifications, Virginia plants were modeled as accurately as possible, using information from permits and compliance records and, if plant specific data were not available, best possible market/industry estimates were used. The IECM-based approach of cost estimation was compared to EPA, DOE and industry-level estimates of costs, and the estimates were found to be in close range.

Assumptions used:
Certain key assumptions were made in this cost assessment. Typical plant performance, gross and net energy production, and parasitic load estimates were used. Cost of coal, ash disposal, and electricity prices were based on market estimates and verified with professional scientists and vendors.

Cost estimation – approach and results:

Costs / MW-hour and costs/lb Hg removed were the two key measures of cost-effectiveness calculated by this study. Both estimates are in 2005 constant dollars and reflect market-based conditions. These measures were calculated using the following formulae:

$$\textbf{Net Costs / MW-hr} = \frac{\text{(Net Marginal Costs of Hg controls)}}{\text{MW generated* Total working hours * Capacity Factor}}$$

OR- mathematically, the cost assessment can be interpreted as:

$$\textbf{Net Costs / MW-hr} = \frac{\text{Net Marginal Costs of Hg controls}}{\text{MW generated * 7580 * 0.80}}$$

Costs / lb removed (X % level of Hg removal) =

$$\frac{\text{(Net Marginal Costs of Hg controls)}}{\text{lbs of Hg reduced by the Hg controls}}$$

Generally, Virginia facilities operate at about 80 percent of maximum capacity. However, variability on a plant-by-plant and unit-by-unit basis exists for this factor. Tables 6-8 and 6-9 below summarize the two measures of cost assessment for Virginia-specific coal-fired power plants.

Table 6-8 Costs of mercury control under CAMR-only scenario (Hg controls only)

Net Marginal costs of controls for varying levels of Hg control		CAMR-only (if only mercury control technologies were retrofitted)
Costs / MW-hr	**65% reduction**	$ 1.50 - $ 5.00
	80% reduction	$ 1.70 - $ 11.00
	90% reduction	$ 3.47- $ 12.14
Costs / lb removed	**65% reduction**	$ 51,772 - $ 162,381
	80% reduction	$ 41,535- $ 166,666
	90% reduction	$ 117,300 - $ 248,000

A review of Table 6-8 indicates that costs of retrofitting mercury-only (CAMR only) controls have a wide range. The costs range from $ 1.50 through $ 5.00 for achieving a 65 percent emission reduction (2015 levels of control) and the costs proportionately increase with higher levels of mercury control. Estimates of costs per pound removed show a range of $51,772 through $248,000, depending on the size of the power generating facility, quality and type of controls. ACI was the considered control technology chosen for the CAMR-only based scenario, and costs of the sorbent generally used in ACI ranged from $ 0.52 /lb through $ 0.89 / lb. Cost estimates as above are in 2005 constant dollars, thus allowing for ease of comparison across inflation.

Table 6-9 Costs of mercury control under a CAIR-CAMR scenario (co-benefits)

Marginal costs of controls under varying levels of Hg reduction		**CAIR-CAMR-based scenarios(co-benefits based)**
Costs / MW-hr	**65% reduction**	$ 4- $ 7
	80% reduction	$ 1- $ 3
	90% reduction	$ 1- $ 4
Costs / lb removed	**65% reduction**	$ 40,000 - $ 60,000
	80% reduction	$ 20,000 - $ 50,000
	90% reduction	$ 65,000 - $ 90,000

Table 6-9 clearly shows that Hg removal under a co-benefit scenario provides the most cost-efficient outcome. Costs range from a low of $ 1.00 to a high of $ 7.00. Costs per pound removed indicate that existing CAIR-based resources with Hg specific control upgrades allow for attainment of 65- 70 percent level of Hg removal. Once the 70 percent level of Hg removal threshold is reached, costs of achieving any additional level of Hg removal escalate and can reach as high as $ 90,000 per lb. A closer review of the data also indicated that older plants with no fabric filters, limited CAIR based controls, and poorer generation capacity were the facilities with higher costs of Hg removal ($ / MW-hour and $/lb removed). Such a cost pattern is in line with industry and academic research reports. EPA estimates that in order to achieve 90 percent mercury reduction using ACI costs would be between $ 5,000-$ 28,000/lb of Hg removed. On the other hand, DOE estimates it to be between $ 25,000-$ 70,000/lb of Hg removed.

Conclusions

- The costs of mercury control at coal-fired power plants are affected by a number of different parameters, including what technologies are chosen, what regulations are in place, and the market-based determination of demand versus supply of energy.

- A number of options for reducing mercury emissions from coal-fired power plants are commercially available, and others are being developed. A number of control technologies for the reduction of mercury are available to coal-fired power plants, allowing the facility to choose the best fit in terms of cost-effectiveness.

- The DEQ cost assessment was based on a thorough review of existing and future projected mercury controls by Virginia-based electric generating units. Specifically, best available information on control technologies (performance, constraints, market prices of inputs and by-product disposal estimates) was used in this analysis. The results support the view, which is widely held by EPA, U.S. DOE, industry research and other state agencies, that mercury control is more cost-effective if coal-fired power plants adopt a multi-pollutant, post-combustion control technology sequence. Specifically, a combination of SCR, FGD, Fabric Filter and ACI was found to have the most cost-effective configuration.

Acknowledgements:
Virginia DEQ Staff (Vijay A. Satyal and Doris McLeod) wish to acknowledge the technical inputs provided by Chris Frey – North Carolina State University and Glenn Sappie and assistance in research and document preparation by Amy Karwan (Washington and Lee Intern ’07) and Doug Sharo (M.S. - VCU Center for Environmental Studies graduate 2008).

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Chapter 7- Human Health Risks Assessment

VCU-CES Recreational Fish Consumption Survey

As part of this study, DEQ contracted with VCU's Center for Environmental Studies (VCU-CES) to obtain Virginia-specific fish consumption data collected in areas where mercury-fish consumption advisories are in effect. Additionally, VCU-CES was tasked with estimating the associated health risks from resulting methylmercury exposures. VCU-CES developed a fish consumption survey and worked with DEQ staff to identify the launching and fishing locations where anglers could be surveyed. The survey was designed to obtain information on fishing behaviors, fish consumption, and demographic data on the anglers and families. During the summer of 2007, a team from VCU-CES administered the survey to 158 anglers at boat launching and fishing sites. Surveys were completed for anglers who were fishing at 17 locations on 5 rivers: the James River below Richmond, the Chickahominy, Pamunkey, Mattaponi, and upper Piankatank Rivers. These rivers are affected by methylmercury contamination, have been surveyed in previous similar investigations and are used by anglers for recreational fishing.

The surveys were administered to anglers from all 17 locations on all 5 rivers, predominantly on Friday, Saturday or Sunday. Approximately 44 percent of all respondents and their families consume the fish that they catch from these waters. Half (50 percent) of the anglers, not their family members consume some fish that they catch, and more men (54 percent) than women (43 percent) were reported to consume the fish with elevated methylmercury levels. The most commonly consumed fish were catfish, spot or croaker, sunfish and largemouth bass; catfish and largemouth bass are two of the species on the fish consumption advisory. Catfish also represented the largest number of meals and total amount of self-caught fish consumed per year. The data on fish consumption were analyzed with DEQ data on methylmercury concentrations in fish that had been collected in previous years to estimate the amount of methylmercury consumed in fish yearly. In order to estimate total methylmercury from all fish consumption, canned tuna and purchased fish consumption were added to mercury exposures from self-caught fish. Mercury levels in tuna and purchased fish were taken from national data.

The methylmercury exposures determined from survey data and DEQ fish tissue levels were compared to the dose of mercury exposure that the EPA has set (and VDH uses) as the dose without appreciable health risks, based on the reference dose or RfD. The RfD for methylmercury established by EPA is based on recommendations from the National Research Council (NRC), a body of the National Academy of Sciences. The NRC reported that there is evidence that the kidney, liver, cardiovascular and immune systems could be affected by methylmercury, but a NRC committee found that neurodevelopmental problems are the most appropriate basis for setting an exposure limit for methylmercury and that strong scientific evidence exists from human and animal studies to link certain levels of methylmercury exposure and neurological problems. These problems include poor performance on tests that measure attention and motor function, which are linked to IQ. Following the recommendations of the NRC, the RfD for methylmercury was established based on preventing adverse effects on neurological development in young children.

VCU-CES's analysis of the fish consumption and fish tissue concentrations was performed using risk assessment software that provided probabilistic levels of potential exposure to methylmercury. This program randomly selects certain values, as defined, to use in the equations for determining total mercury from all the fish consumed. The analysis indicates that a significant number of anglers who regularly catch and consume significant amounts of catfish and large mouth bass from the affected waters are exposed to methylmercury at levels above the U.S. EPA reference dose of 0.1 ug/kg-day.

Utilizing the information obtained from various statistical methods, VCU-CES modeled the loss of IQ points from prenatal exposure to methylmercury through the maternal diet, specifically mercury from consumption of mercury-contaminated fish. To model the loss of IQ points from prenatal exposure to methylmercury through the maternal diet, the target population of interest is women of childbearing age. To approximate this group, the survey results were divided by gender and age group and the subsample from women 16 to 49 years old (n=52) was used for risk assessment. Two of the survey results used were from female anglers who had been interviewed; the remaining 50 survey results used were from anglers who reported women aged 16 to 49 living in their households who ate fish that the angler caught from the river where interviewed. Because information was not obtained on fish-meal frequency and meal size for family members, it was assumed that these 50 women had the same fish-meal frequency and size as their anglers. Using the survey results and fish mercury concentrations from DEQ's fish tissue database, a probability distribution of ingested doses was created through a Monte Carlo simulation process. Based upon the estimated maternal exposure to current fish mercury concentrations, the VCU-CES study estimated future levels of IQ changes due to 2010 and 2018 levels of controls to result in average (mean) avoided IQ deficits of 0.03 IQ points. The VCU study estimated change in IQ points to approximate a net loss of 0.03 as a result of exposure to mercury.

Note: the following chart is provided to help give some perspective on IQ scores.

Descriptive Classifications of Intelligence Quotients

IQ	Description	% of Population
130+	Very superior	2.2%
120-129	Superior	6.7%
110-119	High average	16.1%
90-109	Average	50%
80-89	Low average	16.1%
70-79	Borderline	6.7%
Below 70	Extremely low	2.2%

Source: From; Wechsler, David, WAIS-III Administration and Scoring Manual, San Antonio, Texas: Psychological Corporation, 1997.

The survey conducted by VCU-CES indicated that there are limitations with the study, including but not limited to:

- This survey obtained data from only a few women and no family members and further surveys would be needed to obtain direct fish consumption information on women and children in anglers' families;

- Language barriers prohibited some Spanish-speaking anglers from participating in the survey; and
- The risks of combined exposures to multiple contaminants in fish are unknown.

The above is a summary of the report prepared by VCU-CES. The entire report prepared by VCU-CES provides more detailed information on the sampling surveys, survey results, methods used to examine fish consumption and risks assessment. The report is included as Appendix B. Information obtained from the VCU-CES study was provided to DEQ to be utilized in the monetized economic analysis associated with avoided IQ deficits due to reduced exposure from the consumption of recreationally-caught freshwater fish, which is discussed in the next chapter of the report.

Chapter 8- Assessment Of Potential Monetary Benefits Of IQ Changes Associated With Reduced Methylmercury Consumption

Summary

This chapter of the report attempts to quantify and monetize, to the extent feasible, the economic benefits associated with modeled avoided IQ deficits due to reduced exposure from the consumption of recreationally-caught freshwater fish.

The monetization of the human health risk effects (IQ being the human health effects of measurement) builds upon the findings of the VCU-CES study (Appendix B) and adopts the approach utilized by EPA to conduct the economic benefit analysis at the federal level (U.S. EPA 2005). This regional assessment focused on estimating the changes in exposures to women of childbearing age because adverse health effects in children have been linked to prenatal mercury exposures (Sorenson et al. 1999). This report builds on the VCU-CES study that focused on select counties of eastern Virginia where fish advisories for mercury existed and using consumption surveys, IQ losses were estimated. IQ losses were then monetized to evaluate the economic benefit of mercury emission controls (or impacts of no reduction in emissions).

EPA's CAMR analysis indicated a monetized impact of $15 million solely due to power plant emissions over the entire United States (3 percent discount rate and Year 2000 dollars); however, such an analysis is not representative of Virginia, Virginia-specific individual consumption patterns and DEQ's fish tissue data. The DEQ assessment used 10 years of birth data for only the select counties where fish consumption patterns were surveyed to quantify economic impacts associated with the average (mean) avoided IQ deficits of 0.03 IQ points found in the VCU-CES study and associated with methylmercury consumption through 2010 and 2018. Economic losses to the exposed populations of interest involved an assessment of two scenarios – worst case and most likely. Under the worst-case scenario, the estimated net per capita income earning loss to children is $337.00, or $4.8 million across all 14,364 children born in the select counties. Under the "most likely" scenario, it was estimated that 6,104 pre-natal children (i.e., less than half of the 14,364 children born in the select counties) would be exposed to methylmercury and would thus have net income losses totaling $ 2.05 million. The two monetized scenarios are estimates of impacts for areas where risk assessment of methylmercury exposure due to fish consumption was undertaken.

Introduction

This chapter sets forth the analysis of economic monetary benefits (impacts) of implementing mercury emission controls (or not installing controls). This analysis builds upon the VCU-CES study – Fish Consumption and Human Health Risks – that used DEQ's fish tissue data and reference dose recommendations set forth by EPA (and used by VDH) to compute potential changes in human health effects (IQ level being the endpoint[3]), given existing fish consumption patterns and current levels of methylmercury bio-accumulation.

A fuller understanding of DEQ's monetization of human health risks associated with freshwater fish consumption is incomplete without a contextual appreciation of the U.S. EPA's Clean Air

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[3] Economic endpoints are well-defined, economically meaningful effects associated with a contaminant- U.S. EPA National Center for Environmental Economics (NCEE).

Mercury Rule-based Regulatory Impact Analysis (US EPA 2005b) and follow-up update assessment done by Griffiths, et al. (2007). EPA narrowed its focus of human health risk assessment due to methylmercury based fish contamination to recreationally-caught freshwater fish only. Target populations of interest were narrowed to women of childbearing age (as also cited in the VCU-CES study) but also focused on only freshwater exposures in the eastern half of the United States and measured the changes in IQ levels as economic endpoints.

DEQ's estimation of the monetary benefits (or impacts) of mercury emissions (of implementing emission controls) replicates the U.S. EPA approach and specifically the updated Griffiths et al. (2007) study but narrowed its focus to freshwater-based recreational anglers across select counties of the Commonwealth. The chart below provides a visual understanding of this section of the report in terms of the various components and related "data inputs" and the "outputs." Following the visual representation of the study, a summary is provided of the economic benefit assessment approach, data used and related results.

<u>Summary of methodology, assumptions and data used</u>

A visual interpretation of the procedure below depicts the process by which monetization of human health risk effects is undertaken using the findings from the human health risk study.

<u>Overview of DEQ approach to monetized impacts of mercury emissions</u>

Fish tissue data from DEQ + Fish consumption data

Compare consumption with EPA Reference Dose → VCU-CES study

Compute levels of IQ point losses →

Net IQ points lost (prenatal methylmercury exposed children in select VA counties only)

- EPA est. lifetime earnings
- EPA est. of loss in lifetime earnings per IQ point (Salkever 1995)
- Average number of births (1996-2006) for select counties with IQ losses estimate

DEQ economic benefit analysis

(this section of the report)

Estimate of net future earnings loss per child[4]

The above graphic interpretation is also explained in detail in the following sub-sections.

- ***Procedure for monetizing IQ losses (gains) and assumptions used***

The methods used for this section of the study are primarily based upon the approach adopted by EPA and utilized EPA estimates on the relationship between IQ points lost and related net loss in future earnings potential and average lifetime earnings data (US $2000). EPA estimated average present value of future earnings using the total average annual earnings for the population, also in five-year intervals, broken out by sex and education. The EPA also summed the earnings across age intervals, assuming a 3 percent discount rate and a 1 percent annual gain in productivity and used the Gross Domestic Product (GDP) deflator to convert $366,021 (1992 dollars) into $472,465 (2000 dollars). Furthermore, expected value of foregone future earnings associated with IQ decrements was adopted by U.S. EPA from assessment by Salkever (1995) that used data from the National Longitudinal Study of Youth (NLSY) and a statistical model to estimate the linkage between IQ levels, educational attainment and future earnings potential.

DEQ used that estimate as well, to capture the loss in future lifetime earnings for children born to the susceptible sub-population of women of childbearing age from the sampled counties in the Commonwealth. Summarized below are the equation and related steps that were used to quantify the monetary impact of potential IQ losses associated with mercury emissions.

<u>Net change in future lifetime earnings for total targeted population (children)</u> =

Lifetime earnings *** *% change in lifetime earnings / IQ point* *** *IQ points lost due to mercury emissions* *** *# of births (for select counties of interest)*

where:

Lifetime earnings estimate: $472,465 (U.S. EPA estimate in 2000 dollars)

% change in lifetime earnings per IQ point: 2.379 percent decrease in future earnings or 0.0238

[4] Estimate of net future lifetime earnings loss per child is specific to the child only and limited to the select counties where fish consumption surveys were undertaken. It does not translate into any economic impacts to the counties.

IQ points lost due to mercury emissions: VCU-CES study-based estimates of change in IQ points lost

 # births: Annual average for the last 10 years (1996-2006) for the select counties (VDH).

Numerically, this can be interpreted as:

Loss per child in lifetime earnings = $472,465 * 0.0238* 0.03 * # of children born in select Virginia counties between 1996-2006.

Steps used to implement this procedure are:

1. Lifetime earnings estimate was multiplied with percent change in earnings per IQ point.
2. Product of Step 1 was then multiplied with VCU-CES study-based net change in IQ points lost
3. Finally, this combined value from Steps 1 and 2 was multiplied with total average number of births across the select counties of Virginia where fish consumption surveys were conducted, to obtain monetized estimates of potential future loss in lifetime earnings per child in the select counties of the Commonwealth.

- ***Key supporting assumptions:***

It must be noted that this study makes some key assumptions, and any interpretation of the results without consideration of the assumptions would lead to misinterpretation of the results:

1. **Monetary impact to children only and not a fiscal impact:**

   The monetary impact to the children due to prenatal exposure to methylmercury is the monetary impact to the individuals (in this case, children of the select counties) alone. This estimate should not be reflected as costs to the family, county or city, or the Commonwealth at large, as this is an individualistic economic endpoint measurement and not a fiscal and/or welfare impact assessment of a region due to mercury emissions. Furthermore, this estimate is on the higher end or more of an “upper bound” estimate and assumes that 100 percent of all children in the select counties experienced pre-natal exposure to methylmercury. Research indicates that susceptible sub-populations are usually responsive to fish advisories and thus, actual estimates of exposures and thus, monetized impacts of IQ losses would be lower than what is summarized in the following section.

2. **Site-specific economic impact only:**

   This measure is specific to the select counties as identified earlier in the Fish Consumption and Human Health Risk assessment study by VCU-CES. Estimates of monetary impacts of IQ losses from this study cannot be generalized for all the children across the Commonwealth. If such an assessment is to be considered, a careful extrapolation has to take into account likely areas of freshwater fishing by anglers, locations of fishing and deposition-induced, mercury-contaminated waters and, more specifically, good information is needed on the consumption rates by women of childbearing age in other non-select study sites.

3. **Comparing costs and benefits simultaneously is not feasible:**
The economic costs of control technologies (for coal-fired power plants) as identified in the earlier chapter of this report, is very dependent on market availability of inputs for coal, dynamics of electricity supply and demand and, more importantly, the size and efficiency of various coal-fired power plants across Virginia, in terms of performance of mercury control technologies (co-benefit and individual controls). The cost assessment across each plant varies by the timeline by which each plant seeks to break even on their capital costs of installation of new control technologies or upgrading the retrofits. Economic benefits (through reductions in mercury emissions and related IQ gains) are an individualistic measure of pre-natal exposure-based potential IQ deficits in children. The economic estimates of forgone lifetime earnings are based on EPA estimates and updated using the latest GDP deflator. Comparing the costs of control technologies by electric generating units which are added to the costs of energy generation and distribution is different from the net economic benefits of reduced mercury exposure through lower levels of methylmercury contamination, which is a more individualistic measure and has no implications for the economic health of a workforce of a specific industry, or a city or county as a whole. Lastly, mercury depositions in streams of interest are from all sources, not just from electric generating units; thus, any determination of control technologies for coal-fired power plants using the economic impact to children due to methylmercury would be difficult and complex.

4. **Recreationally-caught freshwater fish assessment only:**
This assessment was undertaken on recreationally-caught freshwater fish consumption only. Commercial fish consumption and related health effects were not feasible and, therefore, not the focus of this effort. However, Shimshack et al. (2007) have evaluated the role of responses to U.S. Food and Drug Administration (FDA) advisory that informed citizens of the potential sub-populations at risk from consuming store-bought fish that is contaminated by methylmercury. The study did find that generally, targeted populations across the United States did respond to informational advisories by significantly reducing the consumption of appropriate fish species.

- ***Results:***

Adopting the above mentioned steps and modeling equation, we get the following results in terms of monetary impact of IQ losses associated with methylmercury exposure to women of childbearing age.

Table 8-1 Monetary impact of IQ losses (select counties) due to mercury emissions

Lifetime earnings est. (Year 2000 dollars) **(A)**	EPA's dose-response slope (B)	Net IQ points lost (C)	Net impacts per child (D= A*B*C)
$ 472,465	0.0238	0.03	$ 337.34

Table 8-1 indicates that the economic impact in terms of future forgone lifetime earnings per child in the select counties alone would be approximately $337.34, which is a relatively very marginal economic impact per child. Two likely scenarios of economic impact were assessed using this IQ loss estimate per child of 0.03.

- **Most likely scenario:** According to the VCU-CES report, from a total sample size of 150 respondents, only 42 percent of the target population of interest - women of childbearing age - (16 to 49) ate the fish they caught. Assuming this rate of consumption reflects the consumption rate across the select counties, 42 percent of the total births over the past 10 years were computed, and the economic impact for that specific sub-population of pre-natal exposed children was assessed.

  Economic impact to select counties alone due to 42% methyl-mercury exposure:

  = Net economic impact per child * Number of births (42% exposure rate)

  OR

  = $ 337 * 6104 = $ 2.05 million (across an annual average of 6,104 children)

- **Worst-case scenario:** The worst-case scenario reflects the assumption that all children across the select counties of assessment were exposed over the last 10 years to methyl-mercury exposure. If such an assumption is considered, the economic impact is summarized below:

  Economic impact to select counties alone due to 100% exposure to methyl-mercury exposure:

  = Net economic impact per child * 10 year average of annual number of births

  OR

  = $ 337 * 14,364 = $ 4.8 million

Conclusions

The above section indicates the net economic impact for the select counties across the Commonwealth to be approximately $337.00 per child with a most-likely economic impact estimate of $ 2.05 million and a worst-case scenario of $ 4.8 million. This assessment uses the EPA based CAMR impact analysis procedure and updated Griffiths et al. (2007) estimates on lifetime earnings potential, the dose-response slope (Salkever, 1995) and annual average 10-year birth data for the select counties across Virginia (VDH). It must also be noted that this economic benefit assessment is a very simplistic version of benefit-transfer assessment and generalizing the economic estimates across the entire Commonwealth to all potential pre-natal exposed children may not be realistic and appropriate.

Chapter 8 References

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Chapter 9- Conclusions

Virginia would benefit from reduced mercury deposition as a result of implementation of pollution controls required by CAIR and CAMR. The following are the findings of this report.

Mercury Deposition Modeling

- Mercury sources located outside of Virginia contribute to the mercury deposition occurring within the state. Global sources are responsible for the largest amount of mercury being deposited within the state.

- Mercury deposition would be predicted to decrease statewide in future years as a result of implementation of emission controls in use to meet requirements of the CAIR and the CAMR. Virginia benefits from mercury reductions occurring in surrounding states, particularly emissions reductions from EGUs.

- Emission sources located in Virginia contribute to mercury deposition within the state, and the greatest impacts from the in-state sources are simulated near the source locations. This includes EGU sources and non-EGU sources.

- Examining deposition patterns for EGU and non-EGU sources indicates that, in general, EGU sources tend to impact a larger area compared to non-EGU sources. This is likely due to non-EGU sources having shorter stack heights and lower exit velocities, which result in less dispersion of mercury.

- The modeling results were calculated by using requirements that must be met under the CAIR and the CAMR. The Washington, D.C. Circuit Court of Appeals has recently issued opinions vacating both of these rules.

Potential Changes to Mercury Fish Tissue Concentrations

- Based on available information from multiple experiments and field experiences, mercury that is air-deposited into aquatic ecosystems can be expected to contaminate fish.

- Lakes and wetlands are especially sensitive to even small amounts of added mercury because these environments are very efficient in transforming the mercury into a form that is readily accumulated by fish.

- Reduction in mercury inputs into a waterbody is expected to result in lowered concentrations of mercury in the fish after the ecosystem readjusts to the lower mercury levels in the environment.

- It is reasonable to expect a proportional lowering of fish mercury concentrations over time in response to decreases in mercury deposition rates from the air.

- The time frame needed before these lowered fish concentrations could occur depends on how efficiently mercury is processed by the aquatic ecosystem and picked up by the fish.

- Each individual waterbody is expected to react slightly differently due to natural variances in the chemical and physical conditions and differences in food-web structure.

- Lakes are expected to respond quickest (within a few years to decades) to reduced mercury deposition, with wetlands requiring more time to equilibrate to the lowered mercury inputs.

- The projected reductions in mercury-air-deposition rates after 2010 and 2018 estimated by the ICF model (based on CAIR and CAMR) suggests that fish mercury levels may become lower in the future such that some species may no longer warrant a fish consumption advisory.

- The VDH issues fish consumption advisories when average concentrations of mercury in fish exceed 0.50 ppm.

- The DEQ has recently proposed the adoption of a fish tissue criterion for mercury of 0.30 ppm, which is lower than the current threshold concentration used by the VDH to issue fish consumption advisories. If the State Water Control Board adopts this fish tissue criterion for mercury, in the future DEQ may classify some waterbodies as impaired due to elevated mercury contamination in fish before the VDH would find it necessary to issue a fish consumption advisory.

- Of the thirteen mercury-sensitive waterbodies in Virginia with current fish consumption advisories due to mercury contamination in fish, the fish mercury levels may be lowered enough in the future (to below 0.5 ppm mercury level currently used by the VDH) such that three or four of these advisories may no longer be warranted.

- In all but two of the advisory areas, at least one species of fish may have reduced mercury levels in the future that could allow for its removal from the fish consumption advisory and, in one case (Dismal Swamp Canal), the advisory area may be reduced.

- Under the projected reduced air deposition rates for the future (based on CAIR and CAMR), nine to ten of the current fish consumption advisories will likely remain in place for at least one species of fish.

- Average mercury concentrations for at least one species of fish could remain higher than 0.30 ppm, so all of these waterbodies could remain classified as impaired by DEQ.

Pollution Control Technology Costs

- The costs of mercury control at coal-fired power plants are affected by a number of parameters, including what technologies are chosen, what regulations are in place, and the market-based determination of demand versus supply of energy.

- A number of options for reducing mercury emissions from coal-fired power plants are commercially available, and others are being developed. A number of control technologies for the reduction of mercury are available to coal-fired power plants, allowing each facility to choose the best fit in terms of cost-effectiveness.

- The DEQ cost assessment was based on a thorough review of existing and future projected mercury controls by Virginia-based electric generating units. Specifically, best available information on control technologies (performance, constraints, market prices of inputs and by-product disposal estimates) was used in this analysis. The results support the view, which is widely held by U.S. EPA, U.S. DOE, industry research and other state agencies, that mercury control is more cost-effective if coal-fired power plants adopt a multi-pollutant post-combustion control technology sequence. Specifically, a combination of SCR, FGD, Fabric Filter and ACI was found to have the most cost-effective configuration.

Fish Consumption Trends in Virginia's Waterways and Monetization of Human Health Risk Effects (IQ level)

- Based upon the estimated maternal exposure to current fish mercury concentrations, the VCU-CES study estimated future levels of IQ changes due to 2010 and 2018 levels of controls to result in average (mean) avoided IQ deficits of 0.03 IQ points.

- Under the worst-case scenario, the estimated net per capita income earning loss to children is $337.00, or $4.8 million across all 14,364 children born in the select counties. Under the "most likely" scenario, it was estimated that 6,104 pre-natal children (i.e., less than half of the 14,364 children born in the select counties) would be exposed to methylmercury and would thus have net income losses totaling $2.05 million. The two monetized scenarios are estimates of impacts for areas where risk assessment of methylmercury exposure due to fish consumption was undertaken.

Appendix A- Final ICF report

Appendix B- VCU-CES report