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MERCURY EMISSIONS FROM COAL-FIRED POWER PLANTS:
AN EVALUATION OF REDUCTION STRATEGIES
USING THE ANALYTIC HIERARCHY PROCESS

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By

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ABSTRACT

MERCURY EMISSIONS FROM COAL-FIRED POWER PLANTS: AN EVALUATION OF REDUCTION STRATEGIES USING THE ANALYTIC HIERARCHY PROCESS

By

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The U.S. Environmental Protection Agency (EPA) is currently developing mercury emission regulations for the electric utility sector. As is the case with most environmental policy decisions, this is a complex undertaking. This research project evaluates a range of mercury emission reduction strategies from a multi-objective perspective.

In-depth interviews and surveys were administered with representatives of the three key stakeholder groups associated with this policy decision to determine their strategy preferences and desired evaluation criteria. This provided the inputs to a multi-criteria decision analysis using the Analytic Hierarchy Process. The analysis revealed significant differences among the stakeholder groups with respect to how they perceived the alternative reduction strategies and the importance they placed on the various evaluation criteria. The study revealed that certain reduction strategies could be eliminated from the current strategy debate because they are not preferred by any of the three stakeholder groups. In addition, a strategy regulating multiple pollutant emissions at one time appears to hold the greatest promise for achieving stakeholder consensus. It is also recommended that the EPA employ a collaborative problem solving approach involving the key stakeholders to further the policy debate and build consensus.

DEDICATION

This thesis is dedicated to Aaron, who deserves much more than being the subject of the "dedication" section of my thesis for tolerating me through this ordeal called graduate school. You thanklessly took care of me, believed in me, listened to my complaints, hugged me, consoled me, and cheered for me every step of the way. Toward the end when I was at my worst, you still loved me and, even more amazingly, proposed to me! I will spend the rest of our lifetime together thanking you for your love and support.

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This thesis involved the collection of a considerable amount of data, which means that a considerable amount of people voluntarily took the time to answer my questions and fill out lengthy surveys. These individuals were not rewarded in anyway but with simple thanks, and I would like to thank them again for their considerable patients and time.

Additionally, I would like to thank my first and second major professors: Drs. Jeff Riedinger and Cynthia Fridgen. Thank you both for your advice, patience, and guidance during the confusion of my early years of graduate school. Dr. Riedinger also deserves thanks for serving on my thesis committee, as does Dr. Emmett Braselton, who introduced me to the complex world of toxicology. Thank you for your patience and time in helping me understand the "science" behind the "policy."

I went through three jobs, two moves, two major professors, and a great deal of confusion, before I met Dr. Jo Ann Beckwith, who served as my major professor through the last and toughest years of grad school. To her I owe the greatest thanks. Jo Ann was strict enough to keep me on task, but kind enough to keep me from going crazy. In academia, it is often hard to find a professor who still believes that their primary job objective is teaching, but Jo Ann definitely prioritizes her students and cares deeply about their academic, professional, and personal success. I am lucky to have had her assistance.

Lastly, I want to thank my parents and friends, who are my true support system. Thank you for always being there when I needed you and helping me get through this.

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CHAPTER 1

PROBLEM ANALYSIS

PROBLEM BACKGROUND

While legislative and policy decisions are often difficult to make and plagued by complexity, environmental policy decisions have unique characteristics that pose even greater challenges for decision-makers and affected parties. For example, decisions regarding environmental policy usually involve uncertainty, require a great deal of complex scientific input, create winners and losers with the distribution of costs and benefits often unclear, and involve multiple actors who maintain diverse (and often conflicting) interests, opinions, and values. One such pending environmental policy decision follows the United States Environmental Protection Agency's (EPA) December 15, 2000, decision to regulate mercury emissions from electric utility steam-generating power plants. The EPA must choose a mercury control strategy for this sector and finalize mercury emission regulations by December 15, 2004.

Mercury is a naturally occurring element that cycles in the environment as a result of natural and anthropogenic activities. When mercury enters a water body, it may transform to merthylmercury, which is a readily bioavailable form that efficiently biomagnifies in the aquatic food chain. Methylmercury is highly toxic to humans and wildlife, who are exposed primarily through consumption of contaminated fish (ATSDR 1999).

According to the EPA, electric utility steam generating units are the largest source of anthropogenic mercury emissions in the United States, estimated to emit 43 tons of mercury, or 1/3 of current US emissions (EPA 1999). During the last three decades significant controls have been placed upon the use and disposal of mercury from many sources. However, the power plant sector lags far behind in terms of mercury reduction efforts. Due to the adverse toxicological effects of mercury, and its persistence in the environment, the EPA has determined that a policy solution that reduces the largest anthropogenic source of mercury releases into the environment is needed.

PROBLEM STATEMENT

There are many possible mercury emission reduction frameworks that could reduce and/or eliminate this source, including but not limited to fuel switching to cleaner burning fuels or renewable resources, demand-side management, or installing pollution control technology. Different reduction strategies have different implications in terms of effectiveness, cost, feasibility, efficiency, cost distribution, and stakeholder acceptance. Selecting one reduction strategy over another will involve trade-offs — trade-offs that might be viewed as desirable by some stakeholders but be unacceptable to other stakeholders. Therefore, a critical analysis of all possibilities is needed to determine which strategy or combination of mechanisms is preferred overall or preferred from specific stakeholder perspectives. The stakeholders in this case include well identified interests including the electricity industry, government regulatory agencies such as the EPA, and environmental groups engaged in this issue.

RESEARCH DIRECTIONS

The two main objectives of this research are:

1. To develop a multi-criteria decision framework for exploring and evaluating alternative strategies for reducing coal-fired power plant mercury emissions; and
2. To recommend a preferred mercury reduction strategy for the coal-fired power sector.

Questions to be addressed in the research include:

- What mercury reduction strategies are preferred for the coal-fired power sector?
- What are the major barriers to successfully implementing alternative mercury reduction strategies?
- What criteria should be used to evaluate different reduction strategies?
- Is there common ground among the stakeholders in terms of their positions, objectives and concerns regarding mercury reduction strategies for coal-fired power plants?
- What conflicting positions exist among the stakeholders and can any of them be resolved?
- What are the key trade-offs among the mercury reduction strategies and does any one strategy or combination of strategies have greater potential for stakeholder acceptance than the others?
- What are the strengths and weaknesses of applying the Analytic Hierarchy Process in this type of evaluation?

This analysis will provide guidance to the U.S. EPA regarding which mercury reduction strategy they should apply now that a decision to regulate has been made.

OUTLINE OF THESIS

The broad scope of this chapter has been necessary to introduce properly the work presented in this thesis, which is centered on the complex decision problem of how to regulate mercury emissions from coal-fired power plants. In chapter 2, this background information is expanded upon, including a detailed discussion regarding the factors that contribute to the complexities and importance of this research problem. To accomplish this, a three-section literature review is conducted to explore the different aspects of this decision problem. The first section focuses on the characteristics of environmental decision-making and the use of multi-criteria decision aids. The second section contains a review of the literature on the toxicological aspects of mercury contamination that create the urgency and need for issue resolution. The third section sets forth the options or strategies for mercury reduction identified in the literature.

Chapter 3 provides a detailed discussion of the research design used in this study, which is modeled after the Analytic Hierarchy Process (AHP). This two-phased, multi-step process is explained and examples are given to help the reader gain a full understanding of the AHP and its role in multi-criteria decision making. In Chapter 4, the AHP model is put into operation and results from the process are reported and analyzed. Chapter 5 contains a summary of the study and suggestions for future work.

CHAPTER 2

PROBLEM FOCUSED LITERATURE REVIEW

This literature review is broken into three sections. The first section focuses on the characteristics of environmental decision-making and the use of multi-criteria decision aids. The second section reviews the literature on the toxicological aspects of mercury contamination that make it such an important issue to be resolved. The third section sets forth the options or strategies for mercury reduction identified in the literature.

ENVIRONMENTAL DECISION-MAKING

An environmental decision is a decision concerning an issue or an action that could or will have a foreseeable effect on the environment. Environmental decisions can vary in many ways. They can occur at any administrative level (e.g., international, national, state, city); be collective or personal in nature; be site-specific or program-related; involve a positive or negative effect on the environment; and/or cause risk-benefit, spatial, temporal or social dilemmas (NCEDR 1996).

While policy decisions in general are difficult to make, environmental policy decisions have unique characteristics that make them even more difficult. According to the National Center for Environmental Decision-Making Research (1996), aspects of environmental decisions that make them more difficult include:

- new stakeholders are involved compared to traditional societal problems (especially laypeople/affected people);
- the problems often do not fit within administrative boundaries;
- the distribution of costs and benefits is unclear;
- the valuation of environmental assets (and hence options) is very difficult;
- more scientific input is necessary than for other sorts of problems;
- the actions selected take a long time to realize;
- they involve great uncertainty.

The mercury emissions issue possesses many of these characteristics. For example, scientific uncertainty made the EPA's decision regarding the regulation of mercury emissions from the electric utility sector very complex. In 1990, Congress amended the Clean Air Act and ordered the EPA to promulgate regulations establishing emission standards for large sources of hazardous air pollutants, including mercury. Because of the scientific uncertainty surrounding the level and health impact of hazardous air pollutant emissions from the electric utility sector, Congress exempted this industry from regulation. Instead, Congress ordered EPA to study toxic hazardous air pollution from power plants in order to determine if regulation was necessary in order to protect public health. Several major studies (e.g. the EPA's Mercury Study Report to Congress 1997, the EPA's 1998 Utility Air Toxics Study, the National Research Council 2000 Toxicological Effects of Methylmercury study) were published over the course of ten years before a positive determination was made in December 2000, and the strategy EPA will use to reduce mercury emissions will not be determined until 2004.

Mercury fate and transport tendencies also make it a difficult chemical to regulate due to scientific uncertainty. In the atmosphere, most mercury is in elemental vapor form, which can circulate for up to one year (EPA 1997a). This allows it to be transported long distances from the original emission sources. Controlling the pathway of mercury is difficult, because it cycles within the environment by moving between the air, water and soil. Because there is no method to link deposition or ambient concentrations to exposure concentrations for these pollutants, it is difficult to determine effective emission reduction strategies. In addition, although the EPA has made estimations regarding mercury emission amounts from different sources, these sources are quick to deny their share of the mercury pollution problem because, they say, EPA's estimates are flawed and it is still not scientifically clear exactly what their contribution is. Without this proof, it is difficult to promulgate and enforce reduction strategies.

In addition to the decision-making obstacle scientific uncertainty presents, the global circulation and unclear source contribution aspects of mercury emissions create administrative decision-making difficulties. Mercury is a global problem, being emitted by sources and deposited all over the world. Coordinating and reaching consensus on environmental decisions involving different countries, cultures, economies, and industries is extremely difficult if not impossible.

Finally, uncertainty is a key obstacle in the decision to regulate mercury emissions. There are many uncertainties involved in environmental regulation. Uncertainties that exist in the mercury regulation issue include the effectiveness of different control strategies, the appropriate target mercury reduction level to protect public health, what the reduction strategies will cost, and whether the cost will be worth the benefit. For example, requiring utilities to implement demand side management programs is estimated to cost anywhere from $800,000 - $2.8 million per plant and has an unknown reduction potential (EPA 2000a). All of these questions and uncertainties, particularly regarding effectiveness and cost, complicate the mercury reduction decision-making process.

The psychological aspects of decision-making, particularly with respect to the environment, also contribute to the difficulty in designing and implementing policies with broad public acceptance. Simply setting forth accurate factual information about an environmental issue and its management options seldom meets with success in the public arena because hey are viewed through a lens of beliefs, values and worldviews (Bazerman et al. 1997). Every individual has their own set of beliefs and values; therefore, it is important to understand the psychology of individual and group action in environmental domains in order to understand why environmental decision-making is so complex.

The environment is a complex system of resource stocks, providing a variety of valuable service flows. Environmental resources, for the most part, are public goods, meaning they are neither indivisible in consumption nor excludable in use (Perman et al 1996). The implications of these two characteristics result in entitlement battles due to the promotion of self-interest and exploitation of the resource. To compound these issues, these valuable services to which everyone feels entitled are available in limited quantities. Many environmental issues and conflicts revolve about the allocation of resources (e.g. air, water, land) and deal with issues of both procedural and distributive justice or notions of fairness (Knetsch 1997). They not only involve different interests and feelings of entitlement, but different values as well. A person's position on an environmental issue is an expression of their fundamental values, beliefs, and ethics. It touches on people's core ideological beliefs (Thompson and Gonzalez 1997). The environment is not just a conglomerate of resources to be allocated, but a symbol of personal views and worldviews. These views can create major impediments to the successful resolution of environmental disputes.

Multi-Criteria Analysis

Few decisions involve consideration of a single criterion. Even the most straightforward question, such as which melon to purchase at the grocery store, involves multiple objectives. The melon should be ripe, inexpensive, juicy, and large. Many times, these objectives conflict, i.e. the ripest melon may be expensive, or the largest melon may be less juicy, complicating the decision.

In many cases, a variety of conflicting factors and considerations must be weighed before a feasible alternative is identified. The more multi-faceted a problem is and the more conflicting the objectives are, the more difficult the decision-making process is and the more necessary a decision aide becomes. When a decision-maker - whether they are a grocery shopper, scientist, government official, or business leader – is faced with a choice between alternatives, a mechanism for identifying the best solution is desirable. One such mechanism is multi-criteria analysis (MCA).

MCA is a method employed by decision-makers to address a general class of problems that involve multiple attributes, objectives, and goals (Zeleny 1982). An important branch of applied mathematics and operational research, MCA is a decision making tool that enables the rigorous selection of the most preferred alternative in a situation where several criteria apply simultaneously (Mendoza and Prabhu 2000). There are many MCA methodologies and approaches, such as the ranking method, rating method, and pairwise comparison technique. Some more modern MCA tools incorporate these methodologies, including data envelopment analysis, operational competitiveness rating analysis, and the analytic hierarchy process (Parkan and Wu 2000).

MCA can aid in the decision-making process in a variety of ways (Beinat and Nijkamp 1998):

- MCA can be used to aid the identification of the most suitable solution from multiple decision alternatives and environmental management options.
- The effects of alternative decision options can be presented in a variety of forms, such as monetary units, physical units, quantitative judgements, etc.
- It brings out the positions, objectives and concerns of the decision actors, making it possible to understand, justify, and negotiate the main issues involved in the decision.

This also enables the identification and resolution of potential conflicts at an early stage of the decision process.

- Trade-offs between different objectives and concerns are exposed, making it possible to thoroughly analyze the pros and cons of different options.
- It offers a framework for analyzing different choices against different future scenarios.

The MCA concept received little attention until the late 1960's. By 1970, MCA was the fastest growing and most innovative of the operational research and management science fields (Zeleny 1982). In the late 1970's, a large variety of practical applications began to appear, furthering its growth. More than 1,000 books and articles were written on MCA and its applications during that decade, and the growth of its popularity continues. MCA is not only established as one of the most dynamic and widely applied areas of operational research and management science, it is now able to stand on its own and bring its research results directly to practicing managers and decision makers. In fact, most of the MCA activities take place outside and independently of the official operational research and management science undertaking, including application in many environmental management-related areas, including land use management, environmental planning, waste management, and energy management (Zeleny 1982).

MCA is well suited to environmental management decision-making. Making environmental management decisions involves interplay among a variety of human and natural systems components. Often, due to differing interests and values, there is little agreement among the various stakeholders as to what single factor or set of factors should be used to or given more weight in evaluating and selecting among policy options. It is in these types of multi-dimensional situations that multi-criteria analysis is valuable. For instance in the land use arena, multi-criteria analysis is used to formulate indicators encapsulating a wide diversity of attributes and environmental assets in a spatial setting (Beinat and Nijkamp 1998). It facilitates multiple perspectives from multiple actors to be addressed in planning decisions. MCA is helpful, in the presence of multiple concerns and objectives, to analyze trade-offs between conflicting results, and search for compromise and acceptable environmental management solutions.

The Analytic Hierarchy Process

This study seeks to address a complex problem, which involves a multitude of possible mercury reduction alternatives and evaluation criteria. Multi-criteria analysis can provide a framework to tackle such a complex decision making environment. This method of analysis provides a logical and systematic process for making better decisions in complex decision situations with conflicting objectives, uncertainty, and different perspectives (Leung et al. 1998).

A recent addition to the multi-criteria analysis literature is the Analytic Hierarchy Process (AHP), which provides a systematic and logical process for dealing with both quantitative and qualitative data related to complex, multidimensional problems. It is based on the principle that subjective judgments of the decision-maker are as important as empirical data when making decisions. AHP is useful when neither logic nor intuition alone is sufficient to determine which of several options are most desirable. As stated by its founder, Thomas Saaty (1994, pg. 21), "AHP is about breaking a problem down and then aggregating the solutions of all the sub-problems into a conclusion. It facilitates decision making by organizing perception, feelings, judgements and memories into a framework that exhibits the forces that influence a decision." It is important to note that AHP does not replace decision-making, but provides a conceptual framework for systematic thinking about difficult problems along with a set of analytical tools to make the decision-making process easier.

Less than three decades old, AHP has already created a voluminous body of literature in many different fields as an innovative way to address multifaceted, complex problems. The versatility of this approach has led to applications in many diverse areas. For example Saaty (1990) provides a list of nearly 100 different applications up to 1990, including energy resource allocation, policy/strategic planning, forestry management decision-making, and environmental conflict resolution.

Decisions made using AHP occur in two phases: (1) hierarchic design and (2) evaluation (Vargas 1989). Designing the hierarchy involves breaking the problem down into a hierarchy of decision-making elements. The problem is modeled using a hierarchical structure, as a tree containing the overall goal at the top, followed by a layer of subgoals of the overall goal, then criteria and subcriteria that must be satisfied to fulfill the subgoals of the overall goal. At the bottom of the tree is a set of policy alternatives. Arranging the goals, criteria, and alternatives this way allows the decision maker(s) to see the complex relationships inherent in the situation and assess the importance of each issue at each level.

The literature cites the many benefits and disadvantages of AHP. Most users agree that the major benefit of this method is its ability to facilitate complex decision-making by organizing multiple perceptions, feelings, judgments, memories and data into manageable decision-making elements (e.g. Vargas 1989, Hamalainen 1990, Saaty 1994). Some of the most notable benefits found in the literature pertaining to AHP as a group decision-support tool include:

1. AHP permits thorough modeling of the decision, inducing people to make explicit their tacit knowledge; include judgements, intuition, emotion as well as logic (Saaty 1994).
2. The use of pairwise comparisons forces AHP users to articulate the relative importance of criteria and then to decide the relative contribution of the alternative to the criteria (Carlsson and Walden 1995).
3. The sophistication and user-friendliness of Expert Choice software (Expert Choice, Inc., 1996) allows AHP users to quickly build and solve a multiple criteria decision problem (Carlsson and Walden 1995).
4. The hierarchical feature of AHP allows easy and natural structuring of the problem so that the user can clarify and consider all the relative, diverse problem aspects (Carlsson and Walden 1995, Hamalainen 1990).

5. AHP is practical in that the decision-maker is free to remain inconsistent, but receives feedback on the frequency and level of inconsistent judgements (Hamalainen 1990).

Carlson and Walden (1995) pointed out four weaknesses of the AHP as a decision-support system pertaining to group decision making:

1. AHP users almost never use the seven (very strong importance) and the nine (extreme importance) scale because they do not perceive them to be much different from five (essential or strong importance).
2. AHP users must rely too heavily on their experience and intuitive judgement.
3. An arbitrary starting reference point is needed in pairwise comparison that may change perceptions of a multiple criteria problems.
4. Pairwise comparisons eliminate the longer chains of interdependence, which the users perceive during an AHP evaluation.

TOXICOLOGICAL ASPECT OF MERCURY

Sources of Mercury in the Environment

Mercury is a naturally occurring element that, like all elements, exists in the same quantities now as when the Earth was first formed. Geologically bound mercury can be mobilized or released to the environment by natural processes or human activities, and can also be re-emitted. Natural mechanisms for mercury emission to the environment include volatilization from soils, aquatic environments, and vegetation, as well as volcanic and other geothermal activities (Nriagu 1979). Anthropogenic sources of mercury include metal production, chlor-alkali and pulp industries, waste handling and treatment, and coal, peat, and wood burning (EPA 1997a). Re-emitted mercury includes transfer of previously deposited mercury (released naturally or anthropogenically) to the atmosphere via biological and geological processes[1].

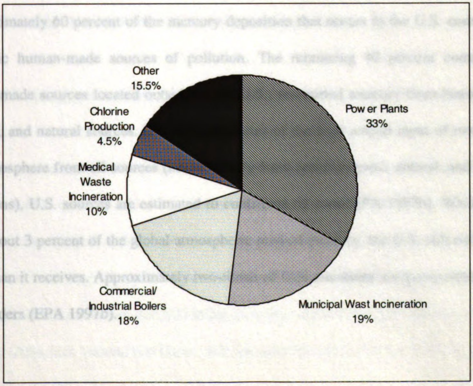
Although a great deal of uncertainty remains, it has become increasingly evident that anthropogenic emissions of mercury rival or exceed natural inputs. According to EPA's Mercury Report to Congress (1997b), the amount of mercury mobilized and released into the environment has increased by a factor of between two and five since the beginning of the industrial age. Current estimates suggest that 50-75 percent of the total yearly input of mercury into the atmosphere from all sources is the result of anthropogenic releases. A recent paper reported estimates of global anthropogenic mercury emissions reaching as high as 71 percent of total mercury emissions if re-emitted anthropogenic mercury is considered in the estimates (Jackson 1997).

The most recent total annual estimate for all anthropogenic mercury emissions to the air in the U.S. was 158 tons (316,000 pounds) (EPA 1997a). While this estimate has a number of uncertainties, it is likely low, due to lack of full accounting for mercury use at chlor-alkali plants, underestimation of previously emitted mercury that is deposited and re-mitted from soils, water, or plants, and possibly other poorly-characterized sources (i.e. mobile source emissions).

[1] The fluxes of re-emitted mercury to the atmosphere are not clearly established; more study in this area will be required to document and assess this potential secondary source, which can contribute to long-term cycling of mercury in the environment.

In its mercury report to Congress, the EPA characterized the percentage contribution of mercury emissions from U.S. anthropogenic sources (see Figure 1). The EPA believes that 86 percent of these emissions comes from processes that result in the combustion of mercury-containing material, including municipal waste combustion (19 percent); coal and oil-fired commercial/industrial boilers (18 percent); medical waste incinerators (10 percent), hazardous waste combustion (4 percent); and residential boilers (2 percent). Coal-fired electric utilities are the single largest source of mercury pollution in the U.S., responsible for 33 percent of the total mercury emissions from all sources. These plants release mercury when burning coal for fuel, which contains trace amounts of mercury. The EPA estimates that the industry emitted 43 tons of mercury in 1999 from 1,149 units at 464 coal-fired plants (EPA 1999b).

Figure 1: Mercury Contributions from United States Anthropogenic Sources (EPA, 1997a)



Mercury Fate and Transport

Mercury can be discharged directly to land and water through industrial wastewater releases or the disposal of waste-containing batteries and other sources of mercury. However, because of the relatively volatile nature of mercury and the way in which it is released, a much larger fraction of total releases to the environment consist of releases to air. Air emissions are transported through the atmosphere and eventually deposit onto land or water bodies. Scientists now believe that atmospheric deposition is responsible for the bulk of mercury loading to terrestrial and aquatic ecosystems.

Mercury deposition can occur very close to the source or, depending on the chemical form in which it is emitted, it can be transported great distances - even crossing international borders. The highest deposition rates in the U.S. occur in the southern Great Lakes, the Ohio Valley, the Northeast and scattered areas in the Southeast. Approximately 60 percent of the mercury deposition that occurs in the U.S. comes from domestic human-made sources of pollution. The remaining 40 percent comes from human-made sources located outside of the U.S., re-emitted mercury from historic U.S. sources, and natural sources. Based on estimates of the total annual input of mercury to the atmosphere from all sources (i.e., 5000 Mg from anthropogenic, natural, and oceanic emissions), U.S. sources are estimated to contribute 52 tons (EPA 1997b). While this is only about 3 percent of the global atmospheric pool of mercury, the U.S. still contributes more than it receives. Approximately two-thirds of U.S. emissions are transported outside our borders (EPA 1997b).

Once mercury enters waters, either directly or through air deposition, it can bioaccumulate in fish and animal tissue in its most toxic form, methylmercury. Mercury is so efficiently bioaccumulated in the aquatic food web that the concentration of mercury found in predators at the top of the food web (for example, predatory fish and fish-eating birds and mammals) can be thousands or even millions of times greater than the concentrations of mercury found in the water.

Mercury Exposure

For the general U.S. population, the dominant pathway for human and wildlife exposure to mercury is the consumption of fish, marine mammals, and crustaceans (NRC 2000). Women of childbearing age, and people who regularly and frequently eat highly contaminated fish (or large amounts of moderately contaminated fish), are the most likely to be at risk from mercury exposure. Those groups include subsistence fishermen (people who fish for their food) and some Native American populations.

Freshwater fish (caught by recreational or subsistence fishermen) from contaminated waters have been shown to have particularly high levels of methylmercury. Mercury contamination is the most frequent basis for fish advisories. Because of the health hazards associated with mercury and the levels of mercury detected in fresh water fish, health officials have issued fish consumption advisories in thousands of water bodies nationwide, including all of the Great Lakes and their connecting waters – more than 52,000 lakes and more than 238,000 miles of rivers. As of July 2000, 40 states and one territory (American Samoa) had issued fish consumption advisories for mercury. Of those states, 13 have issued state-wide advisories, covering every inland lake and stream; the remaining 27 states issued advisories for more than 1,900 specific water bodies (EPA 2000).

High mercury levels also have been found in certain saltwater fish. In March 2000, for example, Florida, Georgia, North Carolina and South Carolina issued a joint fish consumption advisory because of high mercury levels in large king mackerel.

Certain species of commercially available saltwater fish, such as shark and swordfish, also have high levels of mercury. The U.S. Food and Drug Administration (FDA) issues consumption advice for commercial marine fish. The FDA plans to re-evaluate its current advice in light of a July 2000 report by the National Research Council that confirmed EPA's mercury reference dose, i.e., the level at which people could be exposed to mercury without the risk of health problems.

Health Effects of Mercury Exposure

The National Research Council July 2000 report completed a review of the latest scientific evidence regarding the health effects of methylmercury. Methylmercury causes a wide range of adverse effects in multiple organ systems throughout the life span of exposed humans and wildlife. In humans, epidemics of mercury poisonings following high-dose exposures in Japan and Iraq demonstrated that the fetal central nervous system is the organ widely viewed as the most sensitive to mercury exposure.

The database on neurodevelopmental effects is extensive and includes studies documenting neurological dysfunction and developmental abnormalities that occur following both acute and chronic mercury exposure. Ingested methylmercury is almost completely absorbed into the blood and distributed to all tissues (including the brain); it also readily passes through the placenta to the fetus and fetal brain. Children born of women exposed to relatively high levels of methylmercury during pregnancy are at special risk of neurological problems and have exhibited a variety of developmental neurological abnormalities, including delayed onset of walking and talking, cerebral palsy, and reduced neurological test scores. Far lower exposures during pregnancy have resulted in delays and deficits in learning abilities in the children (NRC 2000). This data confirmed EPA's assessment of the health risks related to mercury exposure.

Mercury also poses risks to fish-eating wildlife, including some birds and mammals, such as the loon, mink, and otter. Adverse effects include death, reduced reproductive success, impaired growth and development, and behavioral abnormalities (EPA 1997c).

Economic Impact of Mercury Pollution

The contamination of our waterways and fish, and the health risk it imposes on people and wildlife, are not the only threats mercury poses. Mercury contamination also threatens the health of our economy. Sport fishing plays a significant role in the lives of over 35,245,000 American adults. A substantial industry has evolved to provide goods and services to meet the diverse needs of the nation's anglers. U.S. anglers who went fishing during 1996 spent nearly $37.8 billion for goods and services in many businesses throughout the country. The economic impact of these expenditures totaled nearly $108.4 billion and rippled throughout the economy with effects felt at the local, regional and national levels (American Sportfishing Association 1998).

MERCURY REDUCTION POLICY

Regulatory Status of Coal Fired Utilities

When Congress amended the Clean Air Act in 1990, they ordered the EPA to promulgate regulations establishing emission standards for each category or subcategory of major sources and area sources of hazardous air pollutants, including mercury. Although electric utilities met the definition of a major source, they were expressly exempt from regulation. Instead, Congress ordered EPA to study toxic hazardous air pollution from power plants in order to determine if regulation was necessary in order to protect public health (CAA Section 112(n)(1)(A) 1990).

As part of the regulatory finding process, the EPA published two reports to Congress in 1997. The first was the Utility Air Toxics study, which identified mercury emissions generated by coal-fired utility boilers as the hazardous air pollutant of greatest concern to human health of all emissions from this source. The Mercury Report to Congress was the second report, and it identified coal-fired power plants as the largest source of anthropogenic mercury emissions in the US, accounting for one-third of all emissions in the country.

To further inform the mercury regulatory decision, using the authority of section 114 of the Clean Air Act, the EPA requested information from all coal-burning power plants regarding the mercury content of the coal they burn. Certain plants were also required to test the amount of coal being emitted from their plant. The data gathering, officially called an Information Collection Request (ICR), occurred throughout 1999. The purpose of the ICR was to collect enough information to improve estimates of the amount of mercury being emitted by coal-fired power plants. The analysis of the data collected concluded that coal-fired power plants are a major source of mercury emissions, responsible for 43 tons of the mercury emitted in 1999 from 1,149 units at 464 plants.

Additionally, at the direction of Congress, the EPA funded the National Academy of Sciences to perform an independent evaluation of the available data related to the health impacts of methylmercury. This study confirmed the EPA's assessment of the health and environmental hazards caused by mercury. On December 14th, 2000, EPA announced that it had decided that mercury air emissions from power plants should be regulated because they are the largest source of anthropogenic mercury emissions in the country and, of all the hazardous air pollutants emitted from this source, mercury poses the greatest health risk. EPA plans to propose a regulation to control air toxics emissions, including mercury, from coal- and oil-fired power plants by the end of 2003 and will issue final regulations by December 2004.

Mercury Reduction Categories

Options for mercury reductions fall into several categories, ranging from alternatives that completely eliminate the possibility of mercury contamination, to those that reduce contamination and/or the likelihood of contamination (EPA 2000a). These categories include:

- Substitution: Using alternative products or process inputs that are mercury free and either less toxic than mercury or non-toxic. For example, using renewable resources to generate electricity rather than coal would completely eliminate mercury emissions associated with electricity production.
- Recycle/Safe Disposal: Ensuring proper handling of products containing mercury when end of useful life is reached to guarantee minimal or no air or water contamination.
- Energy Efficiency/Conservation: Reducing or eliminating the demand for mercury products or process inputs. For example, increasing energy efficiency in appliances and windows reduces energy consumption and, therefore, reduces energy production by-products (i.e., mercury emissions).
- Mercury Reduction Technology: Where mercury is a pollution by-product of manufacturing, energy generation, or waste disposal, in-process or end-of-pipe control technologies can be effective in reducing emissions of mercury and other hazardous substances. The U.S. Department of Energy is currently funding five projects that explore different control technology approaches to reducing mercury and fine particulates from coal-fired utility boilers, including dry carbon-based sorbent injection and high efficiency electrostatic precipitators (DOE 2000).
- Remediation: When mercury spills occur (in a classroom science lab, for example), proper spill response planning and clean-up (followed by proper disposal) can help reduce the severity of the contamination.

- Education: Informing the general public about the hazards of mercury reduces the risk of mercury exposure to people and the environment. Education can also lead to a greater willingness to engage in demand side management activities.

Existing Strategies Used to Reduce Mercury

The leading sources of mercury are well defined and, during the last three decades, voluntary efforts have been made to reduce mercury releases and significant controls have been placed upon the use and disposal of mercury from many sources. For example, there have been many regulations created by the EPA to address mercury and its release into the environment. Mercury releases to the air are governed in the United States by the Clean Air Act, under which mercury and mercury compounds are considered Hazardous Air Pollutants (HAPs). Recently, the EPA established National Emission Standards for Hazardous Air Pollutants (NESHAPs) for mercury emissions, which cover three specific source categories: ore processing facilities, mercury cell chlor-alkali plants, and sewage sludge dryers.

Under the Clean Air Act Amendments of 1990, the EPA regulates HAPs emissions by source category. The Act requires EPA to regulate all categories of "major sources," which it defines as any source that releases ten tons per year of any one HAP, or 25 tons per year in total HAP emissions. Sources regulated under the Act's "major source" provision include chemical manufacturers, ore processing facilities, and pulp and paper mills. These and other major sources are subject to Maximum Achievable Control Technology (MACT) standards. The EPA has developed MACT standards for many sources including hazardous waste incinerators and medical waste incinerators, which call for a 50 percent reduction of mercury emissions over the next five years.

In addition to federal regulations, many states and cities have enacted laws to reduce mercury contamination. For example, Minnesota has banned the disposal of fluorescent lamps, requiring all businesses and household to recycle these mercury-containing products. New Hampshire passed a law in June 2000 prohibiting the sale of certain mercury-added products, establishing notification and disclosure requirements for permissible mercury-containing products and establishing limitations on the use of elemental mercury. Within the last year, San Francisco, California; Duluth, Minnesota; and Ann Arbor, Michigan; DeForest, Stoughton and Dane County, Wisconsin; and Boston, Massachusetts passed ordinances banning the retail sale of mercury thermometers.

Regulation is not the only mechanism means by which mercury reductions have been made. Many businesses and organizations have established voluntary programs to help curb the amount of mercury releases. Health Care Without Harm is a non-profit collaborative organization that encourages environmentally responsible health care practices. Their "Mercury Free Medicine" campaign awards hospitals that pledge to phase out the use of mercury-containing products. So far, 584 medical facilities have pledged to go mercury-free (NWF 2000). In December 1997, the Thermostat Recycling Corporation (TRC) launched a program to recycle mercury-switch thermostats in nine states. The TRC is a private corporation established by thermostat manufacturers

Honeywell, General Electric, and White-Rodgers. Since the program's inception, TRC has recycled 274 pounds of mercury from thermostats. TRC collected and processed more than 110 pounds of mercury in the first six months of 1999 (EPA 2000b).

Mercury Reduction Options for the Utility Sector

Pollution control strategies for coal-fired utilities fall into three categories: pre-combustion, post-combustion, and energy efficiency/conservation (EPA 2000a).

Pre-combustion techniques for reducing mercury emission are utilized in the process before fuel is burned to produce energy. These methods employ chemical, biological, or other alternative techniques to remove, or reduce the possibility of, high percentages of ash. There are four techniques that fall under this category.

- Coal Cleaning: Mechanical devices using pulsating water or air currents are used to physically stratify and remove the ash components that are imbedded in the coal, which contain trace minerals including mercury. This is done before the coal is crushed and introduced into the boiler (EPA 1997d). This technique also reduces acid rain-related emissions of sulfur dioxide and other hazardous air pollutants.
- Coal Switching: Switching from coal that is high in mercury per Btu to one that is low in mercury per Btu can reduce mercury emissions (CCAP 1998). Switching from one source of coal to another can also reduce emissions due to changes in coal characteristics that improve the mercury collection efficiency of existing control equipment (MPCA 2000).

- Fuel Switching: This option involves switching to a less polluting fuel source to achieve desired mercury reductions. Not only would switching to cleaner fuels, including natural gas and renewable resources, eliminate emissions of mercury, but it would also largely eliminate particulates, other heavy metals, sulfur dioxide, and also reduce nitrogen oxides and carbon dioxide (EPA 2000a).
- Co-Firing: A percentage of coal burned at existing power plants is replaced with cleaner fuel sources, such as natural gas and wind power.

Post-Combustion technologies clean flue gases that are emitted from coal burning. They are generally located in the ductwork leading to the smokestack. Examples include:

- Wet Scrubbing: Scrubbers are currently used to remove sulfur dioxide on about 25 percent of the coal-fired utility generating capacity in the US (Center for Clean Air Policy 1998). This technique also has been shown to remove mercury from the flu gas.
- Electrostatic Precipitators: These are the most frequently used particulate matter control device on utility boilers. They remove particulate-bound mercury.
- Carbon Injection: This technique involves the direct injection of activated carbon into the flue gas stream of a utility boiler. The activated carbon is porous and, therefore, has a high surface area, allowing it to absorb a broad range of mercury and other trace contaminants (EPA, volume VIII 1997). The used carbon and attached mercury are then captured by existing particulate matter controls, such as an electrostatic precipitator, and disposed of in ash ponds or landfills.

- Carbon Filter Beds: Rather than injecting carbon into the flue gas, the flue gas is evenly distributed throughout a bed of carbon.

Energy efficiency involves the implementation of strategies that increase the efficiency of energy production and/or decrease the demand for energy use. Energy efficiency and conservation practices offer many benefits for energy producers, consumers, and the environment. These practices lower energy production-related emissions; provide energy cost savings to consumers and businesses; preserve fuel supplies; and enhance utility profits by increasing productivity and reducing energy and material use, disposal costs, and environmental compliance costs. In its State Scorecard on Utility Energy Efficiency Programs, the American Council for an Energy-Efficient Economy concluded that electric utilities could save up to 100,000 megawatts of electrical demand by tuning up residential air condition systems and installing more efficient air conditioning systems and lighting in the commercial sector. This could be enough savings to stall the need to build new power plants to meet increased electricity demand throughout the next decade.

Opportunities for energy efficiency and conservation include:

- Demand-Side Management: Demand-side management (DSM) programs consist of the planning, implementing, and monitoring activities of electric utilities which are designed to encourage consumers to modify their level and pattern of electricity usage (DOE 1997). They can entail energy efficiency measures that enable consumers to perform the same function with less energy, such as the installation of energy saving appliances and lighting, or load-management programs that reduce demand during peak loads, such as entering into contractual arrangements with customers who can self-generate power.

- Co-Generation: Producing heat and electric power simultaneously improves the efficiency of electric production and overall energy use by recapturing waste heat that would otherwise be exhausted. Co-generation extracts much more usable energy from the same amount of fuel. This can be done in a number of ways, but most commonly involves using waste heat from the steam or a hot water line to generate electricity (M2P2 1996).
- Alternative Policy Approaches: Alternatives to traditional command-and-control regulation can provide environmental benefits and cost savings by achieving the largest pollution reduction at the lowest cost. Such alternatives may be divided into three categories: (1) performance standards such as Emissions Cap Programs where a ceiling of allowable emissions is set and there is flexibility regarding how the limits are met; (2) information strategies such as a "Right-to-Know" program where mercury emission levels are made available to the public creating an incentive for the polluting industry to be a "good neighbor" and reduce; and (3) market incentive approaches such as a mercury emissions trading program. A prominent example of market-based incentives to achieve environmental protection in use today is the sulfur dioxide emission-trading program where sulfur dioxide emission allowances are traded between industries to reduce acid rain. See http://www.epa.gov/airmarkets for more information regarding EPA's Acid Rain Program and other market-based EPA regulatory programs.

CHAPTER 3

RESEARCH DESIGN

This chapter presents the research design, subjects, evaluation procedures, and ethical considerations used to assess which strategy stakeholders prefer to reduce mercury emissions from coal-fired power plants.

THE ANALYTIC HIERARCHY PROCESS

This research study uses a multi-criteria analysis method known as the Analytic Hierarchy Process (AHP), as originally formulated by Thomas Saaty (Saaty 1980), to evaluate mercury reduction strategy preferences among a diverse set of stakeholders. Although there are many different multiple criteria decision aids that could be applied to this study, AHP was chosen because it provides an appropriate decision-making framework for the problem at hand. The benefit of using this method is improved efficiency and results for group decision-making. As an approach, it encourages compromise and consensus building among diverse interest groups. This is achieved by AHP's unique ability to allow criteria to be considered individually and aggregated into overall preferences. AHP is simple in construct, yet extremely powerful. It is also practical, as it does not require inordinate specialization to master and communicate and utilizes readily available and user-friendly decision support software.

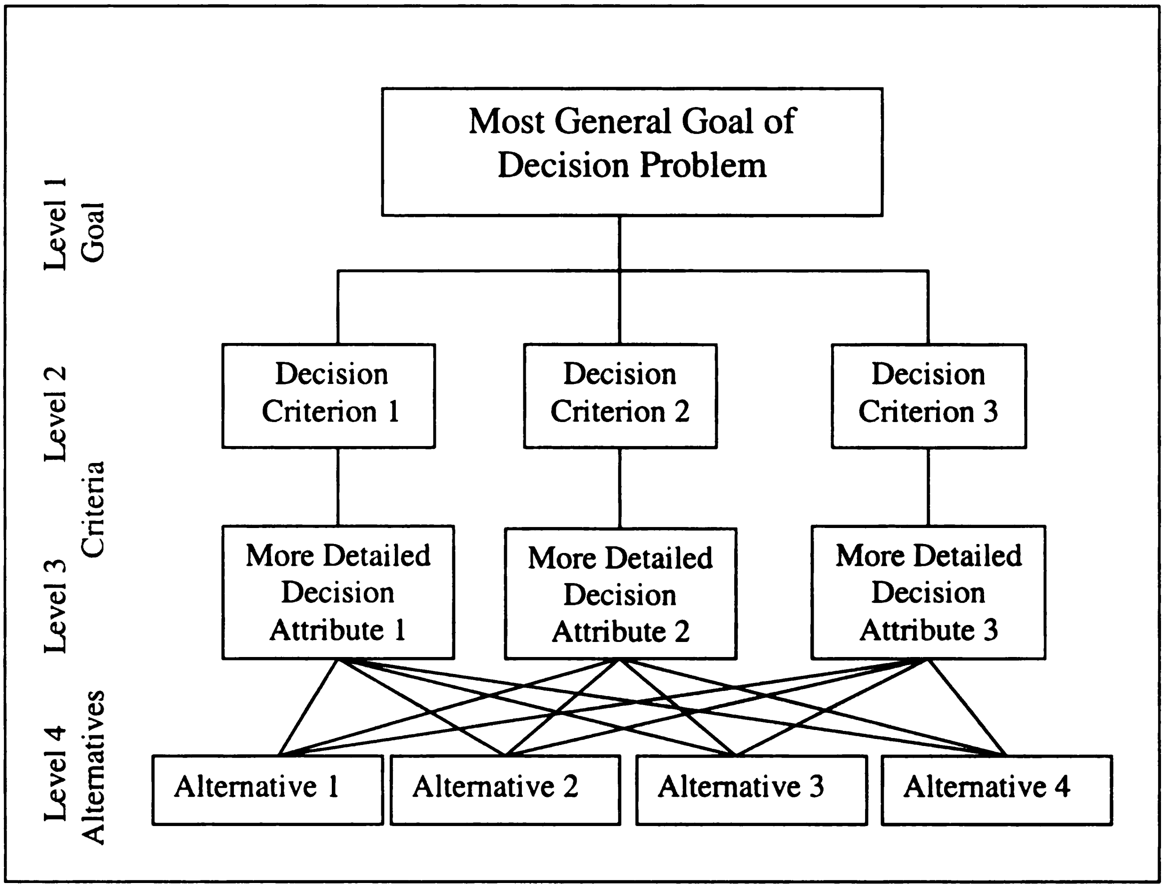
AHP implementation has two sequential phases. Phase one is the process of designing the decision hierarchy, which involves decomposing the decision problem into a hierarchy of interrelated decision elements (goal, evaluation criteria, and solution alternatives). The second phase is the evaluation of the hierarchy, which is a four-step process:

1) Collecting input data (judgments) by pairwise comparisons of the decision elements,
2) Calculating relative weights of the decision elements to determine local priorities,
3) Synthesizing the relative weights and priorities to determine the best alternative,
4) Analyze sensitivity to changes in judgment.

Phase One: Hierarchy Design

The first step in applying AHP to a decision problem is to break the problem down into a hierarchy of interrelated decision elements (Saaty 1980). An overall goal or objective is placed at the top of the hierarchy, which is followed by lower levels of evaluation criteria that contribute to the quality of the decision. The lower the hierarchy level, the more detailed the criteria. The number of hierarchy layers depends on the complexity of the problem and the degree of detail the researcher requires to solve the problems. For the purposes of this study, a three layer hierarchy will be used. The last level of the hierarchy contains the alternatives or solution choices. Arranging the goals, criteria, and alternatives this way allows the decision maker(s) to see the complex relationships inherent in the situation and assess the importance of each issue at each level. The standard design of an AHP decision hierarchy is depicted in Figure 2.

Figure 2: A general presentation of a decision hierarchy for AHP



To begin structuring the hierarchy for this study, the researcher first identified the overall goal: to reduce mercury emissions from coal-fired power plants to a target level. This was determined by exploring the overall question behind the thesis research topic selected. The remaining hierarchy decision elements were determined using a two-step process. First, a literature review was conducted to aid in the decomposition of the decision problem by exploring different existing mercury reduction strategies. As stated in the literature review above, the literature revealed three basic mercury reduction categories (EPA September 2000):

- pre-combustion techniques, which are utilized in the process before fuel is burned to produce energy;
- post-combustion technologies, which clean flue gases that are emitted from coal burning; and
- energy efficiency, which involves the implementation of strategies that increase the efficiency of energy production and/or decrease the demand for energy use.

The second step in determining the decision elements of the hierarchy involved conducting interviews with experts in the issue area. This second step was implemented to strengthen the overall design of the hierarchy, but is not required by the AHP. In fact, many different examples of hierarchy construction techniques can be found in the literature. For example, the researcher can construct the hierarchy alone, selecting the goal, criteria, and policy alternatives based on independent knowledge or a review of the literature. Another technique involves a group approach, where stakeholders brainstorm together to design the hierarchy. This group approach was applied successfully by Leung et al (1998) to address a complicated fishery management policy decision in Hawaii.

In this research study, it was believed that using only one expert to design the mercury reduction strategy hierarchy would have implanted a weakness in the design because of the inherent risk of subjectivity, e.g. two different experts could structure the same problem differently, yielding two different choices of action. To ensure the integration of appropriate decision elements, decrease the level subjectivity, and provide credibility to the overall research design, a series of in-depth interviews were conducted with a range of key, expert stakeholders.

The in-depth, semi-structured interview is a qualitative interviewing technique that involves asking informants open-ended questions, and probing wherever necessary to obtain data deemed useful by the researcher. Unlike quantitative interviewing, which typically involves the use of a structured survey instrument that asks all respondents the same questions about their attitudes and behaviors, the in-depth, semi-structured interview has specific objectives to cover within the course of the interview and the researcher is permitted some freedom in meeting them (Berry 1999).

This interview style was chosen for this study because of its ability to elicit information that results in a holistic understanding of the interviewee's point of view. Also, it allows the respondent to freely speak more in his or her own words with regard to the topic of interest, allowing the interviewer to adapt the interview to capitalize on the special knowledge, experience or insights of respondents. These benefits result in more complete information and a more thorough investigation.

Although there are many benefits to the in-depth, semi-structured interview technique that have made it the obvious choice for this research endeavor, there are disadvantages to this technique as well. Because the researcher is gaining information from the informant, as opposed to direct observation, the researcher's findings are open to the vagaries of the informant's interpretation and perception of reality (Minichiello et al 1995). Whereas participant observation enables the researcher to directly observe the informant in his or her everyday life, resulting in a richer understanding of the informant's perspective, researchers using the in-depth interview technique are limited to the informant's situational perspective, thus deprived of the ethnographic context. Although this may seem like a substantial method weakness, it can be overcome by adopting intrusive yet ethically sound methods. A high level of interaction with the informant during the interview process will increase the validity of the data gathered. Some researchers dismiss this weakness altogether, stating that during the interview the informant is operating within an ethnographic context, and it is from this context that the informant makes decisions about what to say (Minichiello et al 1995).

In this study, the purpose of the interviews was to:

(a) identify any additional mercury reduction strategies to add to the preliminary list identified in the literature review;

(b) identify evaluation criteria to be applied in the multi-criteria analysis; and

(c) gain insight to the values and beliefs systems that underpin the stakeholder's position on the issue of mercury reduction strategies.

The individuals selected to identify the policy alternatives and evaluation criteria elements for the hierarchy can be divided into three different interest groups, all who hold a key position in the mercury emissions debate. These groups are environmental organizations (four interviews conducted), governmental agencies (five), and the electric utility industry and associated research organizations (four).

The individuals selected to represent the environmental organization stakeholder group have had a long history of working specifically on reducing the environmental damage caused by power production, particularly with regard to mercury emissions. Each interviewee were selected on the basis of their policy expertise and pre-existing knowledge of the mercury emissions issue. Their involvement in the issue spans from grass roots organizing to decision-maker education to policy analysis to assisting in regulation oversight and creation. These individuals have either advanced legal or scientific backgrounds.

Government agency representation can be divided into two areas: regulatory policy creation and pollution technology research and development. The five government agency employees were selected because of their past and present involvement in either the mercury regulatory determination itself, or research and development of mercury control technologies for the utility sector. All government agency interviewees have a long history of working for their respective organizations and on this issue in particular.

The individuals representing the utility sector interests are either employed by a specific utility company or a nonprofit electric power research organization. These individuals have been selected because of their scientific, technical, and/or legal background working with the issue of mercury emissions from coal-fired power plants. Those employees interviewed from the utility companies are environmental scientists that investigate mercury emissions and controls on behalf of their employer. Individuals representing electric power research organizations research science, emission control technology, and policy options for the energy service industry.

One additional interview was held with a representative from a Washington D.C.-based non-partisan research organization to gain an additional informed expert opinion. This person has an extensive background in the research area and was used as because of their research and experience in identifying cost-effective approaches to reducing mercury emissions associated with electric power generation. This individual represents a nonprofit organization, which investigates solutions to environmental problems with a goal of reaching common ground between diverse and conflicting interests.

The interviewee recruitment process began with electronic mail message sent to perspective respondents informing them that a letter would be coming via U.S. mail requesting their participation in a university research effort. The letter contained information regarding the research purpose and procedure. The letter also informed the interviewee that their participation was voluntary, and that their identity and responses would be kept confidential. The interviewees were asked to sign and return the letter, indicating their consent to participate, in a postage-paid return envelope (provided). Once the letter was received, a telephone call was placed to determine an interview time that was convenient for the interviewee. Phone calls were placed at the agreed upon time and respondents were asked if their interviews could be audiotape recorded.

The qualitative interviews were conducted during March 2001 and were generally one hour in length. Following the in-depth semi-structured interview paradigm, an interview guide was used to ensure the above issues have been addressed and consistency in topic coverage across the interviews. However, because of the nature of the semi-structured, in-depth interview technique, the subject's responses often lead to further probing questions in addition to those listed in Figure 3. An attempt was made to encourage interviewees to freely volunteer information as opposed to asking for responses to close-ended questions. At the end of the interview, respondents were thanked for their participation and were instructed how to contact the researchers if they had questions or comments.

Phase Two: Hierarchy Evaluation

The next phase of AHP implementation is the evaluation of the hierarchy that, as stated above, is a four-step process.

Step One: Data Collection

Step one involves eliciting judgments that reflect the opinion of the stakeholders involved in the decision problem. A judgment is the numerical representation of a relationship between pairs of decision elements in the decision hierarchy. These pairwise comparisons are made by asking the question: "Which of the two elements is more important with respect to the next higher level element, and how strongly?" Paired comparisons allow the relative weights of decision elements to be obtained by having decision makers focus on a pair of two decision elements at a time (Ra 1999).

Figure 3: In-Depth, Semi-Structured Interview Guide

STAKEHOLDERS' MERCURY REDUCTION STRATEGIES
AND EVALUATION CRITERIA

INTERVIEW GUIDE

1. In your opinion, what strategy do you favor for reducing the amount of mercury that is emitted from coal-fired power plants?
2. If you had to list a number of alternative approaches to reducing mercury emissions from coal-fired power plants, what would be on that list?
3. If you worked for the U.S. Environmental Protection Agency, for example, and had to develop a reduction strategy for mercury emissions from coal-fired power plants, what strategy would you choose? Why?
4. On what basis should decisions regarding mercury reduction strategies be made?
5. What aspects of the mercury reduction strategies you put forward do you like the best? What aspects do you like least?
6. What reduction strategy for mercury emissions from coal-fired power plants are you aware of, but disagree with? Why do you not favor these strategies?
7. Who else would you recommend interviewing?

Note: This is a list of general topics that, at a minimum, will be covered consistently with all subjects across all interviews. Because of the nature of the semi-structured, in-depth interview technique, the subject's responses may lead to further probing questions in addition to those listed above.

Each paired comparison is represented in a square matrix in which the decision elements are compared with respect to the level avove it in the hierarchy. The intensity of relative importance/preference levels are measured using a fundamental scale of the number set: {9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9,} (see also table 1).

Table 1: Scale of Relative Importances/Preferences Used in this Study[2]

Intensity of Importance/Preference	Definition
1	Equal importance/preference
3	Moderate importance/preference
5	Strong importance/preference
7	Very strong importance/preference
9	Extreme importance/preference
2,4,6,8	Intermediate values between the two adjacent judgments
Reciprocals of above nonzero	If criterion x has one of the above nonzero numbers assigned to it when compared to y, then y has the reciprocal value when compared with x.

Data Collection Method

In this study, pairwise comparison judgments for step one and two were collected using a 12-page written survey instrument, developed with expert stakeholder input obtained through the in-depth, semi-structured interviews. The survey was mailed to the original set of 13 experts plus an additional 98 individuals, who were selected using the snowball sample selection strategy. The selection of these additional interviewees was based on the recommendations of the original group of experts based on their background and level of expertise in the issue of mercury emissions from coal-fired power plants.

The survey was divided into three sections. In the first section (Section A), the respondents were asked to rank the six alternative strategies for reducing mercury emissions from coal-fired power plants, which were identified during the interview phase. Section B asked the respondents to judge a series of paired comparisons to indicate the criteria, also identified during the interview process, they believe to be the most important with respect to the overall goal. This was done to determine the relative importance the respondents place on each criterion with respect the overall goal. The last section (Section C) asked the respondents to judge a series of paired comparisons to indicate their strategy preferences with respect to each of the nine criteria. This process resulted in a final preference rating for each strategy based on each criterion.

Terms used to describe the evaluation criteria and reduction strategies were carefully selected and well defined. A table of criteria definitions preceded section B and each criterion was defined on its respective evaluation table. Carefully and thoroughly defining each decision element is extremely important in evaluating the hierarchy. Terms can easily be interpreted differently by different individuals, particular when they represent diverse interests. Every effort was made to promote consistency across survey recipient term interpretation in the survey design.

The written survey was distributed to a representative from each of the three survey groups for pre-testing. Feedback was positive and only one request was made for change. One reviewer thought that the evaluation criteria and reduction alternative definitions

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[2] Pairwise comparisons can be made in terms of preference and importance. Importance comparisons are appropriate when comparing one criterion with another and preference comparisons are appropriate when comparing alternatives with respect to each criterion.

were not clear. In response, the researcher added more detail to each definition to ensure the decision elements were clearly understood and consistent across all survey recipients.

Responses were solicited from a total of 98 individuals in the three stakeholder groups (38 environmental staff, 25 regulators, and 35 industry). A consent form was attached to the front of the survey, which indicated that participation was voluntary and that their identity and responses would be kept confidential. The written survey instrument was distributed through U.S. mail. To ensure a high response rate, a pre-survey e-mail and post-survey postcard were sent, responses were tracked closely, and various follow-up methods used.

Step Two: Relative Weight and Preference Calculation

All of the survey responses were entered into a computer implementation of the AHP called Expert Choice. The numbers derived from the comparisons made in the survey were used to calculate the weighting vector that yields the relative importance/preference of each of the decision elements. Although Expert Choice automatically extracts the relative criterion importance as well as preferences for each strategy, it is important to understand the mathematical process behind its results. For a more detailed explanation of the calculations behind AHP, refer to Saaty 1980.

The input data for the decision problem consist of matrices of pairwise comparisons of elements of one level that contribute to achieving the next higher level. The hierarchy created for the decision problem in this study has three levels. Level one contains the goal (reducing mercury emissions from coal-fired power plants to target levels), level two consists of evaluation criteria (determined by stakeholders), and the alternatives constitute the last level (determined by stakeholders). First, the evaluation criteria are compared to each other in terms of relative importance with respect to the goal. Using the scale in Table 1, judgments are elicited from the survey recipients and inserted into the appropriate matrix cell. If the element on the left is more important than that on the top of the matrix, one of the values from Table 1 is entered, depending on the level of importance. If the opposite is true, the reciprocal value is inserted. Elements compared against themselves always result in a value of 1.

Table 2: Pairwise comparison matrix for level 2

Criteria	Size	Color	Miles/Gallon	Weighting Vector
Size	1	1/3	9	.501
Color	3	1	5	.436
Miles/Gallon	1/9	1/5	1	.064

In the example depicted in Table 2, Size is moderately more important than Color and extremely more important than Miles/Gallon, etc. These judgments now must be translated into meaningful numbers that reflect the weight of each criterion with respect to achieving the overall goal. To obtain this weight, the values in each row are added and then divided by the sum of all the judgments, or the judgments in any column are simply normalized (by dividing each entry by the sum of the entries in that column). This calculation yields the relative importance of the criteria, measured on a ratio scale.

Next, priorities of the alternatives with respect to each criterion are determined using the same method. The alternatives on the last level of the hierarchy are pairwise compared to each other in terms of preference with respect to the criteria on the next higher level. Using the scale in table 1, judgments are elicited from the survey recipients and inserted into the appropriate matrix cell, as illustrated in Table 3.

Table 3: Pairwise comparison matrices for alternative priorities with respect to each criterion

Size	Honda	Ford	Alternative Priority Ratings
Honda	1/9	3	.250
Ford	1/3	9	.750

Color	Honda	Ford	Alternative Priority Ratings
Honda	5	1	.833
Ford	1	1/5	.167

Miles/Gallon	Honda	Ford	Alternative Priority Ratings
Honda	7	3	.955
Ford	1/3	1/7	.045

Step Three: Synthesis

Data synthesis is the third step of the hierarchy evaluation phase. Synthesis is the process of weighting and combining priorities throughout the model after judgments are made to yield the final result. The process evaluates how each of the mercury emissions reduction strategies satisfies the overall goal of reducing mercury emissions from coal-fired power plants.

Using the priority ratings and the weighting vectors calculated in step three, the mercury emissions reduction strategy priorities are developed by inserting the priority values of the alternatives with respect to each criterion into the matrix, multiplying each column of priority vectors by the priority of the corresponding criterion, and then adding across each row. The highest rated alternative is the one that best meets the evaluation criteria, which in Table 4 is Honda.

Table 4: Synthesized priorities

	Size (.501)	Color (.436)	Miles/Gallon (.064)	Overall Priorities
Honda	.250	.833	.955	.560
Ford	.750	.167	.045	.450

Step 4: Sensitivity Analysis

To further analyze the data collected, a sensitivity analysis was performed to investigate the sensitivity of the alternatives to changes in the priorities of the objectives. This type of analysis shows the sensitivity of the alternatives with respect to all the objectives below the goal, as well as the sensitivity of the alternatives with respect to an objective or sub-objective. Sensitivity analysis is useful because it allows the researcher to vary priorities of the objectives to observe how the priorities of the alternatives change. Performing "what-if" sensitivity analyses determines how a change in the importance of an objective would affect the alternatives of choice. Expert Choice also synthesizes or combines the priorities that are derived for each facet of a problem to obtain the overall priorities of given alternatives, as well as how a change in the importance of an objective affects the alternatives of choice.

ETHICAL CONSIDERATIONS

Every researcher, legally and ethically, has an obligation to respect the rights, needs, values and desires of the informant(s) (Creswell, 1994). This is of particular concern in this study where some of the informant's positions and places of employment are highly visible, and sensitive, job-jeopardizing opinions may be solicited.

In this study, every effort was be made to protect the rights of the respondents, including informed consent and guaranteed confidentiality. In addition to University Committee on Research Involving Human Subjects approval, the following safeguards were employed to respect the subject's rights. For the in-depth interviews that were conducted to shape the design of the decision hierarch, subjects were provided (verbally and in writing):

1. A summary explanation of the research, its objectives, purpose, and use of data.
2. An estimate of the total amount of time required on the part of the subject (number of sessions, frequency of testing, etc.).
3. Notice that their participation was voluntary.
4. Assurance of confidentiality and anonymity to the maximum extent possible .
5. Disclosure of all data collection devices and activities.
6. Instructions on whom (name and phone number) to contact regarding any questions or concerns that may be raised by participating in the study, as well as contact information for the IRB.

The interviewees were asked to sign and return the letter that provided them with the above information in a postage-paid return envelope (provided), indicating their consent to participate (see Appendix II).

A similar procedure was followed for the written survey, although written consent to participate was not requested from the respondents. Complete anonymity was determined necessary to guarantee an adequate response rate because of the political volatile nature of the research study topic. Consent was requested instead in a letter attached to the front of the survey instrument that included the statement: "You indicate your voluntary agreement to participate by completing and returning this questionnaire." (see Appendix III).

CHAPTER 4

DATA PRESENTATION AND ANALYSIS

This chapter presents the analysis of the data collected from the in-depth, semi-structured telephone interviews and the written survey instrument. These data were used to develop and utilize a multi-criteria decision framework to evaluate alternative strategies for reducing coal-fired power plant mercury emissions. This process included the use of the AHP software Expert Choice.

HIERARCHICAL DESIGN

As discussed earlier, a literature review was first conducted to develop a list of current mercury reduction strategies. This tentative list was then incorporated into an interview guide used to conduct 13 in-depth, semi-structured interviewees with experts from three different stakeholder groups. These interviews yielded more substantive information regarding the most preferred mercury strategies for coal-fired power plants as well as the criteria that should be used in selecting a strategy.

Utility Industry Interview Responses

Interview responses regarding strategy evaluation criteria varied across the three stakeholder groups. The four utility industry interviewees favor a strategy that is gradual and phased to ensure economic feasibility and avoid compromising business viability and energy reliability. The strategy must allow both for modifications based on new science and compliance flexibility so that each plant operator has latitude in selecting which reduction method works best. In addition, the strategy should undergo benefit-cost analysis to ensure that the benefits achieved warrant the cost and are attained at the least cost. Planning certainty was also mentioned, which mostly centered on the interviewees' desire to have Congress develop a multi-pollutant strategy so that regulations for all key pollutants (i.e., NO_x, SO_2, CO_2, and Hg) are developed simultaneously.

The criterion of paramount importance when selecting a strategy to reduce mercury emissions from coal-fired power plants, according to the utility industry interviewees, is scientific defensibility. In fact, those surveyed are not convinced that emission reductions are even warranted because of critical gaps in scientific research.

One issue the industry respondents identified is understanding mercury cycling and transformation through air and water on a global and regional scale to determine what impact changes in mercury source emissions would have on receiving waters and fish. The interviewees believe that this is important for discussions about strategies for managing mercury since the results of any management strategy should be clear and demonstrable health benefits. For example, one interviewee mentioned research conducted by a utility research organization that indicates, of the 2,300 metric tons released annually by human activities around the world, only 2 percent is attributable to U.S. coal-fired power plants. If this is the case, said another interviewee, then mercury emission reductions from U.S. power plants are not necessary because the reductions will not result in improvements in U.S. ecosystems.

Another unanswered question to which the interviewees pointed involves source attribution. According to them, there is currently no strong scientific evidence tying the mercury found in particular waterways and resident fish to particular sources and source categories. A major obstacle to identifying source contributions is not knowing the impact of background mercury on mercury concentrations and deposition rates[3]. Without this information, the interviewees agreed, it is impossible to effectively reduce mercury emissions because it is unclear which sources should be controlled.

Because of the scientific uncertainty that surrounds this issue, the utility interviewees believe that mercury regulation determinations should be put on hold until the above questions are answered. This will likely not occur for four or five more years, one interviewee said, which is something that the environmental community will not tolerate. All four of the interviewees indicated that the environmental community has neither the scientific background nor expertise necessary to participate in a helpful way to this debate. One interviewee stated that environmentalists are involved in the mercury issue not only because they want to reduce mercury exposure, but they also want to eliminate coal as a fuel source entirely. According to the utility experts interviewed, environmentalists' lack of scientific research on the issue combined with their agenda to eliminate coal often results in unrealistic, unreasonable, and unscientifically based proposals.

[3] Background mercury is already present in natural systems and continues to be mobilized in the environment. It is either a naturally occurring component of soil, water, and plants or a legacy of human activities like mining.

A criterion related to scientific defensibility is cost-benefit, which was also discussed as having strong importance when evaluating mercury reduction strategies. In order to measure the benefit of a reduction strategy, and then to compare it to the cost of strategy implementation, the interviewees said, it is important to understand the scientific aspects of mercury fate and transport and its impact on health.

During the interviews, each person was asked to identify what they viewed as their preferred strategy for mercury emissions reduction. The main mercury emission reduction strategy offered by the utility industry interviewees is a receptor-based strategy, which would involve setting numerical emission limits for single plants based on their specific and quantifiable pollution contribution. Most noted that this is not possible because of scientific constraints. The interviewees also mentioned a multi-pollutant approach, where multiple pollutants would be regulated at one time. Additionally, the industry interviewees favored a nationwide emission cap, which would be met by allowing compliance flexibility across the industry. Emission credit trading was offered as a way to meet the emission cap. Once the target was met, a residual-risk approach would follow to address remaining health risks. One strategy that was not favored among utility industry interviewees was one that prescribed specific control technologies as compliance flexibility is very important to the industry.

Environmental Group Interview Responses

According to the four environmental group representatives interviewed, there is adequate scientific evidence that the mercury emitted from coal-fired power plants in the U.S.

poses a serious health risk to humans and wildlife. The respondents are aware that the utility industry is not comfortable with the scientific evidence and that not all of the knowledge gaps have been addressed, but they believe this is not an excuse to do nothing. One interviewee stated that the precautionary principle should be applied in this situation because providing too much protection of public health is preferred over not being protective enough.

The environmentalists favor a mercury reduction strategy that is effective in protecting public health and provides the utility industry with planning certainty. They also desire a strategy that is cost-effective by producing multiple pollution reduction benefits. The environmental respondents require the strategy to be legally defensible and politically feasible to avoid stalling action by industry.

The environmental interviewees prefer the multiple pollutant and numerical emissions cap reduction strategies, although they do not prefer using mercury emission trading to meet the cap and have already developed a target reduction percentage to calculate the cap (90%). The environmentalists agree that compliance flexibility is important, but believe that the strategy could include prescriptive reduction options including a renewable resource portfolio standard and the inclusion of energy conservation and energy efficiency programs/practices. Installing emission control technology was also mentioned as a way to meet the cap, but only if the removed mercury is properly disposed of to ensure it is not just being removed from one media (air) to be placed in another (soil, water, etc). One respondent suggested issuing an ambient deposition standard for mercury similar to standards set for criteria pollutants, admitting this would be difficult to monitor and enforce.

Government Agency Interview Responses

Interviews were conducted with five government agency representatives. Responses varied considerably depending on the agency, department, and area of specialization the interviewee represented. The opinions of those whose work involves the development of regulations and working directly with Congress are much different from those who are more involved with researching, developing, and demonstrating air pollution prevention and control for power plants.

Those working in regulatory development favor a strategy that is "fair" to the utility industry in that it allows for compliance flexibility to optimize pollution reductions in a cost-effective way and planning certainty so that plant owners and operators are aware of future technology needs and, therefore, can make informed pollution abatement choices. These individuals also believe political feasibility is important because a lack of political support means a slow-down in the regulatory development process. They do not want a strategy put forward that is politically uncertain because it may result in lawsuits, etc., that stall action. Interviewees also believe the criteria listed in the Clean Air Act, which they are bound to apply in evaluating different mercury control strategies, are important. In terms of preferred reduction strategies, this set of interviewees favor the multi-pollutant approach because it provides the industry a degree of planning certainty.

The other set of government agency interviewees, who are involved with researching and developing pollution abatement technology, approach this topic from a purely scientific standpoint. Scientific defensibility is very important to these individuals when evaluating a reduction strategy, as is cost-benefit. Arguments similar to those of the utility industry were made regarding mercury fate and transport and actual vs. perceived health risks. This indicates that these interviewees are approaching this mercury regulatory issue from a similar viewpoint.

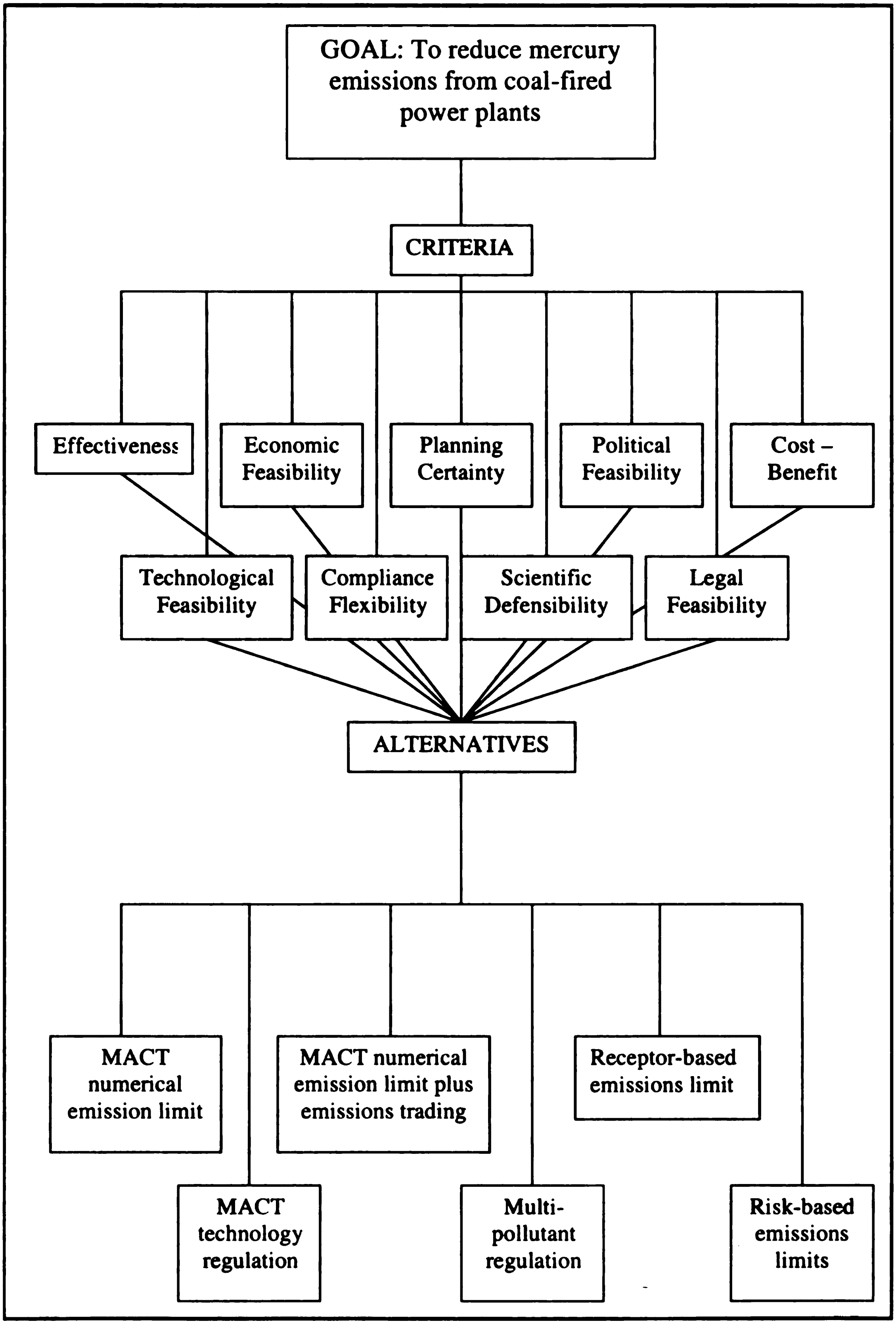
Hierarchical Structure Design

After the interviews were complete, the list of the most prominent mercury reduction strategies and evaluation criteria identified by the interviewees was arranged into a decision hierarchy. Figure 4 shows the final AHP tree.

At the top of the tree is the overall goal, identified by the researcher, of reducing mercury emissions from coal-fired power plants to target levels. On the next level, nine criteria are identified as essential for achieving the overall goal: effectiveness, economic feasibility, technological feasibility, compliance flexibility, planning certainty, political feasibility, scientific defensibility, legal feasibility, and cost vs. benefit. The criteria are defined as follows:

- Effectiveness: the ability of the reduction strategy to achieve the goal of reducing mercury emissions to target levels

Figure 4: AHP decision hierarchy for identifying an optimal strategy to reduce mercury emissions from coal-fired power plants



- Economic feasibility: the impact that reduction strategy implementation will have on business viability and power reliability
- Technological feasibility: the need for new technology to implement the strategy
- Compliance flexibility: the amount of industry latitude the reduction strategy allows in selecting a reduction method/ technology
- Planning certainty: the level of certainty the reduction strategy provides the utility industry regarding future pollutant regulations and pollution control needs
- Political feasibility: the level of existing political constraints in implementing the reduction strategy
- Scientific defensibility: the associated level of scientific certainty justifying the need for the reduction strategy
- Legal feasibility: the need for new or modified laws to implement the strategy
- Cost-benefit: the degree of benefit in terms of mercury emission reductions and associated environmental and health benefits compared to the cost of implementing the strategy

The mercury reduction strategies are presented at the bottom of the tree. The strategies mentioned most often during the interviews and, therefore, included in the decision tree are:

- Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emissions limit and leaves the choice of control technology to the utility industry.

- MACT technology regulation: EPA determines MACT emissions limit and promulgates a technology standard for the utility industry.
- MACT numerical emission limit plus emissions trading: EPA determines MACT emissions limit and leaves the strategy for compliance up to the utility industry including emissions trading.
- Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NO_x, CO_2, SO_2, and Hg) at one time.
- Receptor-based emissions limits: EPA establishes and promulgates mercury emission standards for single plants based on their specific and identified pollution contributions.
- Risk-based emissions limit: EPA establishes and promulgates a mercury emission standard for the utility industry based on risk to human health and the environment.

HIERARCHY EVALUATION

The second phase of the AHP is the evaluation of the hierarchy, which is a four step process:

1) Collecting input data (judgments) by pairwise comparisons of the decision elements,
2) Calculating relative weights and priorities of the decision elements to determine priorities,
3) Synthesizing the relative weights and priorities to determine the best alternative,

Survey Response Rate

A written survey was sent to 98 stakeholders, who were asked to evaluate a series of paired comparisons regarding the identified criteria and mercury reduction strategies. Of the 98 surveys distributed, 35 were mailed to utility industry and research organization representatives, 38 were mailed to environmental organization representatives, and 25 were mailed to government agency representatives. The survey instrument used can be viewed in Appendix IV.

Table 5: Survey response rates by stakeholder group

	Participants Surveyed	Number of Usable Surveys	Response Percentage (%)
Utility Industry	35	17	49
Environmental Org.	38	12*	32
Government Agency	25	8	32
Total individuals	98	37	38

*One survey was returned incomplete and, therefore, not counted here.

The response rates with respect to each stakeholder are summarized in Table 5. Overall, more than 1/3 of the recipients returned usable surveys. The response rate was the highest for the utility industry stakeholder group. Considering the length of the survey and the tense political environment created by the recent EPA positive mercury regulatory determination, this was considered a good response.

Criteria Weight and Strategy Preference Results

One of the major strengths of AHP is the use of pairwise comparisons to derive accurate ratio scale priorities, instead of using traditional approaches of 'assigning' weights. This process compares the relative importance of two elements (e.g., strategy evaluation criteria) with respect to another element in the level above (e.g., the goal of reducing process compares the relative importance of two elements (e.g., strategy evaluation criteria) with respect to another element in the level above (e.g., the goal of reducing mercury). A judgment is made for each pair as to which is more important and by how much.

In this study, a written survey instrument was used to elicit from respondents the importance weights of the nine evaluation criteria and the six reduction strategies for reducing mercury emissions from coal-fired power plants.

Criteria Importance Weighting

Survey participants were asked to compare the relative importance they place on each evaluation criterion when selecting a strategy to reduce mercury emissions from coal-fired power plants. To minimize the demands on respondents and thereby hopefully increase the survey response rate, a diagonal paired comparison approach was used. This allows the minimum number of comparisons necessary to calculate all the priorities. The following 8 paired comparisons were made by all respondents:

- Effectiveness versus Economic feasibility.
- Economic feasibility versus technological feasibility.
- Technological feasibility versus compliance flexibility.
- Compliance flexibility versus planning certainty.
- Planning certainty versus political feasibility.
- Political feasibility versus scientific defensibility.
- Scientific defensibility versus legal feasibility.

On the basis of these eight comparisons the remaining paired comparisons could be extrapolated. The average relative importance or priority weights of the criteria were analyzed by stakeholder group (see Table 6 and Figure 5). For each group, the priority weights for the criteria add up to one.

Table 6: Criteria weights for each stakeholder group

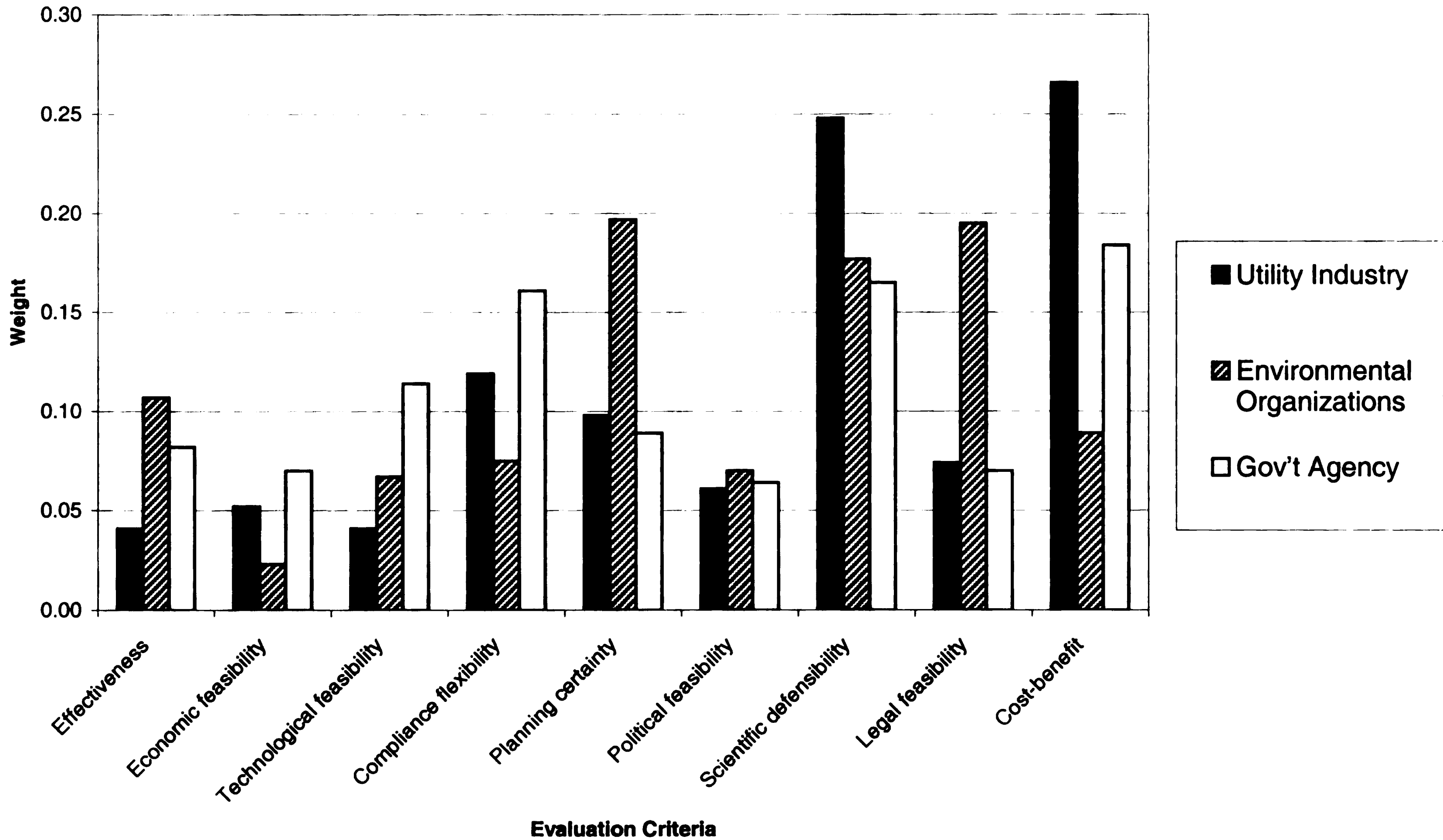
Evaluation Criteria	Utility Industry Weighting Vector	Environ. Org. Weighting Vector	Gov't Agency Weighting Vector
Effectiveness	.041	.107	.082
Economic feasibility	.052	.023	.070
Technological feasibility	.041	.067	.114
Compliance flexibility	.119	.075	.161
Planning certainty	.098	.197	.089
Political feasibility	.061	.070	.064
Scientific defensibility	.248	.177	.165
Legal feasibility	.074	.195	.070
Cost-benefit	.266	.089	.184
Total	*1.000*	*1.000*	*1.000*

Utility Industry Responses

The strongest relative criteria importance weights were observed for the utility industry stakeholder group. To reduce mercury emissions to target levels, the utility industry stakeholder group believes that cost–benefit (.266) and scientific defensibility (.248) are far more important than any of the other criteria. These criteria weights are more than double that of the next most important criterion, compliance flexibility (.119).

These results are not surprising, as the in-depth interview responses revealed the same conclusions. Interviewees consistently indicated that a high of level scientific evidence justifying the need for a certain reduction strategy is very important to them. In addition,

Figure 5: Comparison of evaluation criteria weights



interviewees repeatedly suggested that the evaluation of the degree of benefit (in terms of mercury emission reductions and associated environmental and health benefits) compared to the cost of implementing a reduction strategy is an important factor to consider.

The least important evaluation criteria, according to the utility responses, are effectiveness, i.e. the ability of the reduction strategy to reduce mercury to target levels, and technological feasibility, i.e. the need for new technology to implement the reduction strategy. Both of these criteria have a weighting vector of .041. This suggests that the utility industry thinks the effectiveness of a strategy or the need for new technology to implement the chosen strategy is not as important as the other criteria.

Although the effectiveness criterion was not advocated as strongly during the in-depth interviews as cost-benefit and scientific defensibility, every utility industry representative interviewed mentioned it as being important. Therefore, it is surprising that it is tied with technological feasibility as the least important criteria (.041). The low weighting of the criterion technological feasibility is not surprising, since that criterion was not stressed often in terms of importance during the interviews.

Environmental Organization Responses

The environmental group weighted the criteria planning certainty (.197) and legal feasibility (.195) as more important relative to the other criteria. The fact that environmentalists believe it is important to consider the level of legal constraints that exist for different reduction strategies when choosing between them is not unexpected, since the individuals interviewed are primarily policy advocates whose focus is modifying laws and regulations. The high weight given to planning certainty, on the other hand, is unexpected. This result suggests that the environmental community believes the most important evaluation criterion is the extent to which a strategy provides the utility industry with certainty regarding future pollutant regulations and pollution control needs so that appropriate investments and design decisions can be made effectively and efficiently. Although it was mentioned during the interviews, it was not evident that this criterion was of such importance to this group.

Scientific defensibility is also relatively important to this stakeholder group, receiving a weighting vector of .177. This result is not surprising because many of the environmentalists interviewed stressed the importance of a scientifically valid strategy and believe that the level of existing evidence is adequate to warrant regulation. The utility industry also weighted this criterion very high, in fact the interviewees' biggest complaint regarding the mercury regulatory determination is the lack of scientific evidence demonstrating its need. Although both stakeholder groups agree that this is an important factor, it appears that their definition of scientific defensibility differs since one group believes that there is currently adequate science to warrant mercury regulations and the other does not.

Of least relative importance to the environmental survey group is economic feasibility. This suggests that the impact the reduction strategy will have on power company business viability and customer power reliability is not as important an evaluation criterion. This is not surprising considering many environmentalists indicated that they believe the utility industry often exaggerates the potential cost of regulatory compliance.

Government Agency Responses

The government agency respondents weighted the evaluation criteria more evenly than either of the other two groups (i.e. low of .064 and a high of .184). A weight of .184 is given to the cost–benefit criteria, followed closely by scientific defensibility (.165), and compliance flexibility (.161). All three of these criteria were also mentioned repeatedly during the in-depth interviews. The remaining criteria were weighted relatively equally, with weighting vectors between .114 and .064. These survey results suggest that cost-benefit, scientific defensibility, and compliance flexibility are slightly more important than the other evaluation criteria considered, but the agency survey group weights all the evaluation criteria relatively equally.

It is not surprising that strong importance weights were not given for any of the criteria because most of those interviewed did not strongly advocate for any criterion in particular. It was expressed several times during the in-depth interviews with some individuals from the government agency stakeholder group that their role is to follow the mandates prescribed in the Clean Air Act and that maintaining and advocating particular opinions regarding either evaluation criteria or preferred reduction strategies is inappropriate. Although it was explained to these interviewees that the experience they have with the issue gives them an extremely valuable opinion, those interviewed were still reluctant to express personal judgments.

It is interesting to note that both the utility industry and the government agency respondents selected the same criteria as their top three most important evaluation criteria. For both groups, cost-benefit was the most important decision criterion, followed by scientific defensibility and compliance flexibility.

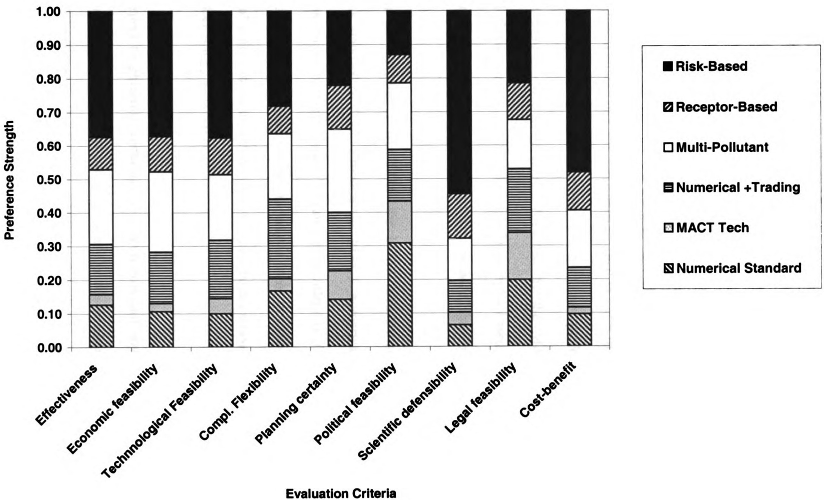
Paired Comparisons of Mercury Strategies

Having determined the relative importance of the nine evaluation criteria, the next step in the AHP is to relate these criteria to the mercury reduction strategies. The survey respondents were asked to use the same 1 (equal importance) through 9 (extreme importance) scale and make paired comparisons between mercury reduction strategies to indicate their level of relative preference with respect to each of the nine different evaluation criterion. Each respondent was required to make 53 pairwise comparisons (see Appendix IV).

Utility Industry Responses

The utility industry's pairwise comparison strategy preference results with respect to each criterion are depicted in Figure 6. In terms of **effectiveness**, the most preferred strategy is the risk-based emissions limit, receiving an overall preference rating of .374, followed by the multi-pollutant regulation strategy (.223), MACT numerical emissions standard plus trading (.149), MACT numerical emissions standard (.127), receptor-based emissions standard (.097), and MACT technology standard (.031).

Figure 6: Utility industry paired comparison results



With respect to **economic feasibility**, the risk-based emissions strategy again is the most preferred, receiving an overall preference rating of .372. The next most preferred strategy is the multi-pollutant regulation strategy at .240, MACT numerical emissions standard plus trading at .152, MACT numerical emissions standard at .107, receptor-based emissions standard at .105, and MACT technology standard at .024.

The risk-based emissions standard is most favored in terms of **technologic feasibility**, as well, receiving a .376 preference rating. The next most preferred strategy is the multi-pollutant regulation strategy (.196), followed by the MACT numerical emissions standard plus emissions credit trading (.173), receptor-based emissions standard (.110), MACT numerical emissions standard (.100), and MACT technology standard (.045).

In terms of **compliance flexibility**, the utility industry still prefers the risk-based emissions standard at .282, although the MACT numerical emissions standard plus emissions credit trading strategy advances considerably (.237). The multi-pollutant regulation strategy is next in the preference rank at .196, followed by the MACT numerical emissions standard at .167, receptor-based emissions standard at .082, and MACT technology standard at .036.

With respect to **planning certainty**, the multi-pollutant approach is the most favored reduction strategy (.249), but not much more preferred than the risk-based emissions standard (.221). The next most preferred strategy is the MACT numerical emissions standard plus emissions credit trading (.174), followed by the MACT numerical emissions standard (.142), receptor-based emissions standard (.130) and MACT technology standard (.084).

In terms of **political feasibility**, the MACT numerical emissions standard is preferred over the other strategies, with a preference weight of .308. The multi-pollutant regulation strategy follows distantly at .198, as do the MACT numerical emissions standard plus emissions credit trading (.155), risk-based emissions standard (.130), MACT technology standard (.125), and the receptor-based emissions standard (.084).

With respect to **scientific defensibility**, the utility industry prefers the risk-based emissions standard (.545) four times more than the next most preferred strategy, the receptor-based emissions standard (.133). The multi-pollutant regulation strategy is next in the preference rank with a weight of .124, followed by the MACT numerical emissions standard plus emissions credit trading (.095), MACT numerical emissions standard (.065), and MACT technology standard (.037).

None of the reduction strategies are preferred strongly over the others in terms of **legal feasibility.** The risk-based emissions standard (.215) is preferred slightly more than the MACT numerical emissions standard (.199), followed by the MACT numerical emissions standard plus emissions credit trading (.191), multi-pollutant regulation strategy (.147), MACT technology standard (.139), and receptor-based emissions standard (.109).

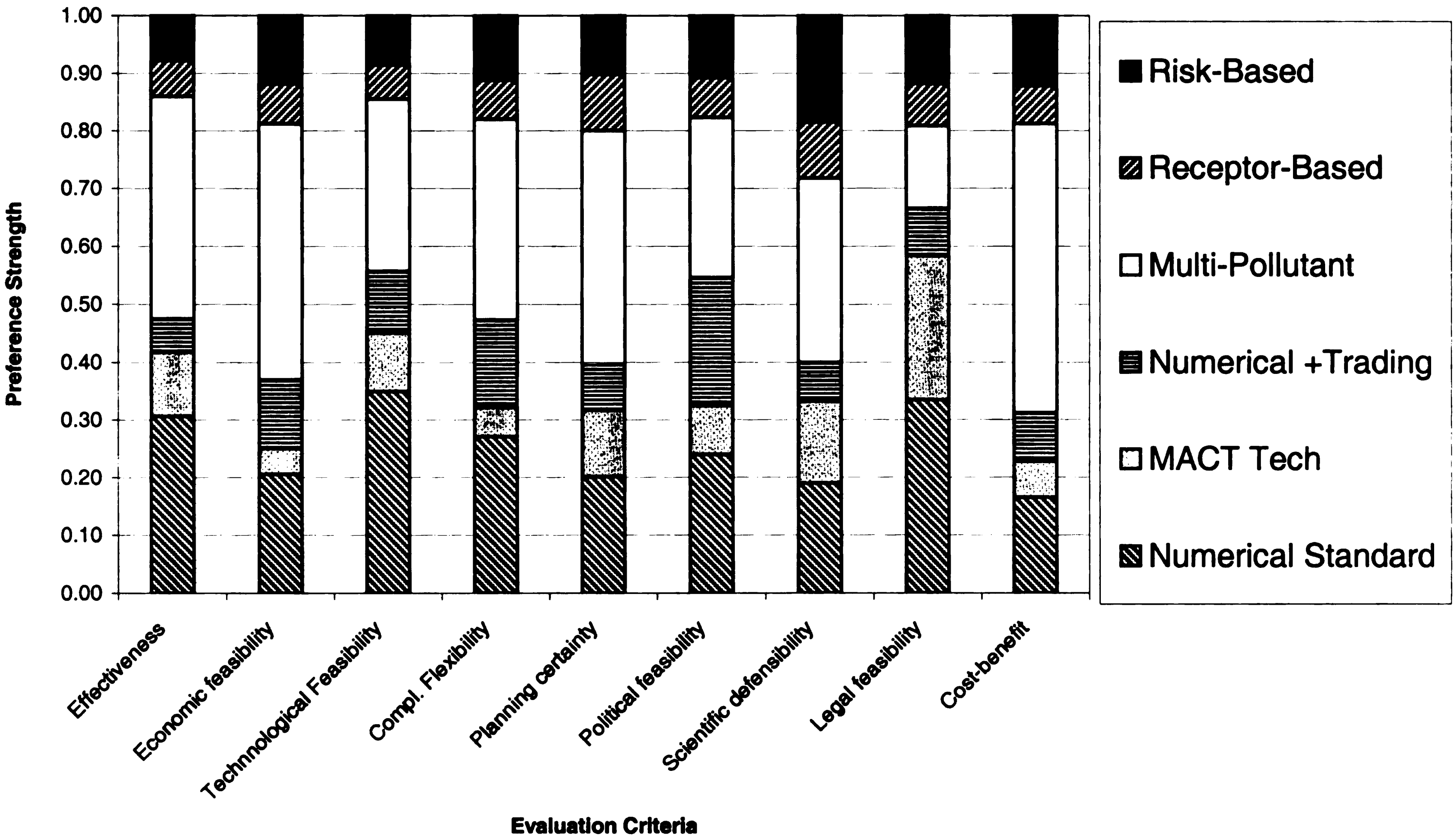
The utility industry expresses a strong preference for the risk-based emissions standard (.481) in terms of **cost benefit** analysis, which is favored almost three times more than the next most preferred strategy, the multi-pollutant regulation strategy (.170). The next most preferred strategies are the MACT numerical emissions standard plus emissions credit trading (.118), receptor-based emissions standard (.114), MACT numerical emissions standard (.097), and the MACT technology standard (.019).

In summary, the risk-based reduction strategy is the most favored among utility industry survey respondents in terms of (in order of preference strength) scientific defensibility (.545), cost-benefit (.418), technological feasibility (.376), effectiveness (.374), economic feasibility (.372), compliance flexibility (.282), and legal feasibility (.215). The only criteria for which the risk-based standard does not rank highest are political feasibility and planning certainty. With respect to political feasibility, the utility industry prefers the MACT numerical emission limit (.308) and in terms of planning certainty, the group favors the multi-pollutant strategy (.249).

<u>Environmental Organization Responses</u>

Figure 7 shows the environmental organization's pairwise comparison strategy preference results with respect to each criterion. With respect to the **effectiveness** evaluation criterion, the environmental organization stakeholder group has a strong preference for the multi-pollutant regulation strategy (.384) and the MACT numerical emissions standard (.306). These strategies are followed distantly by the MACT technology standard (.112), risk-

Figure 7: Environmental organization group paired comparison results



based emissions standard (.078), receptor-based emissions standard (.062), and MACT numerical emissions standard plus emissions credit trading (.057).

The strength of the preference for the multi-pollutant regulation strategy (.443) is even stronger with regard to **economic feasibility**, which is preferred twice as much as the next most preferred strategy, the MACT numerical emissions standard (.206). The MACT numerical emissions standard plus trading and risk-based emissions standard are less preferred, each receiving a preference ranking of .119. The least preferred strategies are the receptor-based emissions standard (.069) and the MACT technology standard (.045).

Both the MACT numerical emissions standard and the multi-pollutant regulation strategy are preferred significantly to the other strategies with respect to **technological feasibility**, receiving .349 and .297 preference ratings, respectively. These strategies are followed in the preference ranking by the MACT numerical emissions standard plus emissions credit trading (.106), MACT technology standard (.102), risk-based emissions standard (.085), receptor-based emissions standard (.060)

In terms of **compliance flexibility**, the environmental organizations surveyed prefer the multi-pollutant regulation strategy (.347) and the MACT numerical emissions standard (.271). Less preferred are the MACT numerical emissions standard plus emissions credit trading (.151), risk-based emissions standard (.112), receptor-based emissions standard (.068), and MACT technology standard (.052).

With respect to **planning certainty**, the multi-pollutant regulation strategy is preferred twice as much (.403) as the MACT numerical emissions standard (.201). The next most preferred reduction strategy is the MACT technology standard (.116), risk-based emissions standard (.102), receptor-based emissions standard (.098), and lastly the MACT numerical emissions standard plus emissions credit trading (.080).

According to the environmental organization stakeholder group, the most **politically feasible** strategies are the multi-pollutant regulation strategy (.277), the MACT numerical emissions standard (.240) and the MACT numerical emissions standard plus emissions credit trading (.222). The strategies that are less preferred in terms of political feasibility are the risk-based emissions standard (.108), MACT technology standard (.085), and receptor-based emissions standard (.069).

The multi-pollutant regulation strategy is preferred the most in terms of **scientific defensibility** with a preference level of .317. Following distantly in terms of preference are the MACT numerical emissions standard at .190, risk-based emissions standard at .185, MACT technology standard at .42, receptor-based emissions standard at .098, and MACT numerical emissions standard plus emissions credit trading at .068.

With respect to **legal feasibility**, the survey results reveal a strong preference for the MACT numerical emissions standard (.334) and the MACT technology standard (.250). The least preferred strategy in terms of legal feasibility are the multi-pollutant regulation strategy (.143), risk-based emissions standard (.118), MACT numerical emissions standard plus emissions credit trading (.081), and receptor-based emissions standard (.074).

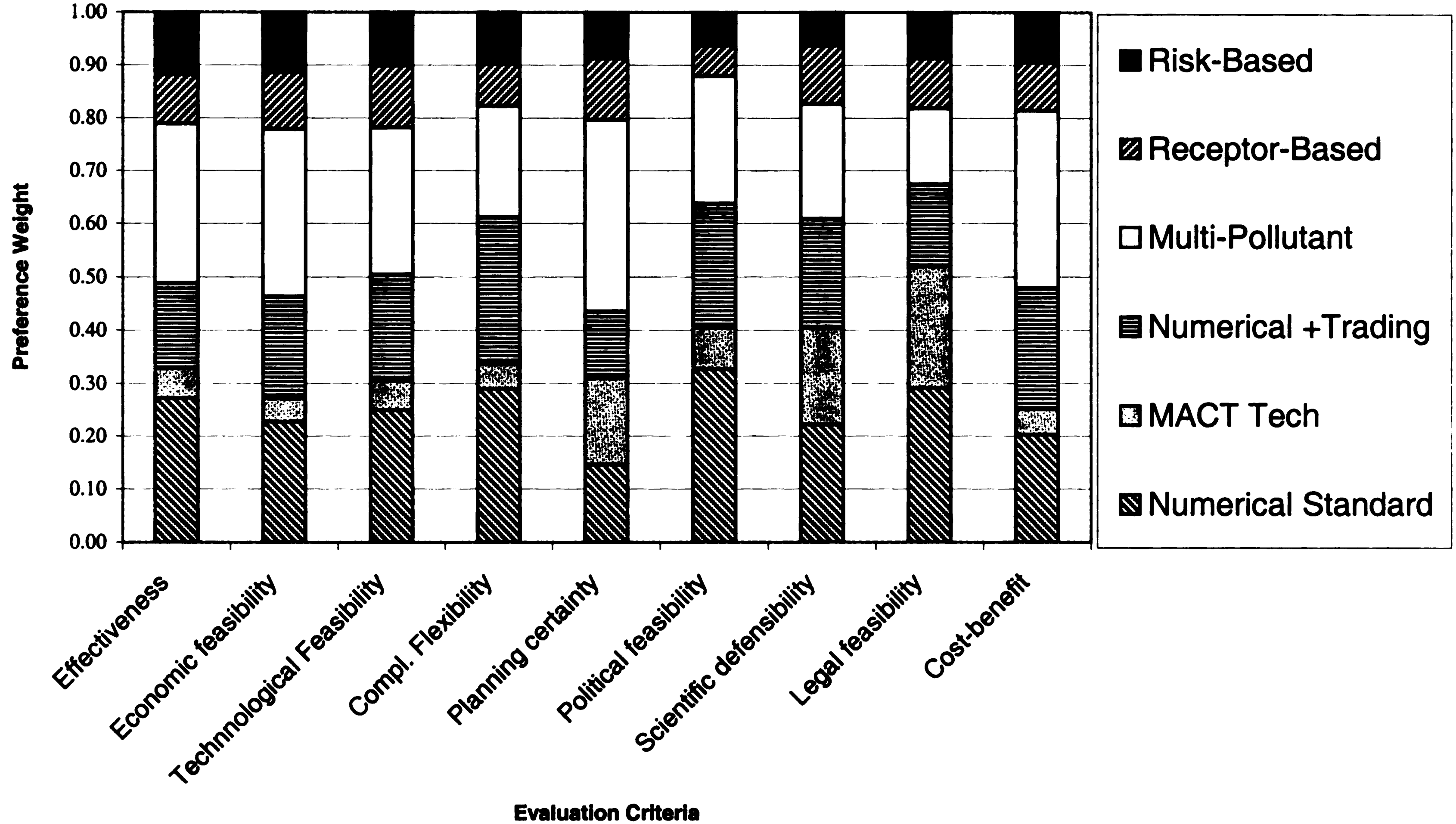
The strongest preference observed for any strategy is for the multi-pollutant regulation with respect to **cost vs. benefit**. Its preference rating is .500, followed distantly by the MACT numerical emissions standard at .165, risk-based emissions standard at.122, MACT numerical emissions standard plus emissions credit trading at .084, receptor-based emissions standard at .066, and the MACT technology standard at .063.

Overall, the environmental group respondents prefer the multi-pollutant strategy with respect to cost-benefit (.500), economic feasibility (.443), planning certainty (.403), effectiveness (.384), compliance flexibility (.347), scientific defensibility (.317), and political feasibility (.277). The only evaluation criteria that the multi-pollutant strategy did not satisfy were legal feasibility (.143) and technological feasibility (.067). The MACT numerical standard is preferred the most with respect to those criteria (.334 and .349 respectively).

Government Agency Responses

Figure 8 shows the government agency's pairwise comparison strategy preference results with respect to each criterion. In terms of **effectiveness**, the government agency survey group prefers the multi-pollutant regulation strategy (.300), followed closely in the preference ranking by the MACT numerical emissions standard at .272. The least

Figure 8: Government agency paired comparison results



preferred strategies are the MACT numerical emissions standard plus emissions credit trading with a preference rating of .160, followed by the risk-based emissions standard at .118, receptor-based emissions standard at .093, and MACT technology standard at .057.

The government agency respondents prefer the multi-pollutant regulation strategy the most (.277) with respect to **technological feasibility**, followed closely by the MACT numerical emissions standard (.249), MACT numerical emissions standard plus emissions credit trading (.199), receptor-based emissions standard (.117), risk-based emissions standard (.101), and MACT technology standard (.056).

The MACT numerical emissions standard, MACT numerical emissions standard plus emissions credit trading, and multi-pollutant regulation are the most preferred strategies in terms of **compliance flexibility**, receiving preference ratings of .298, .275, and .210 respectively. The least preferred strategies are the risk-based emissions standard, receptor-based emissions standard, and MACT technology standard with ratings of .098, .080, and .047, respectively.

The government agency respondents have a strong preference for the multi-pollutant regulation strategy (.361) in terms of **planning certainty**, which is preferred more than twice as much as the next most preferred strategy: the MACT technology standard (.165). This strategy is followed closely in terms of preference by the MACT numerical emissions standard (.146), the MACT numerical emissions standard plus emissions credit trading (.125), the receptor-based emissions standard (.116), and lastly the risk-based emissions standard (.088).

The MACT numerical emissions standard is the most preferred strategy in terms of **political feasibility** by this stakeholder group, receiving a preference rating of .327. The multi-pollutant regulation and the MACT numerical emissions standard plus emissions credit trading strategies are the next most preferred strategies, rating .241 and .233 respectively. The least preferred strategies are the MACT technology standard (.078), the risk-based emissions standard (.063), and the receptor-based emissions standard (.058).

Of the six reduction strategy alternatives, the MACT numerical emissions standard (.222), multi-pollutant regulation strategy (.217), MACT numerical emissions standard plus emissions credit trading (.204), and the MACT technology standard (.183) are all preferred roughly the same in terms of **scientific defensibility**. The next most preferred strategy is the receptor-based emissions standard (.111), followed by the risk-based emissions standard (.063).

The most preferred strategies in terms of **legal feasibility** are the MACT numerical emissions standard (.291) and the MACT technology standard (.229). The MACT numerical emissions standard plus emissions credit trading is given a priority vector of .155 by the government agency stakeholder group, followed by the multi-pollutant regulation strategy at .143, receptor-based emissions standard at .095, and risk-based emissions standard at .087.

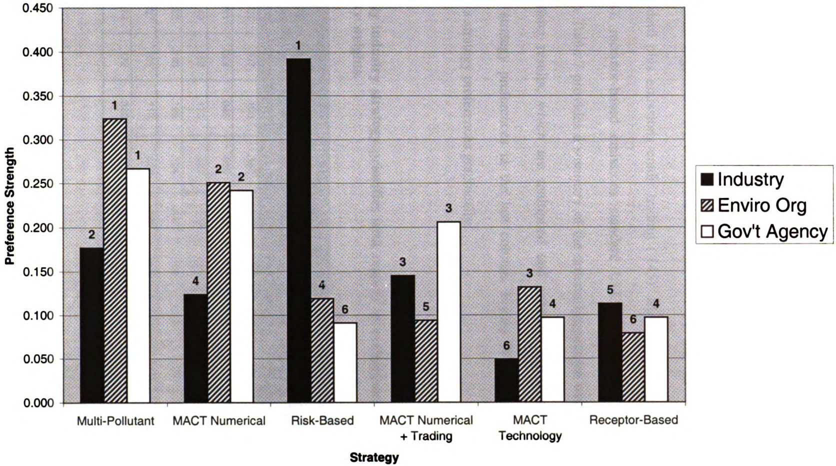
The multi-pollutant regulation strategy is the most preferred strategy in terms of the degree of **benefit compared to cost**. Its preference rating is .335, followed by the MACT numerical emissions standard plus emissions credit trading (.227), MACT numerical emissions standard (.203), risk-based emissions standard (.095), receptor-based emissions standard (.091), and MACT technology standard (.049).

To summarize, the government agency response group prefers the multi-pollutant strategy with respect to planning certainty (.361), cost-benefit (.335), economic feasibility (.315), effectiveness (.300), and technological feasibility (.277). In terms of political feasibility (.327), compliance flexibility (.290), legal feasibility (.291), and scientific defensibility (.222) the group prefers the MACT numerical standard.

Priority Synthesis Results

The remaining task in the AHP is to synthesize the strategic priorities discussed above with the evaluation criteria weightings to determine the relative preferences among the six reduction strategies for each stakeholder group. The tables below present the preference weights for each of the reduction strategies with respect to each evaluation criterion for each stakeholder group. See Figure 9 for a graphical comparison of the synthesized strategy preferences across all three stakeholder groups.

Figure 9: Comparison of overall strategy preferences
(numbers above bars represent rank order)



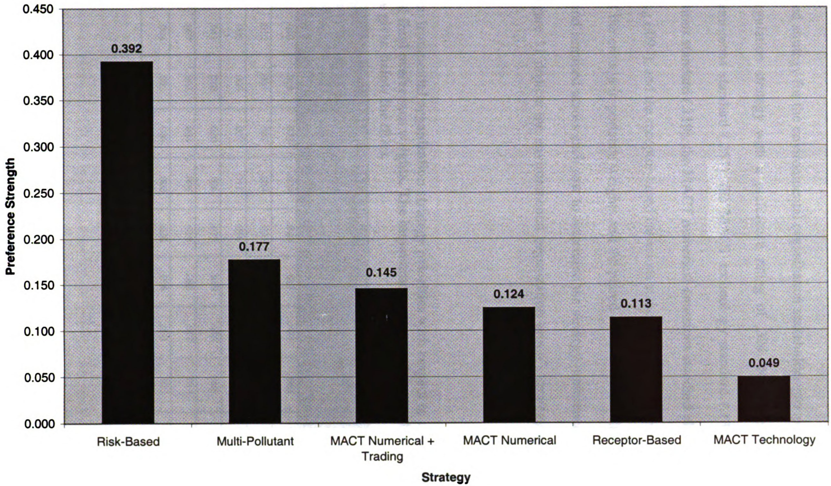
Utility Industry Responses

The synthesis results indicate a strong preference among utility respondents for the risked-based mercury emissions reduction strategy. The synthesized preference weight for this strategy is .392, which is more than twice that of the next most preferred strategy, the multi-pollutant regulation (.176). These are followed by the MACT numerical emissions standard plus emissions credit trading (.145), MACT numerical emissions standard (.124), receptor-based emissions standard (.113), and MACT technology standard (.049). Table 7 provides a summary of the criteria importance weights and the paired comparison results, which are multiplied and summed across each row to determine the strategy preferences in the last column. Figure 10 depicts the utility industry group's strategy preferences graphically.

Table 7: Utility industry strategy priorities with respect to evaluation criteria and final preference weights.

Alternatives	UTILITY INDUSTRY RESPONSES Evaluation Criteria									Strategy Preference
	Effectiv-ness (.041)	conomi easibilit (.052)	Techn. feasibility (.041)	Compl. flexibility (.119)	Planning ertainty (.098)	Political easibility (.061)	Scientific defens (.248)	Legal easibility (.074)	Cost-benefit (.266)	
Numerical Standard	.127	.107	.100	.167	.142	.308	.065	.199	.097	**.124**
MACT Tech Standard	.031	.024	.045	.036	.084	.125	.037	.139	.019	**.049**
Numerical +Trading	.149	.152	.173	.237	.174	.155	.095	.191	.118	**.145**
Multi-Pollutant	.223	.240	.196	.196	.249	.198	.124	.147	.170	**.176**
Receptor-Based	.097	.105	.110	.082	.130	.084	.133	.109	.114	**.113**
Risk-Based Standard	.374	.372	.376	.282	.221	.130	.545	.215	.481	**.392**

Figure 10: Utility industry group overall strategy preferences



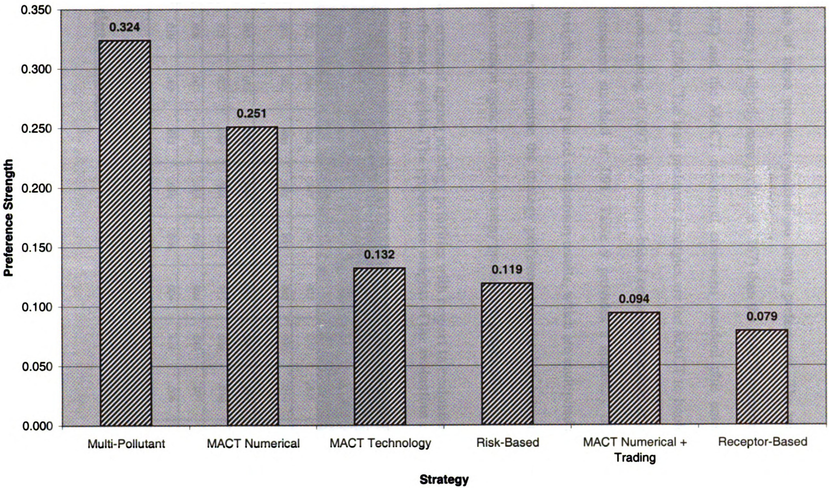
Environmental Organization Responses

The preferred strategy for the environmental organization stakeholder group is the multi-pollutant regulation strategy with a preference rating of .324. Next are the MACT numerical emissions standard (.251), the MACT technology standard (.132), the risk-based emissions standard (.119), the MACT numerical emissions standard plus emissions credit trading (.094), and the receptor-based emissions standard (.079). Table 8 provides a summary of the criteria importance weights and the paired comparison results, which are multiplied and summed across each row to determine the strategy preferences in the last column. Figure 11 depicts the environmental organization group's strategy preferences graphically.

Table 8: Environmental organization strategy priorities with respect to evaluation criteria and final preference weights. The importance weights of the evaluation criteria are given below the titles.

Alternatives	ENVIRONMENTAL ORGANIZATION RESPONSES Evaluation Criteria									Strategy Preference
	Effectiv-ness (.107)	Economic Feasibility (.023)	Techn. Feasibility (.067)	Compl. Flexibility (.075)	Planning Certainty (.197)	Political Feasibility (.070)	Scientific Defens (.177)	Legal Feasibility (.195)	Cost-benefit (.089)	
Numerical Standard	.033	.005	.023	.020	.040	.017	.034	.065	.015	**.251**
MACT Tech Standard	.012	.001	.007	.004	.023	.006	.025	.049	.006	**.132**
Numerical +Trading	.006	.003	.007	011	.016	.016	.012	.016	.007	**.094**
Multi-Pollutant	.041	.010	.020	.026	.079	.019	.056	.028	.045	**.324**
Receptor-Based	.007	.002	.004	.005	.019	.005	.017	.014	.006	**.079**
Risk-Based Standard	.008	.003	.006	.008	.020	.008	.033	.023	.011	**.119**

Figure 11: Environmental organization group overall strategy preferences



Government Agency Responses

The synthesis of these priorities yielded no strong preferences. The multi-pollutant regulation strategy is slightly more preferred (.267) than the MACT numerical emissions standard (.242) and the MACT numerical emissions standard plus emissions credit trading strategy (.206). The least preferred strategies are the MACT technology standard with a preference rating of .097, the receptor-based emissions standard at .097, and the risk-based emissions standard at .091. Table 9 provides a summary of the criteria importance weights and the paired comparison results, which are multiplied and summed across each row to determine the strategy preferences in the last column. Figure 12 depicts the government agency group's strategy preferences graphically.

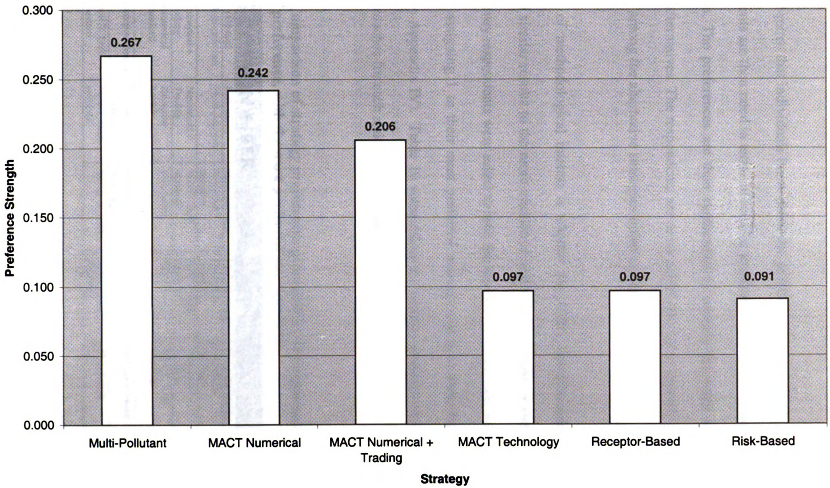
Table 9: Government agency strategy priorities with respect to evaluation criteria and final preference weights. The importance weights of the evaluation criteria are given below the titles.

Alternative	GOVERNMENT AGENCY RESPONSES Evaluation Criteria									Strategy Preference
	Effectiv-ness (.082)	Economic Feasibility (.070)	Techn. Feasibility (.114)	Compl. Flexibility (.161)	Planning Certainty (.089)	Political Feasibility (.064)	Scientific defens (.165)	Legal Feasibility (.071)	Cost-benefit (.184)	
Numerical Standard	.022	.016	.028	.047	.013	.021	.037	.021	.037	**0.242**
MACT Tech Standard	.005	.003	.006	.008	.015	.005	.030	.016	.009	**0.097**
Numerical +Trading	.013	.013	.023	.044	.011	.015	.034	.011	.042	**0.206**
Multi-Pollutant	.025	.022	.032	.034	.032	.015	.036	.010	.062	**0.267**
Receptor-Based	.008	.007	.013	.013	.010	.004	.018	.007	.017	**0.097**
Risk-Based Standard	.010	.008	.012	.016	.008	.004	.010	.006	.017	**0.091**

Strategy Preference Ranking

The AHP requires that individuals break down the problem into components or elements. These elements are then rated in terms of relative preferences through a series of pairwise

Figure 12: Government agency group overall strategy preferences



Strategy Preference Ranking

The AHP requires that individuals break down the problem into components or elements. These elements are then rated in terms of relative preferences through a series of pairwise comparisons. The preferences are then synthesized to identify the order of preference among the alternatives. The respondents are never asked directly to identify their relative preferences among the alternative strategies under consideration.

A question of methodological interest is whether the AHP's deconstruction approach would yield similar results to the more traditional and simple ranking of alternatives. To test this, survey respondents were asked to rank the six mercury reduction strategies from one to six, assigning 1 to their most preferred strategy and 6 to their least preferred strategy (see Appendix IV). Table 10 summarizes the strategy preferences generated by the two approaches for each stakeholder group.

Table 10: Comparison of strategy preferences generated by two approaches (listed in order of preference, with the most preferred strategy first)

	UTILITY INDUSTRY		ENVIRONMENTAL ORG		GOVERNMENT AGENCY	
	AHP	Ranking	AHP	Ranking	AHP	Ranking
Most Preferred	Risk-based	Risk-based	Multi-pollutant	Multi-pollutant	Multi-pollutant	Multi-pollutant
	Multi-pollutant	Multi-pollutant	Numerical standard	Numerical standard	Numerical standard	Numerical standard
	Numerical + Trading	Numerical + Trading	MACT Tech standard	MACT Tech standard	Numerical + Trading	Numerical + Trading
	Numerical standard	**Receptor based**	Risk-based	Risk-based	MACT Tech standard	MACT Tech standard/ **Risk-based (tie)**
	Receptor based	**Numerical standard**	**Numerical + Trading**	**Receptor based**	**Receptor based**	
Least Preferred	MACT Tech standard	MACT Tech standard	**Receptor based**	**Numerical + Trading**	**Risk-based**	**Receptor based**

Utility Strategy Ranking

Using the ranking approach, of the 17 utility respondents, 12 rank the risk-based standard as the most preferred strategy (mean, 1.63; SD, 1.41). Ranking second among the six strategies is the multi-pollutant regulation (mean, 2.56; SD, 1.55). Ranking third is the MACT numerical emission limit including emissions credit trading (mean, 3.25; SD.856) followed closely by the receptor-based emission limit strategy (mean, 3.69; SD, 1.49). The least preferred strategies are the MACT numerical emission limit (mean, 4.44; SD 1.03) and the MACT technology standard (mean, 5.44; SD, .727).

Both the AHP and ranking approaches produced roughly the same strategy preference ranking for the utility industry stakeholder group, except with respect to the numerical emission and the receptor-based strategy rankings. The AHP calculated the numerical standard as the fourth most preferred strategy, followed by the receptor-based strategy, while the ranking results conclude the opposite.

Environmental Organization Ranking

When asked to rank the six reduction strategies, the survey respondents from the environmental stakeholder group almost unanimously select the multi-pollutant emission reduction strategy as their most preferred alternative (mean, 1.25; SD, .621). Only two respondents do not believe this is the best strategy, with one ranking it second and the other ranking it third. The MACT numerical emission standard (mean, 2.67; SD, 1.30) and the MACT technology emission standard (mean, 2.67; SD, 1.07) are both ranked second, followed by the risk-based emission standard (mean, 3.92; SD, 1.68) and the receptor -based emission standard (mean, 4.42; SD, 1.08). The least preferred of the six strategies was the MACT numerical emission standard plus trading (mean, 5.08; SD, 1.34).

Both the AHP and ranking approaches produced the same top three strategy preference rankings for the environmental group. The two least preferred strategies were different. The AHP calculated the numerical plus trading and receptor-based strategies as fifth and sixth in the priority ranking, while the ranking results conclude the opposite.

Government Agency Ranking

It was difficult to determine strategy preferences among the agency respondents because their responses were not uniform, i.e. responses varied greatly for each strategy. Table 11 illustrates the inconsistencies in survey responses; with the most preferred mean score being 2.00 (SD 1.77) and the least preferred being 4.88 (SD: 1.80). For example, according to the mean ranking score, the MACT numerical standard is the second most preferred reduction strategy among government agency employees surveyed (mean, 2.63; SD, 1.69), but when the frequency distribution is analyzed, it is clear that the preferences are widely distributed. Of the total government agency responses, 25 percent rank the MACT numerical standard as the most preferred strategy, 37.5 percent rank it second, 12.5 percent rank it third, 12.5 percent rank it fourth, and 12.5 percent rank it last. This kind of distribution decreases the robustness of the strategy preference ranking for this stakeholder group.

Table 11: Government agency group strategy preference ranking (1=most preferred)

Numerical Standard	MACT Tech Standard	Numerical +Trading	Multi-Pollutant	Receptor-Based	Risk-Based Standard
1	5	3	6	2	4
3	4	2	1	6	5
4	3	2	1	6	5
2	6	3	1	5	4
2	4	1	3	6	5
6	4	3	1	2	5
2	5	3	1	6	4
1	4	5	2	6	3

Both the AHP and ranking approaches produced the same results for the first, second, third, and fourth most preferred strategies. The AHP results indicated that the receptor-based followed by the numerical plus trading strategies were the least preferred, but the ranking results moved the risk-based standard up along side the MACT technology standard tied for fourth place in the preference order, followed by the receptor-based standard. These results infer that the government agency group prefers the risk-based strategy less when forced to articulate relative preferences with respect to each criteria, and to articulate the relative importance of the criteria. In other words, this strategy is preferred until it is deconstructed and evaluated in pieces.

Sensitivity Analysis

To gain a deeper understanding of the stakeholders' reduction strategy priorities, a sensitivity analysis was run on each data set using Expert Choice. Sensitivity analysis allows the researcher to test "what if?" scenarios, i.e. the sensitivity of the reduction strategy priorities with respect to changes in the weighting of the evaluation criteria.

Expert Choice provides four graphical sensitivity analysis modes: dynamic, gradient, performance, and two-dimensional analysis and depicts how well each alternative performs on each criterion when increasing or decreasing the importance of the criteria. Its purpose is to assess that stability of an optimal solution under changes in the parameters.

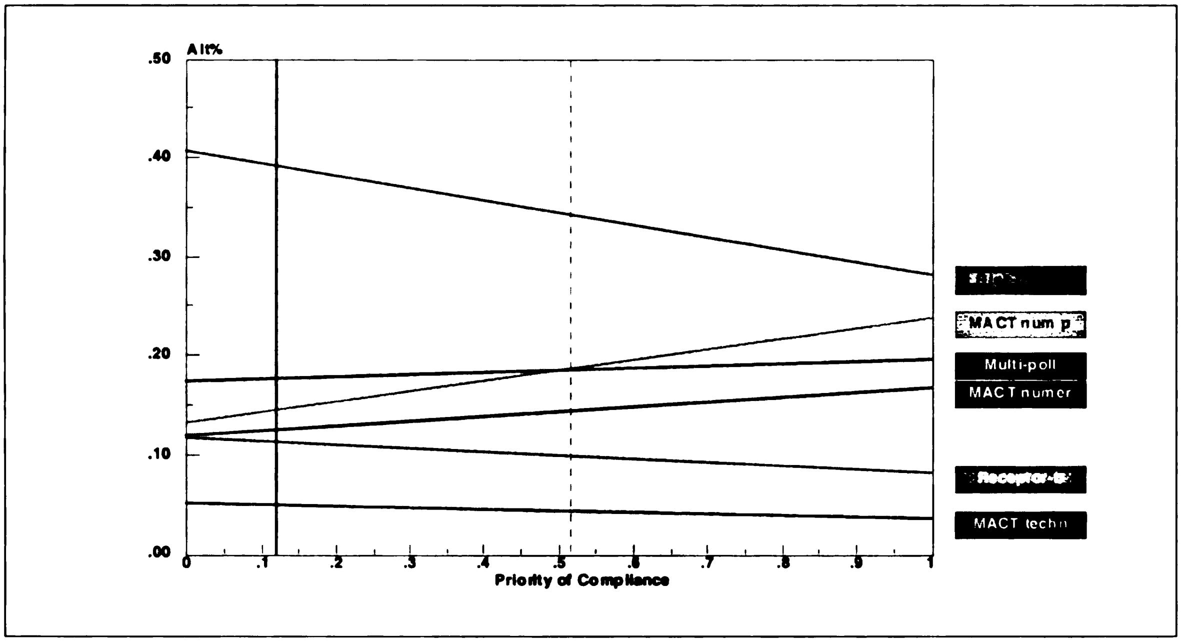
Utility Industry Sensitivity Analysis

The overall emission reduction strategy priorities for the utility industry survey group are:

- Risk-based emission limit (.392)
- Multi-pollutant regulation (.177)
- MACT numerical limit plus trading (.145)
- MACT numerical emission limit (no trading) (.124)
- Receptor-based emission limit (.113)
- MACT technology standard (.049)

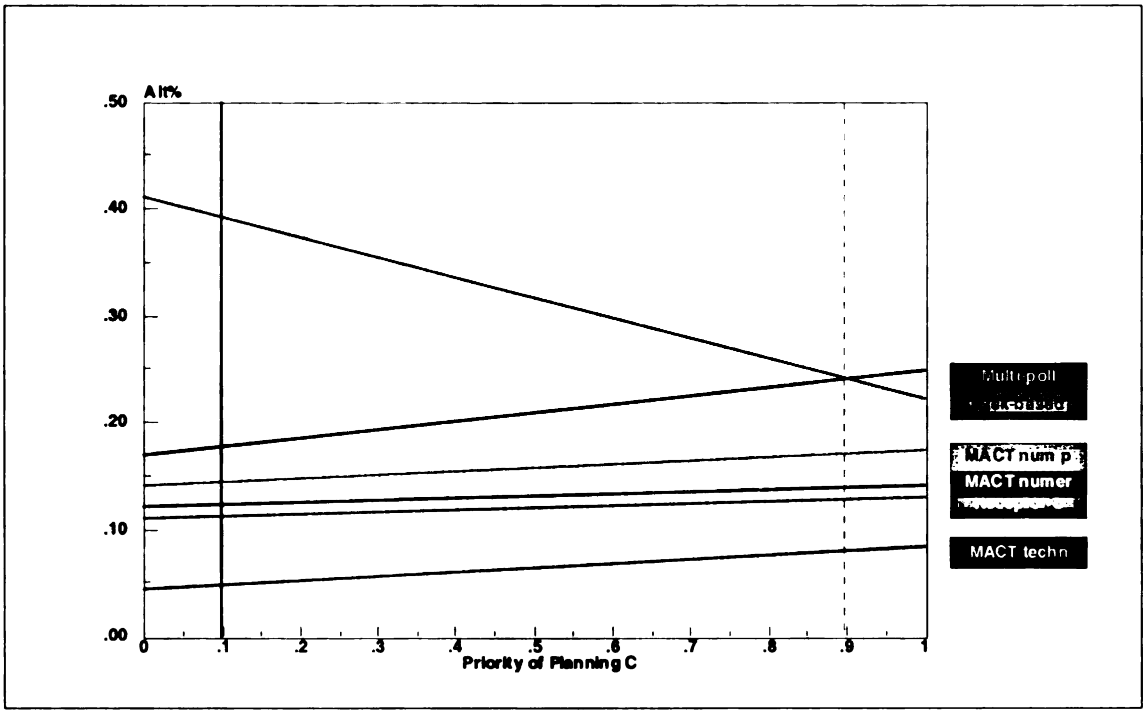
When the sensitivity analysis was run with respect to the criterion compliance flexibility (.119 importance weight), the preference for the numerical emission limit plus trading strategy increases as the weight of the criterion increases, ultimately reaching second in the preference order. The preference level does not increase enough to replace the risk-based emission limit as the most preferred strategy, though.

Figure 13: Sensitivity of utility industry strategy preferences to changes in compliance flexibility criterion weight



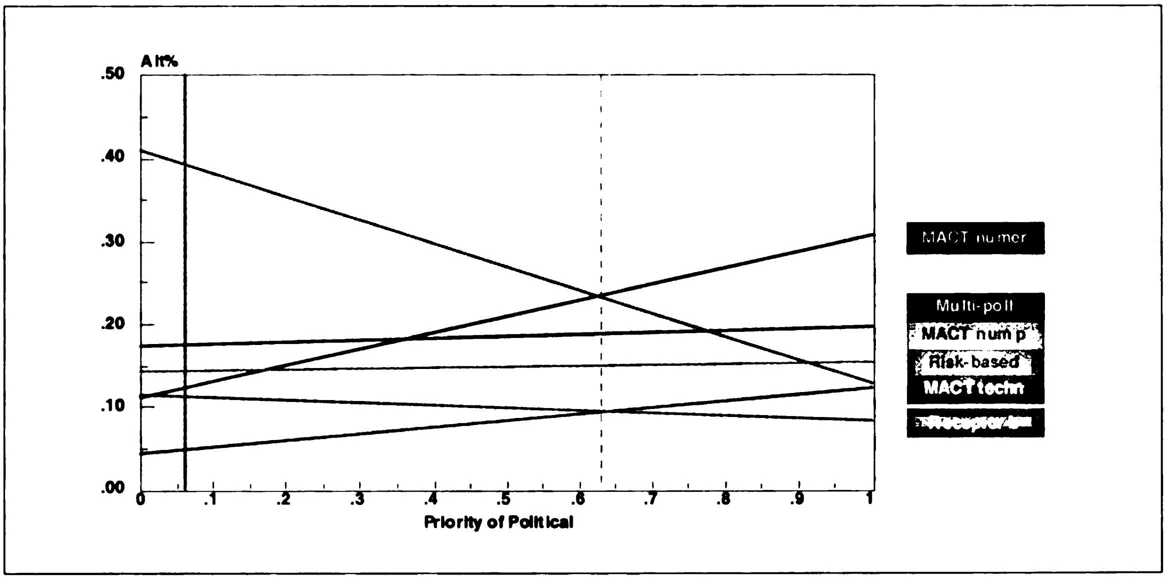
Varying the importance weight of the planning certainty criterion (.98) has a significant impact on the top rated risk-based standard. The preference level decreases from .392 to .222 as the importance weight for planning certainty increases. These results indicate that, if this criterion were more important to the utility industry (>.902), the multi-pollutant regulation, which increased in preference from .177 to .249, would be the most preferred mercury emissions reduction strategy, but only by a small margin. The results also imply that, according to the utility industry, the risk-based standard does not provide much planning certainty, but this is not an issue because planning certainty is not an important evaluation criterion relative to the others.

Figure 14: Sensitivity of strategy preferences with changes in planning certainty criterion weight



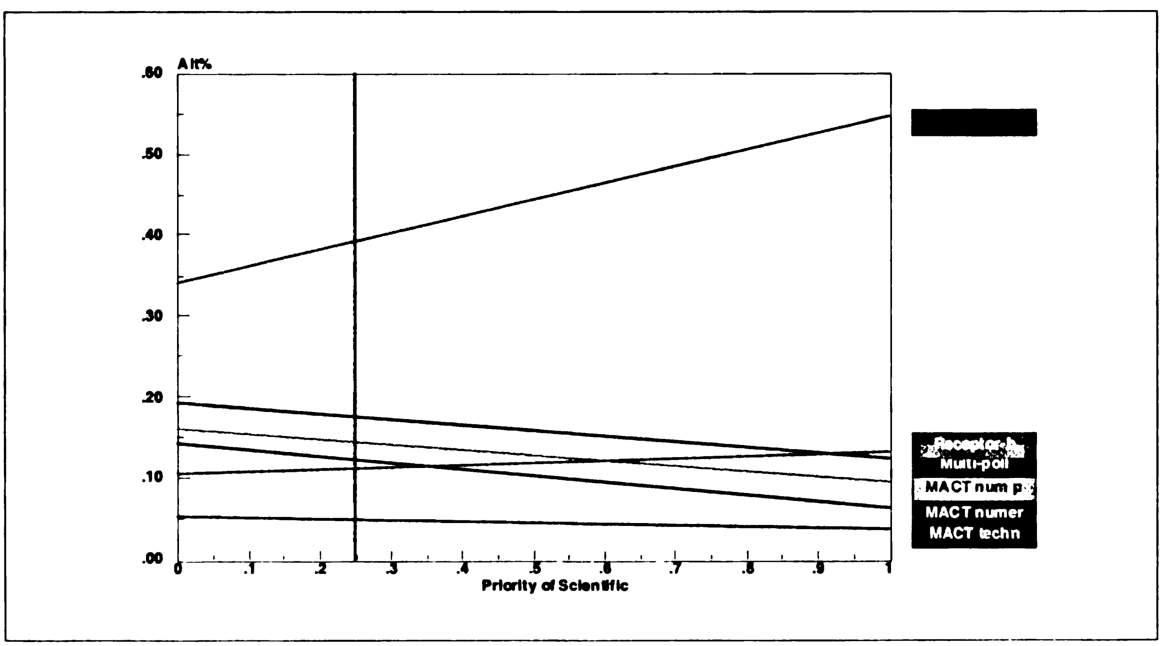
The most sensitive utility industry criterion is political feasibility, although this criterion was not given much weight relative to the other criterion (.061). As the importance weight for this criterion increases, the risk-based standard decreases in preference order from a strong first to fourth (.392 to .130), while the MACT numerical standard increases from fourth to a strong first (.124 to .308). The MACT technology standard also increases in preference from last to fifth (.049 to .125). These results indicate that the utility industry does not believe that the risk-based emission limit is politically feasible, but this criterion is not of much concern relative to the other criterion when evaluating preferred options.

Figure 15: Sensitivity of utility industry strategy preferences to changes in political feasibility criterion weight



Scientific defensibility is an important evaluation criterion for the utility industry (.250), but variations in its weight do not have much impact on the strategy preference order. The preference strength for this strategy with respect to scientific defensibility is so

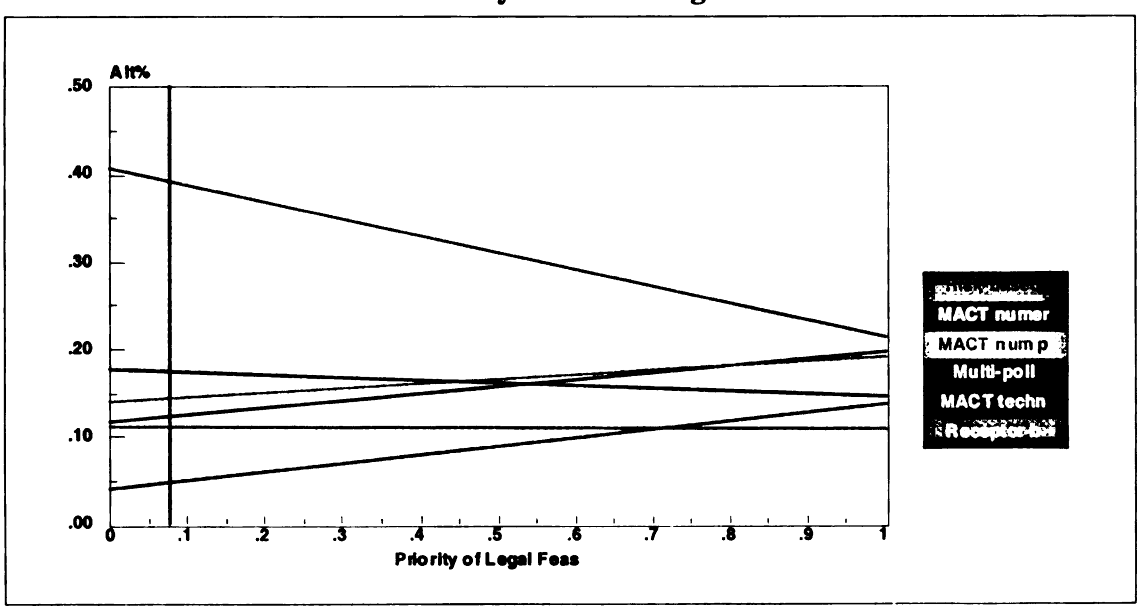
Figure 16: Sensitivity of utility industry strategy preferences to changes in scientific defensibility criterion weight



strong that even if that criterion itself were unimportant to the group (a weight of 0), the risk-based strategy is still strongly preferred (.343), and increases in preference with the criterion importance weight (to a maximum of .545).

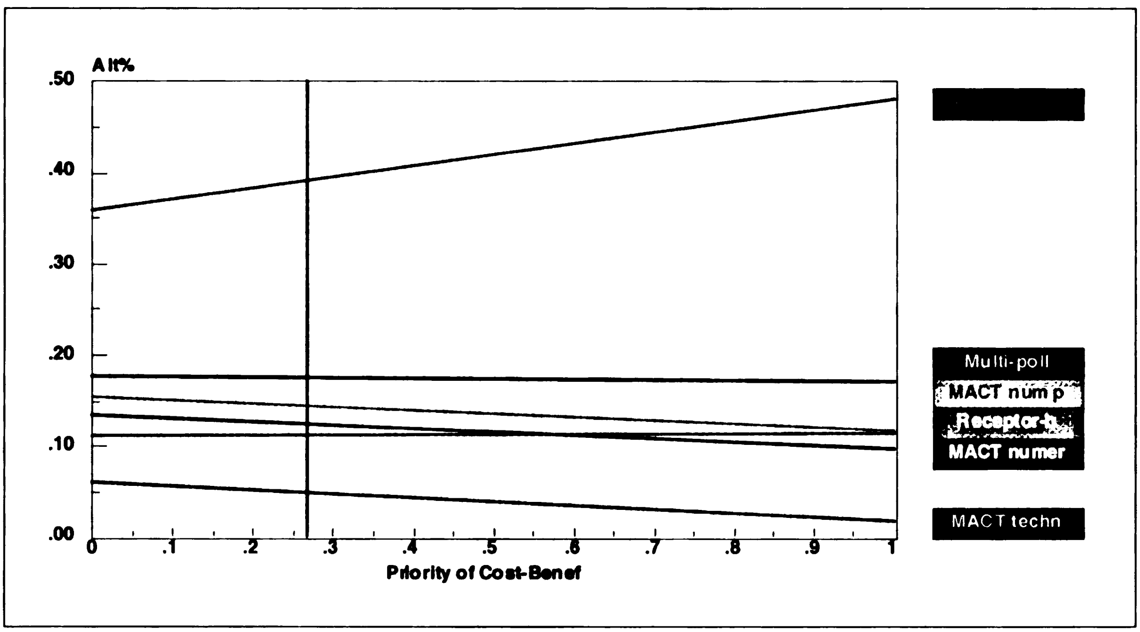
The legal feasibility criterion does not appear to be of relative importance to the utility industry (.074), but its importance weight does have an impact on preference order. If this criterion were considered relatively important, all of the strategies would be preferred relatively equally, the preference for the risk-based strategy would decrease from .392 to .216, the numerical emission limit would increase in the preference order from fourth to second (from .124 to .199). The risk-based strategy still would remain the most preferred alternative.

Figure 17: Sensitivity of utility industry strategy preferences to changes in legal feasibility criterion weight



The cost benefit criterion is considered the most important evaluation criterion relative to the others (.248), but, similar to the scientific defensibility criterion, variations in its weight do not have much impact on the strategy preference order. The preference strength for all the criteria remain fairly equal except for the risk-based strategy, which is preferred twice as much as the next most preferred strategy and only increases in strength from there (to a maximum of .480).

Figure 18: Sensitivity of utility industry strategy preferences to changes in cost-benefit criterion weight



With respect to the effectiveness, economic feasibility, and technological feasibility criteria, small to no changes in preference order were observed after performing the sensitivity analyses, indicating that these factors do not influence the utility industry's strategy preferences. This is validated by the low importance weights assigned to the effectiveness technological feasibility, economic feasibility criteria, which are .041, , .041, and .052 respectively.

In summary, no variations were observed with respect to the most preferred strategy (i.e. the risk-based emission limit) except in terms of planning certainty and political feasibility. A small variation in the preference order is observed with respect to planning certainty, as the multi-pollutant strategy is preferred slightly over the risk based strategy (a difference of .027). A larger variation is observed for political feasibility, where the MACT numerical emission standard advances to first from fourth in the preference order, and the risk-based standard drops to fourth.

Large variations in the final rating indicate that more effort should be spent on verifying the particularly sensitive criterion. The only criterion for which this applies is political feasibility. Even though either no or small variations are observed for all but one of the criterion, the AHP has not produced the optimal reduction strategy for the utility industry. The sensitivity analysis for the utility industry survey group results indicate that a more optimal strategy is one that is viewed by the utility industry as political feasible. Alternatively, it is possible for the risk-based strategy to be the best alternative if the political hurdles are overcome that currently render the strategy infeasible.

Environmental Organization Sensitivity Analyses

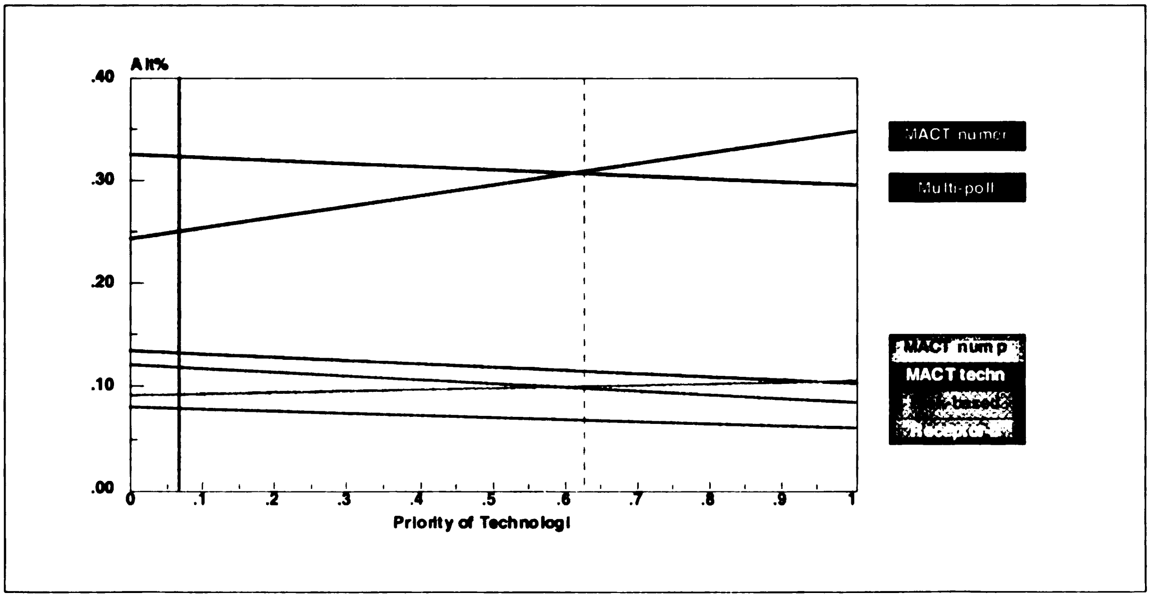
The overall emission reduction strategy priorities for the environmental organization survey group are:

- Multi-pollutant regulation (.324)
- MACT numerical emission limit (no trading) (.251)
- MACT technology standard (.132)

- Risk-based emission limit (.119)
- MACT numerical limit plus trading (.094)
- Receptor-based emission limit (.079)

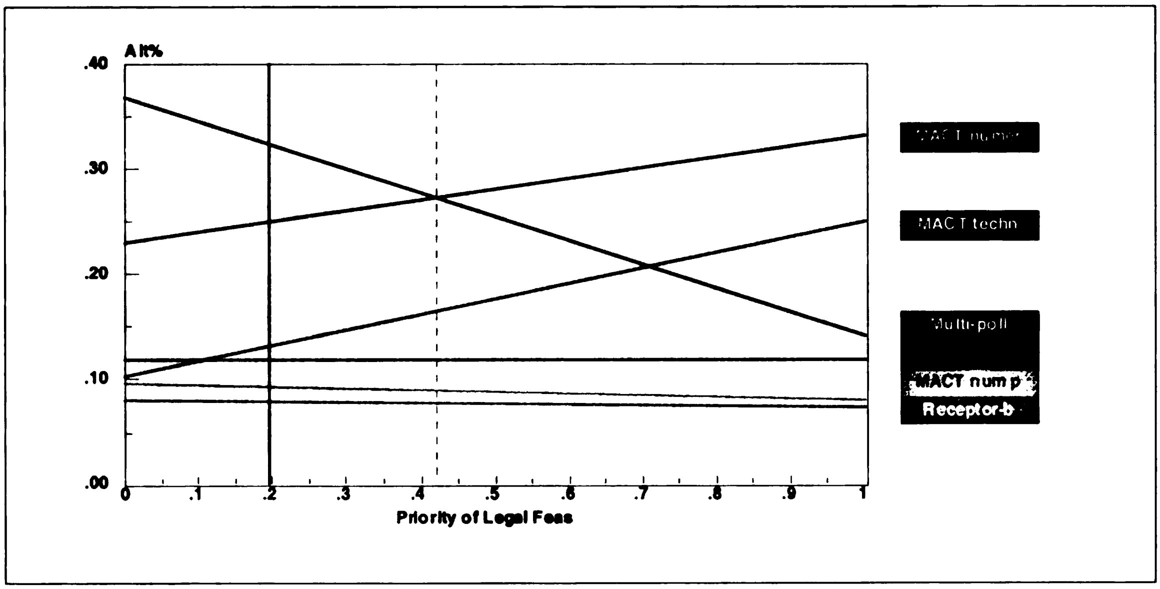
When the sensitivity of the criterion technological feasibility was tested, the overall preference order changed slightly as the weight was increased. The multi-pollutant regulation drops to the second most preferred strategy in terms of technological feasibility (.297), and the MACT numerical emission standard rises to the most preferred (.348). Although this is a variation in the preference order, the multi-pollutant strategy is still preferred strongly relative to the remaining strategies, so this does not decrease the robustness of the AHP-determined top strategy choice.

Figure 19: Sensitivity of environmental organization group strategy preferences to changes in technological feasibility criterion weight



A large variation in preference order is observed when the legal feasibility criterion is given greater weight. The multi-pollutant strategy is less preferred with respect to this criterion, moving down to third in the preference order with a preference level of .144. The top two reduction strategies with respect to legal feasibility are the MACT numerical emission standard (.333) and the MACT technology standard (.250). This is not surprising, since these are the two strategies that are explicitly mentioned in the Clean Air Act as reduction strategy alternatives to reduce hazardous air pollutant emissions.

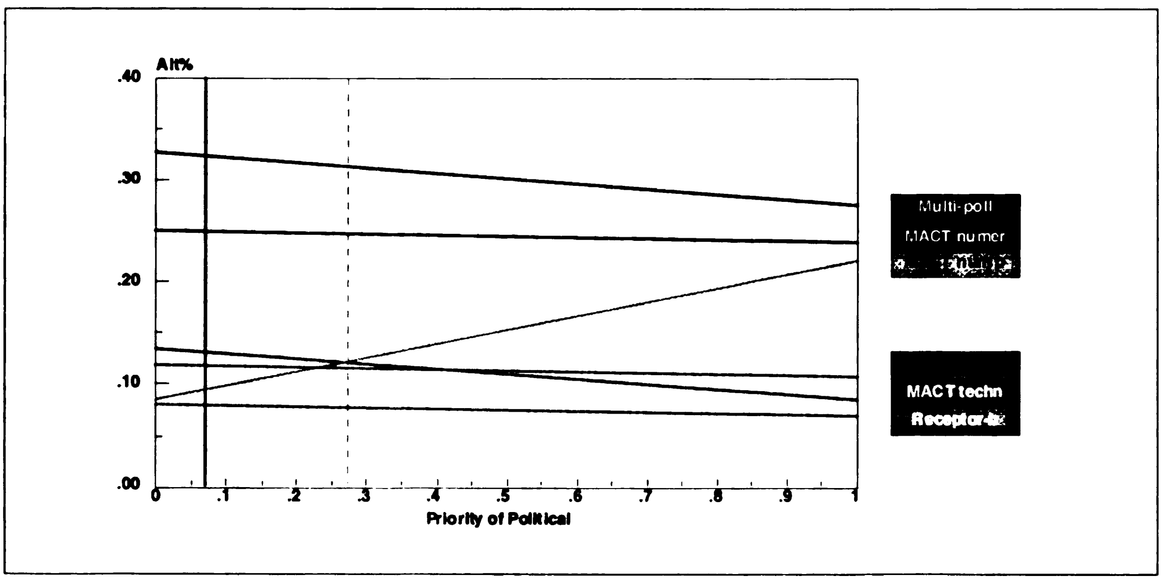
Figure 20: Sensitivity of environmental organization group strategy preferences to changes in legal feasibility criterion weight



With respect to the other evaluation criteria, no variations were observed in terms of the most preferred reduction strategy, the multi-pollutant regulation. The variation in preference order with respect to legal feasibility is large, though. Even though either no or small variations are observed for all but one of this criterion, the AHP has not produced the optimal reduction strategy for the environmental organization survey group. The sensitivity analysis results indicate that a more optimal strategy is one that is viewed by the environmentalists as legally feasible. Alternatively, it is possible for the multi-pollutant strategy to be the best alternative if enabling legislation is passed.

An interesting observation the sensitivity analysis revealed involved the political feasibility criterion and the multi-pollutant strategy. Although the multi-pollutant strategy rates slightly lower when evaluated with respect to political feasibility compared to overall (from .324 to .227), it still remains the most preferred strategy relative to the others. This is surprising, since new laws would have to be enacted to enable implementation of this reduction strategy, which may create political hurdles. It appears that the environmental survey group believes that the stakeholders involved in the mercury regulatory determination favor the multi-pollutant strategy, and that little opposition will occur enacting it into law.

Figure 21: Sensitivity of environmental organization group strategy preferences to changes in political feasibility criterion weight



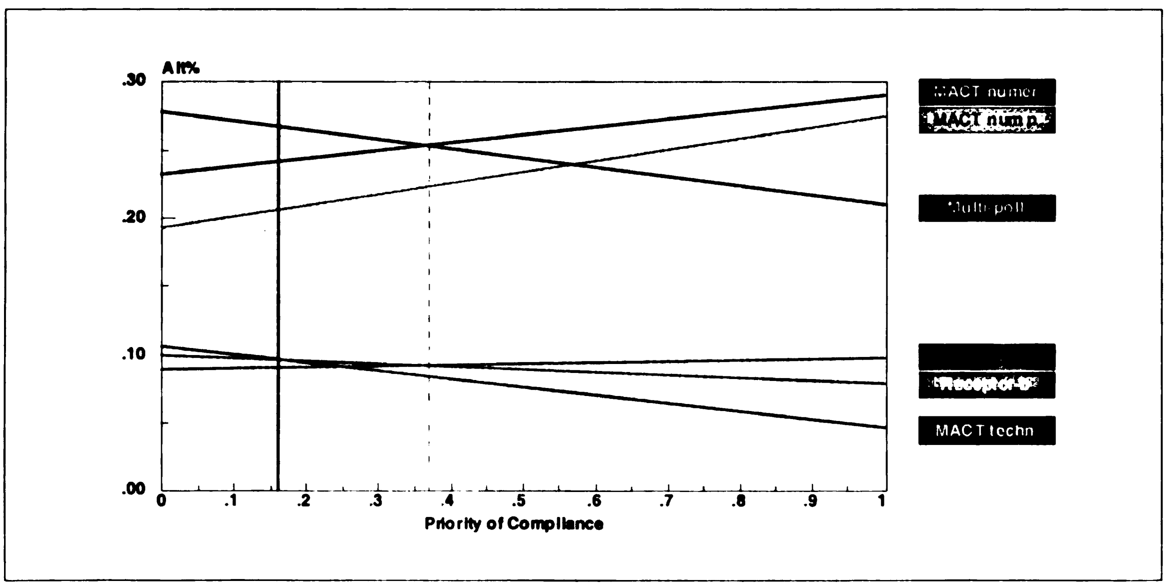
Governmental Agency Sensitivity Analysis

The overall emission reduction strategy priorities for the government agency survey group are:

- Multi-pollutant regulation (.267)
- MACT numerical emission limit (no trading) (.242)
- MACT numerical limit plus trading (.206)
- MACT technology standard (.097)
- Receptor-based emission limit (.097)
- Risk-based emission limit (.091)

The sensitivity test for the compliance flexibility criterion yielded a variation in the strategy preference order for the government agency survey group. When compliance flexibility is given more importance, the multi-pollutant regulation is no longer the most preferred strategy with respect to compliance flexibility. The MACT numerical emission

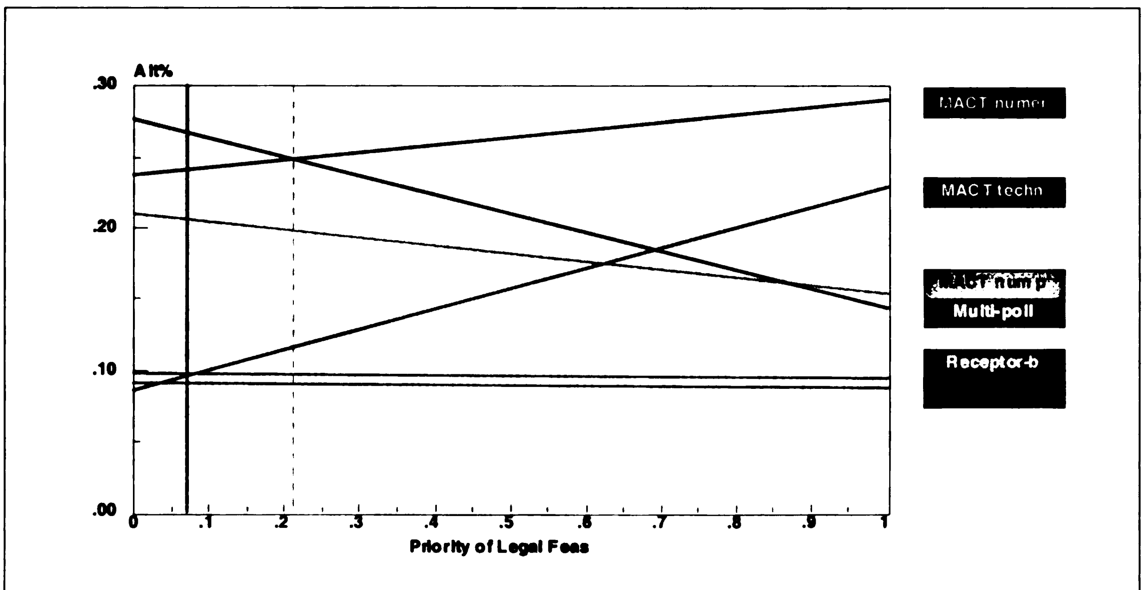
Figure 22: Sensitivity of government agency group strategy preferences to changes in compliance flexibility criterion weight



regulations with and without trading (.290 and .275, respectively) become the preferred strategies. Although not ranked the highest, the preference for the multi-pollutant strategy is still fairly strong (.210).

A large variation in preference order is observed when the strategies are considered with respect to legal feasibility. The multi-pollutant strategy not only drops from first to third in the preference order, it is preferred 2.25 times less. The MACT numerical and technology standards increase in terms of preference to .333 and .250, respectively. These results suggest that the government agency survey group does not believe that the multi-pollutant strategy is legally feasible, which is not surprising since new laws would have to be enacted to permit such a strategy.

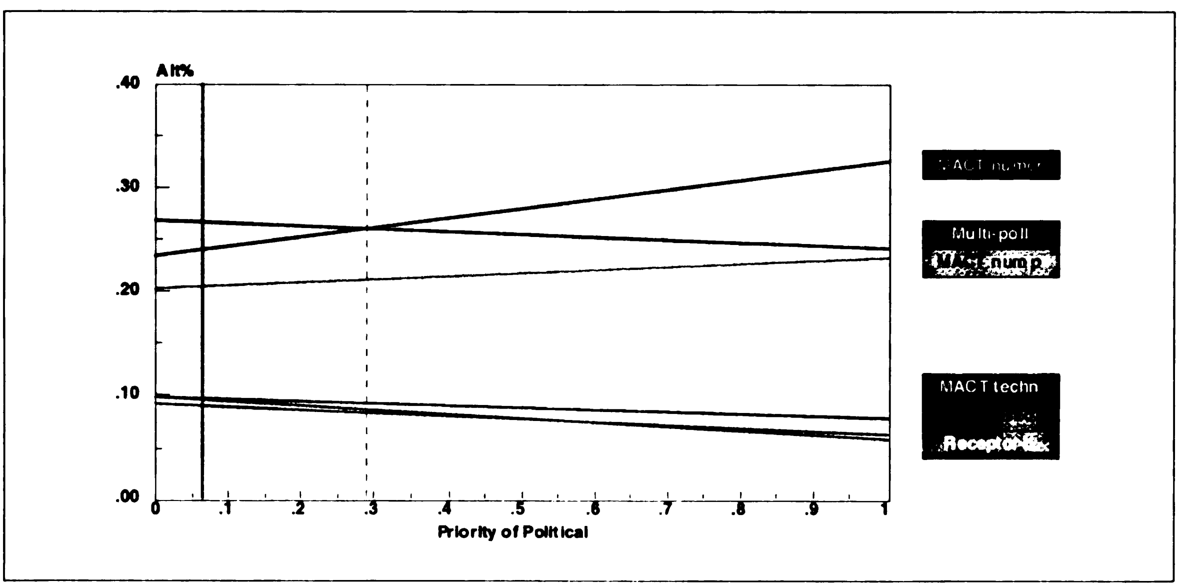
Figure 23: Sensitivity of government agency group strategy preferences to changes in legal feasibility criterion weight



With respect to the other evaluation criteria, no variations were observed in terms of the most preferred reduction strategy, the multi-pollutant regulation. The variation in preference order with respect to legal feasibility is large, though. Even though either no or small variations are observed for all but one of this criterion, the AHP has not produced the optimal reduction strategy for the government agency survey group. The sensitivity analysis results indicate that a more optimal strategy is one that is viewed by the government agency survey respondents as legally feasible. Alternatively, it is possible for the multi-pollutant strategy to be the best alternative if enabling legislation is passed.

A couple of interesting observations were made while performing the sensitivity analysis with respect to the political feasibility criterion. This criterion is not sensitive with respect to the most preferred strategy, the multi-pollutant regulation, which infers that the government agency survey group does not believe there are significant political barriers

Figure 24: Sensitivity of government agency group strategy preferences to changes in political feasibility criterion weight



that would hinder this strategy. Even more interesting is the observation made when analyzing the variation in preference strength of the MACT numerical emission limit plus trading with respect to the political feasibility criterion, which is .222 (compared to .094 overall). This result suggests that the government agency respondents believe that emissions credit trading is politically feasible, which is surprising since a great deal of uncertainty surrounds whether or not emissions credit trading is legal for hazardous air pollutants under the Clean Air Act and safe for humans and wildlife.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This thesis evaluated different strategies for reducing mercury emissions from coal-fired power plants and demonstrated an application of the AHP as a support tool for determining the most preferred mercury reduction strategy among three stakeholder groups. This chapter highlights the key findings of the study, evaluates the AHP as used in this application, and identifies further research opportunities. In particular, the potential role of the study outcomes in advancing the current debate over future mercury emissions reduction strategies is examined.

SUMMARY OF KEY FINDINGS

Below is a summary of the key findings from this study, which are expanded upon in the sections that follow.

- The receptor-based strategy scored consistently poor with respect to all the criteria across all three stakeholder groups.
- The risk-based standard is a controversial strategy.
- The utility industry group prefers the risk-based standard. To optimize this strategy, it would have to be politically feasible.
- The environmental and government agency groups prefer the multi-pollutant strategy. To optimize this strategy, it would have to be legally feasible.

- There is the potential for consensus with regard to the multi-pollutant approach.
- Scientific defensibility is a relatively important criterion to all three stakeholder groups, but definitions for this criterion may differ.

Selection of an Optimal Strategy

After the criteria weights and paired comparison results were synthesized, one clear finding surfaced. Certain aspects of the strategies under consideration were not popular with any of the stakeholder groups. Of all the reduction strategies evaluated, the receptor-based strategy scored consistently poorly with respect to all the criteria across all three stakeholder groups. Overall, this strategy is the least preferred among the environmental and government agency respondents (.079 and .097, respectively), and ranks second to last among utility respondents (.113). These results indicate that this reduction strategy is not a viable solution in selecting an optimal mercury reduction strategy for coal-fired power plants and should no longer be considered as an option.

It is also clear that the risk-based standard is a controversial strategy. Extreme values were assigned to this strategy with respect to each evaluation criterion, but on opposite ends of the relative preference scale. The utility industry group rates this strategy high with respect to all the criteria, while the environmental and government agency groups rate it low. Overall, the risk-based standard was the most preferred strategy for the utility group, preferred 2.2 times more than the next most preferred strategy. The environmental and government agency groups, though, do not favor this strategy, ranking it last and fourth overall. The extreme ratings given to the attributes of this strategy by all stakeholder groups may be the result of a certain degree of strategic voting on the part of the stakeholder groups. This is a reflection of the polarizing nature of this strategy.

The sensitivity analysis revealed that there is no scenario that could be proposed to optimize this strategy. Although the utility industry group prefers this strategy to the others, they would have an extremely hard time getting buy-in from the other stakeholders. As stated above, the environmental and government agency groups rated this strategy poorly with respect to all the criteria, but the most critical issues that would need to be addressed to increase these groups' comfort level with this strategy include technological feasibility, planning certainty, and legal feasibility.

The study results also reveal that all three stakeholder groups approve of the multi-pollutant reduction strategy. The groups unanimously agree that it is the best strategy in terms of planning certainty, and also rate it favorably in terms of cost-benefit. Overall, the environmental organization and government industry stakeholder groups favor this strategy over any other, while the utility industry rate it as their second most preferred strategy.

These results suggest that there is the potential for consensus with regard to the multi-pollutant approach for reduction mercury emissions from coal-fired power plants. The critical issue that must be addressed to optimize this strategy is legal feasibility. All three groups rate the multi-pollutant regulation approach poorly with respect to this evaluation criterion, which is not surprising given that there is currently no legal mechanism available to implement this strategy. This is not an impossible barrier to overcome, though, as there is broad support for this strategy. In fact, all three groups rate this strategy high in terms of political feasibility, suggesting that they believe no significant political barriers exist that would hinder legalization and implementation of this strategy. It is clear that there is an opportunity for strategy optimization here, given the broad agreement on this approach.

Optimization of the Multi-Pollutant Strategy

Adoption of a multi-pollutant regulation strategy would result in the EPA establishing and promulgating emission standards for multiple pollutants (e.g. NO_x, CO_2, SO_2, and Hg) at one time. It is evident that at this broad conceptual level there is support for such a strategy across the stakeholder groups. Yet there is still the major issue of what mechanisms would be employed to achieve the strategy. For instance, the four pollutants to be addressed with this strategy could be reduced using the risk-based standard (the utility industry group's most preferred strategy) or the MACT numerical standard (the environmental and government agency groups' most preferred strategy next to the multi-pollutant strategy).

The fact that at present the details of a multi-pollutant strategy have not be identified means that while there is currently support for the concept, one or more of the stakeholders might reject the specifics of the strategy once they are defined. Thus stakeholder acceptance, which on the surface appears strong for the multi-pollutant regulation approach, is likely contingent on acceptable mechanisms being selected in realizing this strategy in its fully developed form.

Despite this, the fact that the details of a multi-pollutant strategy have yet to be defined also represents an opportunity. It provides an opportunity to bring the key stakeholders together to work collaboratively in fleshing out the elements of a multi-pollutant strategy. It is clear from the interviews and survey responses that the stakeholder groups possess certain perceptions of each other that may not be valid. For instance, the groups tend to view themselves as being further apart than they really are and fail to see the large extent of common ground that already exists. Valid or not, the perceptions which the stakeholders groups have of one another are barriers to achieving a mutually acceptable solution. Instead, it is more likely to result in strategic posturing and positional bargaining. A decision-making process designed to bring these groups into closer contact with one another, early in the multi-pollutant strategy development process, might well assist in reshaping perceptions and reduce positional bargaining practices.

The study findings could assist in the formulation of one or more versions of a more fully elaborated multi-pollutant strategy. For instance, the information regarding which criteria the respective stakeholders value most would aid in the formulation of strategy options that focus on interests rather than positions and the development of a strategy(ies) that offers mutual gains for the stakeholders (Fisher et al. 1991; Susskind et al. 2000).

The study findings also point to issues that will require a lot of work to resolve and which could be potential stumbling blocks in negotiating a multi-pollutant strategy that is mutually acceptable to all. This would allow the negotiation process to dedicate the degree of effort and resources necessary to resolve such key contentious issues. The issue of scientific defensibility is one such issue. All three groups place a lot of importance on a mercury emission strategy being scientifically defendable. Yet the significant differences in how they evaluated the same strategies on this criterion suggests that they have quite different conceptions of what scientific defensibility means.

AHP AND GROUP DECISION MAKING

During the course of this study, some strengths and weaknesses of the AHP were observed. An obvious strength of the method is that it enabled the collection of all the relevant elements of the problem into one model that can be interactively manipulated to reveal interdependencies and potential consequences. The AHP's reliance on pairwise comparisons add to this strength by forcing the stakeholders to articulate the relative importance of the evaluation criteria and then to decide the relative contributions of the alternatives to the criteria. This strength was magnified even more in this study with the in-depth interviews that were conducting prior to structuring the hierarchy, which resulted in the inclusion of accurate decision elements. The stakeholders now have an overall model of the mercury reduction strategy problem, which structures the problem and enables them to see all the factors along with their relative importance and consequences.

Another strength of the AHP is the sophistication and user-friendliness of the Expert Choice software. The AHP is based on a complex mathematical calculation that uses the eigenvalue method to produce a vector of composite weights that serve as ratings of decision elements in achieving the most general objective of the overall problem (Saaty 1980). Having this computational algorithm available in a computer software program reduces the time involved in addressing multi-criteria decision problems and reduces the complexity of the process to enable AHP novices to employ this valuable method.

Expert Choice not only performs the necessary calculations quickly, but also includes a feature that requires the AHP user to make fewer pairwise comparisons, thus increasing the speed of the hierarchy evaluation process. By using this feature, only 53 pairwise comparisons were required to calculate strategy priorities in this study, compared to the 405 comparisons that would have been required otherwise. The disadvantage of using this feature, though, is that the Expert Choice user is not able to take advantage of its inconsistency measure, which indicates when a stakeholder has made an inconsistent judgment. Also, the use of this feature results in less data, which decreases the validity of the results.

SUGGESTIONS FOR FURTHER STUDY

It is evident that, at a broad conceptual level, there is support for the multi-pollutant strategy across the stakeholder groups. Yet there is still the major issue of what mechanisms would be employed to achieve the strategy. Further work should be done to convene the key stakeholders and investigate the elements of a multi-pollutant strategy collaboratively.

Another area that requires more research involves the evaluation criteria. As mentioned above, some of the pairwise comparison results suggest that the stakeholders may use different definitions to describe some of the criteria. Although concise definitions were provided to the survey respondents, the potential for personal interpretation was still a risk. Therefore, research that identifies mutually agreed upon conditions that must be met in order to satisfy each criterion is needed.

A larger sample size would also be desirable in performing a similar study. For the purposes of this study, and considering the length of the survey and the number of questions asked, the response rate met the researchers expectations. A larger response rate would have increased the validity of the study, though, and is therefore desirable.

One possibility for achieving more study participants is to convene each stakeholder group for a meeting, preferably in conjunction with an event at which they are already attending. This way, you have access to a captive audience that does not have to make special arrangements or major time commitments to participate. Also, this would enable the researcher to run a "live" AHP session, where the decision hierarchy is developed as a group and judgments are made and entered into the Expert Choice software using a computer touchpad. Using this approach may also enable the researcher to acquire complete sets of pairwise comparisons, as opposed to the minimal number gathered for this study.

APPENDICES

APPENDIX I

TOXICOLOGICAL ASPECTS OF MERCURY

ENVIRONMENTAL CHEMISTRY OF MERCURY

Mercury is a naturally occurring elemental metal that has three stable oxidation states: Hg^0, Hg^{+1}, and Hg^{+2}, each of which form complexes with many different elements – resulting in numerous inorganic and organic mercury compounds (Nriagu, 1979). Because the speciation of mercury and its chemical and physical form determine its fate, transport, toxicity characteristics, and chemical behavior, it is important that these parameters are taken into account when studying the mercury cycle and its impact on human health and the environment. (Constantinou et al. 1995; Nriagu 1979).

Metallic mercury is the non-polar, elemental form of mercury. At ambient temperatures and pressures Hg^0 is a heavy, shiny, silvery-white liquid metal; the only metal that is a liquid at room temperature. In its liquid form, mercury is reactive in the environment, and readily converts to inorganic mercury. Metallic, or elemental, mercury is water insoluble and extremely volatile under ambient conditions, easily vaporizing into a colorless, odorless gas (EPA 1997b). Because of its high vapor pressure, exposure to elemental mercury is primarily via inhalation. In the U.S., dental amalgams are the major source of exposure, containing 43-54percent elemental mercury (ATSDR, 1997). Recent studies conducted by Health Canada (1995) have indicated that dental amalgams may be responsible for 37 percent of the total mercury intake in individuals with mercury-containing fillings.

Elemental mercury can react with other elements to form inorganic mercurous (Hg^{+1}) and mercuric (Hg^{+2}) salts, such as mercuric chloride ($HgCl_2$) and mercurous sulfate, and Cinnabar (HgS), the most abundant mercury-bearing mineral on the Earth's surface. Of the two inorganic species, the divalent form is most often found in the environment and is of more biological and environmental importance than the mercurous species (Nriagu, J.O. 1979).

While the majority of mercury released into the environment is in the inorganic form, biological processes convert inorganic mercury into organic mercury. Once mercury is available in an aquatic environment, it can be methylated (addition of a CH_3 group). Methylation of mercury occurs abiotically in suspended bottom sediments and biotically by sulfate-reducing bacteria as part of an intracellular process (Nriagu, 1979).

The mercury compounds that are most often found in the environment are the mercuric salts mercuric chloride ($HgCl_2$), Cinnabar (HgS), and mercuric hydroxide $Hg(OH)_2$; the methylmercury compounds methylmercuic chloride (CH_3HgOH) and methylmercuric hydroxide (CH_3HgCl); and, in small fractions, dimethylmercury and phenylmercury (EPA 1997b). According to the National Research Council (2000), the chemical species of mercury that are of toxicological importance (and, therefore, significant for this thesis and discussed in detail below) include the inorganic forms metallic (Hg^0), mercurous

(Hg^{+1}), and mercuric (Hg^{+2}) mercury, and the organic compounds methylmercury (MeHg), dimethylmercury, and ethylmercury.

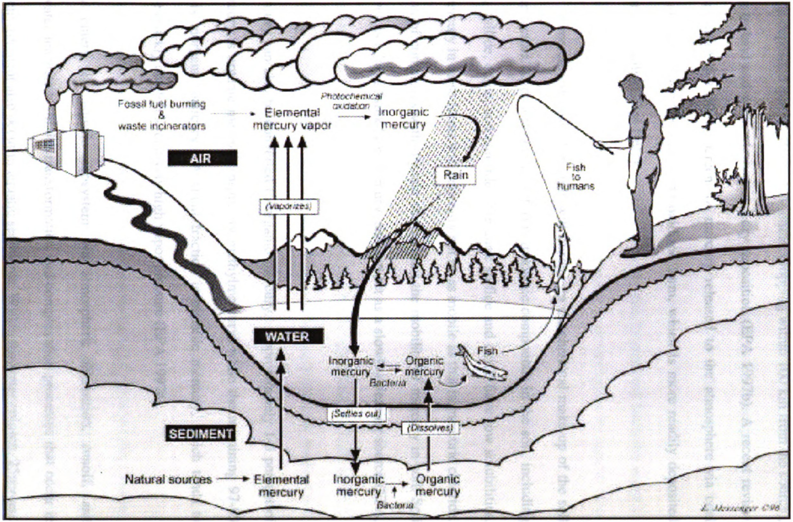
MERCURY FATE AND TRANSPORT

Mercury is a naturally occurring element that, like all elements, exists in the same quantities now as when the Earth was first formed. Geologically bound mercury is mobilized via natural processes or human activities, which begin its cycling in the environment (Nriagu 1979). (See Mercury Sources section below for more information).

Whether by natural or human-influence, once mercury is mobilized it cycles to the atmosphere where it is transformed and transported, deposited from the air to aquatic or terrestrial environments, and sorbed onto soil or sediment particles where the cycle repeats itself (revolatilization from land and surface water to the atmosphere) (see Figure 25.) Although the movement and distribution of mercury can be soundly described, the detailed behaviors of mercury in the environment remain a point of debate.

About half of total anthropogenic mercury emissions enter the global atmospheric cycle (Mason et al., 1994), while the remainder is transported a lesser distance and removed through local or regional cycles (EPA 1997b). Elemental mercury partitions strongly to air and is more abundant in the atmosphere than the oxidized forms (e.g., mercuric and methylmercury), which constitute less than two percent of the total atmospheric concentrations. (Watras and Huckabee, 1994; Fitzgerald, 1986, 1989). Because of its insolubility in water, elemental mercury resonates in the atmosphere for about one year

Figure 25: The mercury cycle



and, hence, can be widely dispersed and transported long distances. In contrast oxidized mercury is deposited quickly (hours to months, dropping within 100 km from the source), returning to land and water via wet and dry deposition (EPA 1997b). A recent review paper suggested that 50-85 percent of mercury released to the atmosphere via coal combustion and incineration is in the oxidized form, which is more readily deposited locally or regionally (Carpi 1997).

The fate of mercury deposited in soils will depend on the chemical make-up of the soil and other factors. Typically, mercury forms inorganic compounds in the soil, including mercuric sulfide, oxide, and chloride. Mercuric sulfide and oxide have low solubilities, so the mercury in these forms will generally not be as mobile as that in mercuric chloride. Formation of complexes with organic matter limit the mobility of mercury in soil. Soil thus serves as a large "sink" for mercury, and can act as a slowly releasing source (EPA, 1997a).

Soil mercury can also be converted to organic mercury. Approximately 1-3 percent of soil mercury is organic mercury (primarily methylmercury) while the remaining 97-99 percent is inorganic mercury. A small fraction is metallic mercury, which tends to volatilize quickly due to its relatively high vapor pressure (EPA 1997a).

Mercury enters the aquatic ecosystem via atmospheric deposition, runoff, and groundwater leachate. Similar transformation and complexation processes that occur in the soil environment also occur in aquatic sediments. Within the water column, 25percent or less of the available mercury is organic (methyl) mercury (EPA 1997a). The majority of mercury in the water column is dissolved inorganic mercury, or inorganic mercury complexed with organic material. Although organic mercury may makeup a very small percentage of total mercury in the aquatic environment, it can bioaccumulate to high concentrations in certain biota. The majority of mercury absorbed by biota is organic (methylated) (EPA 1997a). Once in water, mercury can be removed from the water by deposition to sediments, volatilization to the atmosphere, or absorption by aquatic biota. As with many other chemicals, mercury cycling in aquatic systems is dynamic, so that once released by human activity, it is quite difficult to effectively remediate.

Scientists now believe that atmospheric deposition is responsible for the bulk of mercury loading to terrestrial and aquatic ecosystems. A study examining mercury in sediments found that yearly atmospheric deposition of mercury has increased from 3.7 to 12.5 ug/ square meter since 1825 in northern Wisconsin and Minnesota (Enstrom D.R. and E.B. Swain 1997). Whole blood levels of mercury in loons follow an increasing gradient from West to East across North America (Evers et. al. 1998). This trend is consistent with predicted atmospheric deposition patterns found by U.S. EPA using a computer model that simulates regional mercury transport and deposition (EPA 1997a).

Another study indicated that northern Michigan receives half of the precipitation mercury loading that southern Michigan receives (Hoyer et al. 1995). The data suggests that the mercury deposited originates at least in part regionally; proximity to known anthropogenic sources of mercury to the atmosphere was correlated with mercury loading to the study sites. A recent paper predicted that approximately 83 percent of atmospheric loadings of mercury to the Great Lakes were due to anthropogenic emissions (Shannon, J.D. and E.C. Voldner 1995). Other researchers have looked at the response time of the environment to reduced mercury emissions from human activity. A paper estimated that elimination of the entire anthropogenic load in the oceans and atmosphere would take fifteen to twenty years after a complete cessation of direct and indirect anthropogenic mercury emissions (Mason et al. 1994).

During the 1970's, the mercury burden in Great Lakes herring gull eggs was spatially variable; highest levels were found in Lake Ontario and Lake Superior. Spatial variation may have indicated variation in loading to the lakes. The early 1990's data, however, is characterized by more evenly distributed mercury burdens distributed across the Great Lakes. This is thought to be the result of a shift from point source loading of mercury to diffuse non-point source loading (especially atmospheric deposition) (Koster et al. 1996).

A recent review used a weight-of-evidence approach to assess multiple studies relating to long-range atmospheric transport of naturally and anthropogenically derived mercury. The following conclusions were reached (Koster et al. 1996):

- Approximately 5000 tons of mercury are released to the environment annually, 4000 of this can be attributed to human activities.

- Approximately 3000 tons of the total yearly anthropogenic mercury loading to the atmosphere is transported over several thousand kilometers due to atmospheric circulation patterns.
- Mercury in the sediments of remote lakes is primarily derived from recent airborne deposition rather than re-mobilization.
- Atmospheric deposition to remote aquatic and terrestrial systems is resulting in bioaccumulation of mercury in fish and wildlife.
- Acid precipitation can increase the bioaccumulative properties of mercury.

The evidence demonstrates that anthropogenically derived mercury levels have increased since the industrial period, and this mercury is subject to long-range transport and deposition far from the original source as a result of atmospheric circulation patterns (Jackson, T.A. 1997). Other authors reached the same conclusion in another recent review (Fitzgerald, W.F. 1997).

SOURCES OF MERCURY

The U.S. EPA defines three major categories of mercury emissions: natural, anthropogenic, and re-emitted mercury emissions (EPA 1997a). Re- emitted mercury includes transfer of previously deposited mercury (released naturally or anthropogenically) to the atmosphere via biological and geological processes. The fluxes of re-emitted mercury to the atmosphere are not clearly established; more study in this area will be required to document and assess this potential secondary source, which can contribute to long-term cycling of mercury in the environment.

Natural mercury emissions result from the release of mercury from geologic sources via natural weathering processes, volcanoes and volatilization from soils, aquatic environments, and vegetation to the atmosphere, and other geothermal activities (Nriagu, J.O. 1979). A common mercury-containing mineral is cinnabar (mercuric sulfide); most commercial production of mercury has involved this mineral. Major mercury ore-bearing zones are found in the circum-Pacific region and in the Himalayan and Mediterranean regions. Major mercury mines historically have operated in California, Spain, Yugoslavia, and Peru, although no primary mercury mining is currently done in the U.S. (Nriagu, J.O. 1979). Natural emissions are thought to be primarily n the elemental mercury form (EPA 1997b).

Anthropogenic mercury emissions result from the release of geologically bound mercury to the environment as a consequence of human activities. Although a great deal of uncertainty remains, it has become increasingly evident that antrhropogenic emissions of mercury rival or exceed natural inputs. According to EPA's Mercury Report to Congress (1997b), the amount of mercury mobilized and released into the environment has increased by a factor of between two and five since the beginning of the industrial age. Current estimates suggest that 50-75 percent of the total yearly input of mercury into the atmosphere from all sources is the result of anthropogenic releases. A recent paper reported estimates of global anthropogenic mercury emissions reaching as high as 71 percent of total mercury emissions if re-emitted anthropogenic mercury is considered in the estimates (Jackson 1997).

U.S. EPA divides anthropogenic sources into two main components: point source, and non-point source or area source (EPA 1997a). Point source emissions are sources that are readily identifiable, such as the smokestack on an industrial plant. Non-point sources are more difficult to define and locate, consisting of a large number of small, really dispersed sources which alone may emit smaller quantities of mercury, but when considered together become significant. Non-point mercury pollution can include mercury released from paints, dental preparations, and fluorescent lamp disposal, among a multitude of other potential sources. Municipal landfills can become aggregate sites of smaller sources.

Major categories of anthropogenic point source emissions include combustion, manufacturing, and miscellaneous sources (EPA 1997a). In these processes, mercury is released from a stack in either gaseous or particulate forms. The speciation of mercury emissions is thought to depend on the type of fuel used, flue gas cleaning methods, and the operating temperature. Although methods for mercury speciation of stack emissions are being refined, and there is still controversy in this field, gaseous mercury emissions are thought to include both elemental and oxidized chemical forms, while particulate mercury emissions are thought to be composed primarily of oxidized compounds (ATSDR 1999).

In general, mercury emissions from combustion processes can either be measured directly or estimated based on knowledge of the mercury level in the material burned, and the amount of material burned. This latter approach is more common, but also generally entails more uncertainties. Major sources of U.S. mercury emissions in total amounts and percentages are given in Table 12.

Table 12: Major sources of anthropogenic mercury releases in the U.S. (EPA 1997a)

Mercury Source	1994-1995 (tons/year)	Percent of Total Inventory
COMBUSTION SOURCES		
Coal-fired Utility Plants	51.6	32.6
Oil-fired Utility Plants	0.2	0.1
Coal-fired Commercial/Industrial Boilers	20.7	13.1
Oil-fired Commercial/Industrial Boilers	7.7	4.9
Municipal Waste Combustion	29.6	18.7
Medical Waste Incineration	16.0	10.1
Hazardous Waste Combustors	7.1	4.4
Sewage Sludge Incinerators	1	0.6
Miscellaneous Combustion Sources	3.8	2.4
Total Combustion Sources	***137.7***	***86.9***
MANUFACTURING SOURCES		
Chlor-alkali	7.1	4.5
Portland Cement	4.8	3.1
Pulp and Paper Manufacturing	1.9	1.2
Instruments Manufacturing	0.5	0.3
Miscellaneous Manufacturing Sources	1.3	0.9
Total Manufacturing Sources	***15.6***	***10.0***
AREA SOURCES		
Lamp Breakage	1.5	1.0
Laboratory Use	1.1	0.7
Dental Preparations	0.7	0.4
Landfills	0.08	0.05
Total Area Sources	*3.4*	2.2
OTHER SOURCES		
Geothermal Power	1.4	0.9
Total All Sources	158	100

Because of the relatively volatile nature of mercury and the particular sources that release it, a much larger fraction of total releases to the environment consists of releases to the air, rather than direct discharges to water or land. The total annual estimate for all anthropogenic mercury emissions to the air in the U.S. for 1994-95 was 158 tons (316,000 pounds) (EPA 1997a). While this estimate has a number of uncertainties, it is likely low, due to lack of full accounting for mercury use at chlor-alkali plants (see below), and possibly other poorly-characterized sources (i.e. mobile source emissions). The largest source of mercury emissions on a national level are coal-fired power plants (32.6 percent), municipal waste incinerators (18.7 percent), Commercial and industrial boilers (18 percent) and medical waste incinerators (10.1 percent) (EPA 1997a). Incinerators emit mercury when they burn wastes containing mercury. For medical waste incinerators, waste mercury comes from medical devices like thermometers and blood pressure cuffs. For municipal waste incinerators, mercury is in discarded appliances like fluorescent lights, lamps, and thermostats.

Coal-fired power plants produce mercury by burning coal; the coal contains trace amounts of mercury that are released during combustion. These plants are the single largest source of mercury pollution in the U.S., and are responsible for 33 percent of the total mercury emissions from all sources (EPA 1999d). In 1990, coal-fired power plants emitted 46 tons of mercury, by 1994 emissions jumped another 10 percent to 51 tons, and are expected to climb another 33 percent over 1990 levels, by 2010 (EPA 1998).

In addition to these industries, it is likely that mercury-cell chlor-alkali facilities (plants that manufacture caustic soda and chlorine) are one of the top mercury emitters nationally. Although these plants are estimated to produce 4.5 percent of the nation's annual mercury emissions, that estimate is certain to be very low. These plants use enormous, heated baths of mercury in their manufacturing processes. In 1995 they used in aggregate 165 tons of mercury – and reported emitting only 7.1 tons (EPA 1997a). Because these plants do not incorporate mercury into their products or release mercury in byproducts, they cannot account for the 100-plus tons they used but did not emit. Although these plants cut their usage to 104 tons by 1998, the missing mercury, if emitted into the air, would make the industry – only 10 plants – the largest source in the nation.

MERCURY EXPOSURE AND THREATS TO HUMAN HEALTH

Methylmercury and other forms of organic or inorganic Hg are poisonous to many living organisms in both aquatic and terrestrial ecosystems, and there are many ways that a person can be exposed to mercury through the environment, including (NIOSH 1973):

- inhalation of elemental mercury vapors in ambient air at the work place (dental, health services, chemical, and other industries that use mercury),
- ingestion of drinking water and food contaminated with elemental mercury or methylmercury,
- release of elemental mercury during dental and medical treatments,
- skin contact during use of mercury in the work place, and
- exposure to above background levels in air, soil and water near hazardous waste sites.

Although exposure to mercury can cause many health problems, exposure does not necessarily mean that adverse health effects will result. Health effects depend upon the amount of exposure, the form of mercury, and the route of exposure. For the general U.S. population, dietary intake is the dominant pathway for human exposure to mercury, with fish, marine mammals, and crustaceans that contain methylmercuy in their tissues being the primary sources. (ATSDR 1999; NRC 2000). Another leading contributor to mercury body burden in humans is inhalation of elemental mercury released from dental amalgams (ATSDR 1997). Recent studies conducted by Health Canada (1995) indicate that dental amalgams may be responsible for 37 percent of the total mercury intake in individuals with mercury-containing fillings. Because of the variability in fish consumption habits and number of amalgam fillings among the general population, exposure rates are difficult to measure and, therefore, a great deal of uncertainty rests on these figures.

When exposed to elemental mercury, toxic effects include effects on the central nervous system (i.e., cognitive, personality, sensory, and motor disturbance), increased blood pressure, tremors, rashes, and renal damage. Inhibition of the immune system may also result. Fortunately, mercury is rarely found in the environment as the pure, confined liquid metal, but rather in forms that generally have much lower vapor pressures than elemental mercury (Nriagu 1979).

Due to the high water solubility of some forms of inorganic mercury (e.g., mercuric chloride), the kidneys, which are primary targets for organ damage, process this form. Toxic effects include renal failure, gastrointestinal disturbance, rashes, blisters and ulcers to lips and tongue, weakness and muscle twitching, and elevated blood pressure. Because of its ionic charge, mercuric Hg does not readily penetrate the blood-brain barrier or the placenta (NRC 2000).

Fish consumption advisories have been developed and issued to warn people about the health risks of consuming merthylmercury-contaminated fish, shellfish, and wildlife, and provide guidance as to the amount of fish and wildlife that can be safely consumed by adults, pregnant women, nursing mothers, and children. Although advisories are issued for fish that are contaminated by a variety of chemicals, including polychlorobiphenyls (PCBs), dioxins, chlordane, and DDT, mercury contamination is the most frequent basis for fish advisories (EPA 2000). As of July 2000, 40 states and one territory (American Samoa) had issued fish consumption advisories for mercury. Of those states, 13 have issued state-wide advisories, covering every inland lake and stream; the remaining 27 states issued advisories for more than 1,900 specific water bodies (EPA 2000). Table 13 gives ranges of methylmercury concentrations in certain types of sport fish.

Table 13: Range of Mean Mercury Concentrations for Major Fish Species

Fish	Mercury Concentration (ppm)
Largemouth bass	.001-8.94
Smallmouth bass	.008-3.34
Walleye	.008-3
Northern Pike	.10-4.4
Channel catfish	.001-2.57
Bluegill sunfish	.001-1.68
Common carp	.001-1.8
White sucker	.002-1.71
Yellow perch	.01-2.14

Fish consumption advisories are based on various types of data. A "safe" intake rate for a given contaminant is defined based on toxicological studies on animals and epidemiological data on the effects of given contaminants on humans. Federal Government agencies (e.g., EPA, FDA, ATSDR) issue recommendations on these intake rates as part of their risk assessment programs. States collect data on the levels of individual contaminants in fish in various waters. Selected water bodies are sampled in efforts to obtain data that best represents all the state's waters. It is important to know how many water bodies were sampled in assessing the extent of mercury contamination across a given state.

State officials then use assumed consumption rates (see Table 13) and, based on fish tissue concentrations, issue advisories on the amount of fish that can be safely consumed for particular water bodies. About 85 percent of adults in the US consume fish at least once a month, about 40 percent of adults consume fish once a week, and 1 to 2 percent consume fish almost daily (EPA 2000). Each state government has the authority to decide which contaminants and fish species to issue advisories for, how strict those advisories are, and whether to issue more strict advisories to sensitive populations such as women of childbearing age, children, and high fish-consuming communities. Additional risk assessment factors can also be factored in. A simple formula for the calculation is as follows:

$$\text{“Safe” consumption rate for a given fish} = \frac{\text{“Safe” intake rate for contaminant}}{\text{Concentration of the contaminant in fish}}$$

Calculation of the "safe" intake rate for the contaminant is a key piece of this equation, and has recently been under debate. The EPA and the Agency for Toxic Substances and Disease Registry (ATSDR) have followed different approaches and utilized different core studies in developing their safe intake level for mercury.

EPA terms its "safe" level of ingestion rate for a given contaminant the "reference dose" (RfD). The current RfD for methylmercury is $1x10^{-4}$ mg/kg body weight/day, or 0.1 microgram (ug) /kg -day. The RfD is based on epidemiological studies of a poisoning episode in Iraq in the 1970s, in which consumption of bread prepared from methylmercury-contaminated grain lead to the deaths of hundreds of people. Based on estimates of the varying degree of mercury exposure, researchers have estimated the lowest levels at which mercury-related effects occurred.

The RfD is calculated using the following formula:

$$RfD = \frac{\text{Benchmark Dose}}{\text{UF x MF}}$$

where the benchmark dose is based on observation of effects at lower exposure levels, MF is modifying factor, and UF is uncertainty factor. The purpose of the uncertainty factor is to account for population variability, including variations in the biological half-life of methylmercury, variations in mercury hair:blood ratios, the lack of two-generation reproductive studies, and lack of long-term effects data.

ATSDR calls its "safe" level of ingestion for a given contaminant the "minimal risk level" (MRL). The agency recently released a final Toxicological Profile for Mercury that contained a revised MRL for methylmercury of $3.0x10^{-4}$ mg/ kg body weight/day, or 0.3 microgram/kg-day (ATSDR 1999). The MRL is based on statistical analysis of data collected in the Seychelles Child Development Study, an ongoing study in the Republic of Seychelles in the South Pacific. The researchers have investigated neurodevelopmental impacts on children exposed to mercury prenatally. In contrast to ongoing work in the Faroe Islands, the only mercury-related impairment found thus far in the Seychelles studies was a decreased activity level in boys.

The MRL is calculated using the following formula:

$$MRL = \frac{NOAEL}{UF}$$

where the NOAEL is the "no observed adverse effect level", based on the median hair concentration of mercury in the highest 20 percent exposure levels (15.3 parts per million in maternal hair), and an aggregate uncertainty factor of 4.5 was used to account for variability discussed above.

State health agencies have the discretion in determining which risk level value they will use in establishing its fish consumption advisories. ATSDR noted in releasing its Toxicological Profile (1999) that its new MRL should not be used to set advisories. Based on the current risk values, the EPA RfD will produce fish consumption advisories that will be more restrictive, and will possibly be more protective of human health, than the ATSDR MRL if it were used

If any states decided to use the new ATSDR MRL in determination of advisories, a simple comparison shows the effects this would have compared to application of the current EPA level. The following table shows the mercury fish tissue concentrations that would be tolerable given different fish consumption rates, for a 50 kg (110 pound) person (see Table 14).

Table 14: "Safe" Methylmercury concentrations in fish, based on EPA and ATSDR risk approaches, and different consumption rates*

Fish Consumption Rate	"Safe" Hg Concentration in Fish Based on Two Risk Approaches	
(g/d)	EPA (ug/g)	ATSDR (ug/g)
10	0.50	1.50
20	0.25	0.75
30	0.17	0.50
50	0.10	0.30
100	0.05	0.15
150	0.03	0.10
300	0.02	0.05

*: Assumes 50 kg (110 lb) person.

Table 14 shows that the three-fold higher intake threshold set by ATSDR would translate into three-fold higher permissible fish tissue levels, for given consumption rates. This also illustrates the importance of the consumption rates assumed by the states in establishing their advisories.

The release of the ATSDR Toxicological Profile for Mercury lead to some uncertainty among states regarding the appropriate risk approach to use, even though the agency had stated that it does not recommend that states use the revised minimal risk level in setting advisories. One year after the ATSDR report was released, the National Research Council convened the Committee on Toxicological Effects of Methylmercury to evaluate old and new data on health effects and risk guidelines. On the basis of body of evidence from human and animal studies, the Committee concluded that EPA's RfD for MeHg, 0.1

ug/kg/day, is a scientifically justifiable level for the protection of public health and should be used by states for the development of fish consumption advisories (NRC 2000).

The U.S. Food and Drug Administration (FDA), which issues consumption advice for commercial marine fish, also has established an action level for methymercury of 1 ppm, Because shark, swordfish, king mackerel, and tilefish have been found to contain high levels of MeHg in their tissue, the FDA has warned pregnant women and women of childbearing age against consumption of these species (FDA 2001). As shown in Table 15, methylmercury levels in the top 10 species of fish, which make up approximately 80 percent of the seafood market including canned tuna, shrimp, pollock, salmon, cod, catfish, clams, flatfish, crabs and scallops (FDA 1994), contain less than .21 ppm. Because few people eat more than 2.2 pounds of these species per week, consumption level warnings are considered unnecessary (FDA 1996).

Table 15: Methylmercury Concentrations in the top 10 types of fish consumed by the US population (EPA 1997b)

Fish	Mercury Concentration (ppm)
Tuna	.206
Shrimp	.047
Pollack	.150
Salmon	.035
Cod	.121
Catfish	.020-.160
Clam	.023
Flounder	.092
Crab	.177
Scallop	.042

Because of its organic, lipophilic nature, organic mercury is the most toxic mercury form, and methyl mercury is the form of organic mercury that is of greatest general concern to ecological and human health (ATSDR, 1999; NRC. 2000). A spectrum of adverse health effects were observed following exposure to MeHg, with the severity depending on the magnitude of exposure and the susceptibility of the individual being exposed. Populations at greater risk due to unusually high exposure include recreational and subsistence anglers and Native American populations who routinely consume large amounts of fish (ATSDR 1999). Susceptible populations, i.e., populations that will exhibit a different or enhanced response to mercury than will the majority of people exposed to the same level, include the elderly, people with pre-existing disease, and the younges of the population (the unborn and children) because of their immature and developing organs. Factors that influence a persons level of susceptibitliy include genetic makeup, developmental stage, age, health and nutritional status, and substance exposure history (e.g., smoking) (ATSDR 1999).

The developing fetus is considered much more sensitive to injury by MeHg exposure than adults because of the potential for interference with the growth and migrations of neurons, leading to irreversible damage to the fetal central nervous system (EPA 1997c). Ingested methylmercury is almost completely absorbed into the blood and distributed to all tissues (including the brain); it also readily passes through the placenta to the fetus and fetal brain (EPA 1997c). Infants exposed to acute high doses of MeHg in utero were born with sever disabilities, such as mental retardation, seizure disorders, cerebral palsy, blindness, and deafness (see acute exposure studies section below). Prenatal low dose exposure, resulting from chronic maternal consumption of contaminated fish, produce infants that appear normal during the first few months of life but later display deficits in subtle neurological end points (i.e., IQ deficits, abnormal muscle tone, decrements in motor function, attention, and visuospatial performance). (see chronic exposure studies section below.) The EPA estimates that about seven percent of women of childbearing age are exposed to MeHg at levels exceeding the RfD of 0.1 microgram (ug)/kg/day, and about one percent of women have MeHg exposures three to four times that level (EPA 2000).

The National Research Council July 2000 report completed a review of the latest scientific evidence regarding the health effects of methylmercury. This literature review indicates that MeHg causes a wide range of adverse effects in multiple organ systems throughout the life span of exposed humans and wildlife. Although studies have been conducted on the carcinogenicity, genotoxicity, immunotoxicity, renal toxicity, and hematological and reproductive effects of MeHg, the endpoints that are the most widely studied relate to neurotoxic effects.

The database on neurodevelopmental effects is extensive and includes studies documenting neurological dysfunction and developmental abnormalities that occur following both acute and chronic mercury exposure (NRC, 2000).

Residents living near Minamata Bay, Japan were exposed to high doses of MeHg in the 1950's from ingesting fish contaminated with methylmercury from chemical plant effluent (Watanabe, C. and H. Satoh, 1996). This incident brought to light the severe neurological dysfunction that can result from exposure to high doses of MeHg, particularly when it occurs prenatally. Exposed children expressed mental retardation, primitive reflexes, cerebellar ataxia (loss of coordination), disturbances in physical growth, dysarthria (speech disorder), limb deformities, hyperkinesis (hyperactivity), hypersalivation, seizures, strabismus (misaligned eyes), and pyramidal signs (difficulty instigating, terminating, and altering movement). In addition, the incidence of cerebral palsy among children identifies as suffering from congenital Minamata disease was nine percent, which is above the national incidence (NRC, 2000). According to one estimate, the mean hair Hg concentration of mothers who gave birth to infants with congenital Minamata disease patients was approximately 41 ppm (Akagi et al. 1998); significantly higher than hair Hg concentrations of unexposed individuals, which ranges from .2 ug/g to .8 ug/g (NRC 2000).

There is considerable scientific uncertainty surrounding the data gathered from the Minamata poisoning incident because samples were not taken until the effects of the exposure began to surface, which occurred five to eight years after the births. In Japan, it is an old custom that the umbilical cords of newly-born children are preserved by their parents, so 151 archived umbilical-cord tissue were sampled dating from 1950 to 1969. Results from those tests confirmed exposure increases during this period (Harada et al. 1999).

Another mercury poisoning epidemic occurred in Iraq in the early 1970s following the consumption of wheat treated with a methylmercury containing fungicide. This incident involved higher, more acute exposures that those experienced in Minamata Bay (NRC, 2000). Effects included severe sensory impairments, general paralysis, hyperactive reflexes, crebral palsy, and impaired mental development, severe neurotoxicity, and death (Watanabe, C. and H. Satoh, 1996; NRC, 2000). Maximum maternal-hair mercury concentrations during the time when the study child was in utero served as the index for fetal exposure and ranged from 1 to 674 ppm (Marsh et al. 1987).

CHRONIC EXPOSURE STUDIES

Historically, most toxicological investigations centered on acute exposures. More recent emphasis in environmental toxicology is on chronic, low dose exposures, since most exposures affecting the general population are chronic and low-dose in nature, with diet (fish consumption) as the primary route. A number of epidemiological studies have been carried out on populations exposed chronically to low doses of MeHg. The table below summarizes some key aspects of those studies. Endpoints that have been assessed include status on neurological examination, age at achievement of developmental milestones, infant and preschool development, childhood development, sensory, and neurophysiological functions.

Table 16: Summary of epidemiological mercury toxicity studies

Study Site	Cohort Size	Exposure Biomarker	MeHg/Total Hg Concentration	Age Assessed	# of Children Assessed	End Point	Reference
Amazon	351	Child Hair	Mean, 11.0ppm; 80% > 10ppm	7-12 years	354	Motor function, attention, visual-spatial function, and short-term memory	Grandjean et al. 1999
Results: Children's hair Hg concentrations were significantly associated with decreased scores on all neurobehavioral tests.							
Northern Quebec	247	Maternal hair	Mean, 6ppm; 6% > 20ppm	12-30 months	234	Physical assessment, neurological exam, and developmental screening (DDST)	McKeown-Eyssen et al. 1983
Results: The only findings significantly associated with prenatal MeHg exposure, either before or after adjusting for confounding factors, were abnormalities of muscle tone or reflexes in boys. The risk of an abnormality of tone or reflexes increased seven times with each 10 ppm increase in maternal-hair Hg. No significant association was found between DDST scores and maternal-hair Hg concentrations either before or after adjustment for confounding variables.							
Mancora Peru	369	Maternal hair	Geometric mean, 7.05 ppm; geometric SD, 2.1; range, .9 - 28.5 pm	?	194	Neurological exam and developmental milestones	Marsh et al. 1995
Results: No neurological end point was significantly associated with either mean or peak maternal-hair Hg concentration. No significant association was found between maternal-hair Hg concentrations and the ages at which children sat, stood, walked, or talked. Several elements of the study are not described. The rates of developmental retardation were substantial, especially with regard to speech (13 of 131)							
Sey-chelles Islands (pilot)	804	Maternal hair	Median, 6.6 ppm; mean, 6.1 ppm; range, .6-36.4 ppm	5-109 weeks	789	Neurological exam, DDST-R	Myers et al. 1995a
			Median, 7.1ppm; range 1–36.4ppm	66 months	217	MSCA, PLS, WJTA:LWI, WJTA:AP	Myers et al. 1995a
Results: For the 5-109 week old neurological exam, no association was evident between maternal-hair Hg concentration and questionable and abnormal neurological exam, limb tone, or deep tendon reflexes results. For 5-109 week olds, no association was found between maternal-hair Hg concentration during pregnancy and DDST-R results when normal and questionable examinations were combined, but when abnormal and questionable results were grouped, high maternal-hair Hg concentrations were significantly associated with poor outcomes. For the 66 month olds, general cognitive index scores yielded by the MSCA declined five points between the lowest maternal-hair Hg concentration (<3 ppm) and the highest (>12 ppm) (p=.024). Similar associations were found on the perceptual-performance scale of the MCSA (p=.013) and the auditory comprehension scale of the PLS (p=.0019).							
Sey-chelles Islands (main)	779	Maternal hair	Median, 5.9 ppm; range .5-26.7 ppm;	6.5 months	712-740	Neurological exam, DDST-R, FTII, visual attention	Myers et al. 1995b
			Mean, 5.8 ppm; range .5-26.7 ppm;	19 months	738	Developmental milestones	Myers et al. 1997; Axtell et al. 1998
			Mean, 5.8 ppm; range .5-26.7 ppm;	19 and 29 months	738 at 19 mon & 73[illegible] at 29 mon	BSID (MDI and PDI)	Davidson et al. 1995
			Prenatal mean, 6.8 ppm; range .5 – 26.7 ppm Postnatal mean, 6.5 ppm; range, .9 – 25.8 ppm	66 months	711	MSCA, B-G, PLS, WJTA:LWI, WJTA:AP, CBCL	Davidson et al. 1998

Study Site	Cohort Size	Exposure Biomarker	MeHg/Total Hg Concentration	Age Assessed	# of Children Assessed	End Point	Reference
Results: The mean age at walking was 10.7 months (SD 1.9) for females and 10.6 months (SD=2.0) for males. The mean age for talking was 10.5 months (SD=2.6) for females and 11.0 months (SD 2.9) for males. No association was found between the ages for achievement of the developmental milestones for walking or talking and prenatal or postnatal exposure to mercury. The NOAL for the cohort at 6.5, 19 and 29 months was 5.8 ppm, and 6.8 ppm at 66 months.							
Faroe Islands	182	Maternal hair Cord blood Cord Serum	Mean, 4.08 ppm; range, .36-16.3 ppm Mean, 20.4 ug/L, range 1.9-102 ug/L Geometric mean, 2.5 ug/L; range 1.7-3.7 ug/L	2 weeks, adjusted for 182 gestational age	182	Neurological exam	Steuerwald et al. 2000
Results: The only relationship of significance was the inverse relationship between neurological optimality scores and cord-whole-blood Hg concentrations (a 10-fold increase in cord blood Hg was associated with the equivalent of a 3-week reduction in gestation age).							
Faroe Islands	1,022	Maternal hair	Geometric mean, 4.3 ppm; range 2.6-7.7 ppm	Maternal interviews "during year one"	583	Developmental milestones	Grandjean et al. 1995
		Cord blood Maternal hair Child hair 12 mon Child hair 7 yrs	Mean, 22.9 ug/L Mean, 4.3 ppm Mean, 1.12 ppm Mean, 2.99 ppm	7 years	917	NES, TPT, WISC-R, B-G, CVLT-C, BNT, NAPMS, CBCL, visual acuity, near contrast sensitivity, otoscopy & tympanometry exam, neurophysiological exam.	Grandjean et al. 1997
Results: A significant inverse association was found between age at achievement and children's hair Hg concentration at 12 months. Nursing was associated with both higher hair Hg concentrations in children at 12 months of age and with more rapid achievement (suggesting the beneficial effects of breast feeding). In children 7 years of age, investigators estimate that a 10-fold increase in cord Hg concentration was associated with neuropsychological delays of 4 to 7 months. Visual acuity, contrast sensitivity, auditory thresholds, and visual-evoked potentials were not significantly associated with prenatal MeHg exposures. Slight delays were observed for brainstem auditory-evoked potential at increased cord-blood Hg concentrations (p=.01-.10).							
French Guiana	Appox. 400	Maternal hair	Median, 6.6 ppm; range, 2.6-17.8 ppm	9 months to 6 years	248	Neurological exam, fingertapping, block design, copying, bead memory	Cordier and Garel 1999
Results: Among children 2 years of age and older, the prevalence of increased reflexes was significantly higher with increased Hg concentrations in maternal hair (stronger in boys than girls).							
New Zealand	10,930 mothers screened, 935 "high" fish consumers and 73 "high" Hg moms identified	Maternal hair	"High" Hg defined 4 yr as >6 ppm; mean 8.3 ppm in "high" Hg group; range, 6-86 ppm; only 16 values >10 ppm	4 years	74; 38 "high" Hg, 36 "low" Hg, including 30 matched pairs	DDST, vision, functional, neurological exam	Kjellstrom et al. 1986
				6 years	237; 57 complete sets of 1 high Hg child with 3 matched controls, and 4 incomplete sets	WISC-R, TOLD, MSCA, CDS, BWRT, KMDAT, PPVT, EBRS (psychological and scholastic tests)	Kjellstrom et al. 1989
Results: On the DDST, 52 percent of the 4 year old children in the high-Hg group had an abnormal or questionable result compared with 17 percent of the children in the control group (p<.05). When the cohort was followed up on at 6 years of age, maternal-hair Hg concentration was associated with poorer scores (p values ranging from .0034 to .074) on full-scale IQ, language development, visual-spatial skills, and gross-motor skills (adjusting for confounders).							
Madeira	149	Maternal hair	Geometric Mean, 9.6 ppm; Range, 1.1 – 54.4; 52%>10ppm	6-7 years	146-149	BAEP, VEP, NES: finger tapping, hand eye coordination, con-tinuous performance test,	Murata et al. 1999

Study Site	Cohort Size	Exposure Biomarker	MeHg/Total Hg Concentration	Age Assessed	# of Children Assessed	End Point	Reference
						WISC-R: digit span, block design Stanfford-Binet: bead memory	
Results: Maternal-hair Hg was significantly associated with latencies in brainstem auditory evoked potential and visual-evoked potential.							
Ecuador	75 (36 children, 39 adults)	Blood	Mean, 17.5 mg/L (3.0 in 34 controls)	Children: 3-15 years Adults: 16-57 years	19-40	Pure tone conduction threshold BAEP	Counter et al. 1998
Results: Although the endpoints studied and blood Hg concentrations represented in the cohort were generally unaffected, the associations found were consistent with an effect of Hg at the level of the auditory nerve and the cochlear nuclear complex.							

Abbreviations: **DDST**, Denver Developmental Screening Test (DDST-R is a revised version); **FTII**, Fagan Test of Infant Intelligence; **BSID**, Bayley Scales of Infant Development; **MSCA**, McCarthy Scales of Children's Abilities (general cognitive ability); **PLS**, Preschool Language Scale (expressive and receptive language); **WJTA:LWI**, letter-word recognition subtest of the Woodcock-Johnson Tests of Achievement (reading level); **WJTA:AP**, applied problems subtest of the Woodcock-Johnson Tests of Achievement (arithmetic); **B-G**, Bender-Gestalt Test (visual-spatial ability); **CBCL**, Child Behavior Checklist (social and adaptive behavior), **NES**, Neurobehavioral Evaluation System (finger tapping, hand-eye coordination, and continuous performance test); **TPT**, Tactual Performance Test; **WISC-R**, Weschler Intelligence Scale for Children – Revised (digit span, similarities, and block design); **CVLT-C**, California Verbal Learning Test – Children; **BNT**, Boston Naming Test; **NAPMS**, Nonverbal Analogue Profile of Mood States; **BAEP**, Brainstem Auditory Evoked Responses; **VEP**, Visual Evoked Potentials.

Neurological Status

Overall, the evidence that children's neurological status is associated with low-dose chronic prenatal Hg exposure consists of the following findings:

- Abnormalities of muscle tone or reflexes in boys is significantly associated with prenatal MeHg exposure, though the effect is not dose dependant (the risk of an abnormality of tone or reflexes increased seven times with each 10 ppm increase in maternal hair Hg) (McKeown-Eyssen et al. 1983),
- There is a significant inverse relationship between newborn's neurological optimality scores and cord-whole-blood Hg concentration (a 10-fold increase in cord blood Hg was associated with the equivalent of a 3-week reduction in gestation age. Adjustments for total PCBs and fatty acid concentrations had no effect on results. Mean Hg concentration was 20.4 ug/L) (Steuerwald et al. 2000),
- 7-year old children who performed sub-optimally on a finger opposition test had a modest but statistically significantly higher mean Hg cord blood concentration than children with optimal performance (23.9 versus 21.8 ug/L, p=.04) (Grandjean et al. 1997), and
- Among a cohort of children 9 months to 6 years of age, an association between increased reflexes and higher Hg concentrations in maternal hair for children greater than 2 years of age (stronger in boys than girls) (Cordier and Garel 1999).

Age at Achievement of Developmental Milestones

Recent epidemiological studies provide little evidence of an association between maternal hair mercury below 30 ppm and delayed developmental milestones. Although the main cohort Seychelles Island Development Study (Myers et al. 1997) found that there was an association between age at walking and maternal-hair mercury in boys, Axtel et al. (1998) found that the mean age of boys at walking increased (only slightly) as maternal-hair Hg increased from 0-7 ppm, but decreased from beyond 7 ppm. Therefore, the risk of delayed walking did not appear to be dose related because the size of the effect was small (less than one day) and the association was nonlinear.

Age of achieving developmental milestones was studied by Grandjean et al. (1995) in a 21-month birth cohort of 1,022 infants in the Faroe Islands. The indexes of prenatal Hg exposure used included maternal-hair Hg concentrations, infants' umbilical cord blood, and children's hair samples obtained at about one year of age. Endpoints that are commonly achieved between five and 12 months were selected to measure motor-developmental milestones and included sitting without support, creeping, and getting up into standing position without support. Complete data was available for 53 percent of the cohort (583 infants). No significant association was found between the age at achievement and either index of prenatal exposure, but a significant association was found between age at achievement and postnatal exposure (children's hair). Nursing was found to cause higher hair Hg concentrations in children *and* more rapid achievement of milestones, which suggests that the beneficial effects of nursing on early motor development are sufficient to compensate for any slight adverse impact that low-dose prenatal MeHg exposure might have on the end points.

Infant and Preschool Development

There is some indication of low-dose mercury effects in very young children, but there are difficulties in the measurement of such effects. There are many standardized tests widely used in epidemiological studies to assess the association between low-dose prenatal MeHg exposure and early child development. The Denver Developmental Screening Test (DDST) was used in four different studies (McKeown-Eyssen et al. 1983; Kjellstrom et al. 1989; Myers et al. 1995a and b) to measure infant development. Of those, the New Zealand and Seychelles pilot phase studies revealed an association with prenatal Hg concentrations and children's scores when questionable and abnormal findings were combined (Kjellstrom et al. 1989 and Myers et al. 1995b). The differences between the findings of these four studies could be due to the diversity of ages at which the tests were administered, the different rates of abnormal or questionable examinations, test administration differences, or the use of different criteria to judge results (NRC 2000).

A different test, the Bayley Scales of Infant Development (BSID), was administered to children in the Seychelles main cohort and yielded two primary scores: the mental development index (MDI) and psychomotor development index (PDI). The MDI scores (97.5 and 100.4 at 19 and 29 months respectively) were similar to the expected mean for U.S. children of 100 ± 16. The PDI scores at both ages, though, were markedly higher than the expected mean for U.S. children; approximately 200 Seychelles children at 19 months achieved the highest possible score (Davidson et al. 1995).

The BSID is recommended as a better infant assessment tool than the DDST because the DDST is not sensitive to variations within the range of normal performance, and the BSID is sensitive to prenatal exposures to a variety of neurotoxicants like lead and PCB's (NRC 2000). Among the mercury studies that have assessed infant development, only the Seychelles main study (Davidson et al. 1995) administered the BSID, and no significant associations were found between children's scores and their prenatal exposure.

Childhood Development

There is ample evidence of low dose *in utero* mercury effects on neuropsychological indices in school-age children, particularly in the domains of attention, fine-motor function, confrontational naming, visual-spatial abilities, and verbal memory. The Faroe, New Zealand, and Seychelles pilot study reported significant inverse associations between neurodevelopment and MeHg.

In the Faroe Island cohort (Grandjean et al. 1997), a battery of neuropsychological tests was administered at 7 years of age to 917 of the surviving members of the 1,022 cohort. Increased cord-blood Hg concentration (mean, 22.9 ug/L) was significantly associated with worse scores on finger tapping (preferred hand, p=.05), continuous performance test in the first year of data collection (false negatives, p=-.02; mean reaction time, p=.001), WISC-R digit span (p=.05), Boston Naming Test (no cues, p-.0003; with cues, p=.0001), and the California Verbal Learning Test – Children (short-term reproduction, p=.02; long-term reproduction, p=.05). Investigators estimate that a 10-fold increase in cord Hg concentration was associated with delays of 4 to 7 months in those neuropsychological domains. Most test scores were more strongly associated with cord-blood mercury than with maternal hair mercury. In the case-control portion of the study, the case group scored significantly lower than the control group on 6 of 18 endpoints.

In the New Zealand cohort (Kjellstrom et al. 1989), at age 6, maternal-hair Hg concentration in the high-Hg group (mean, 8.3 ppm) was associated with poorer scores on full-scale IQ, language development (spoken language quotient), visual-spatial skills (perceptual-performance scale), and gross-motor skills (motor scale) ($p = .0034 - .074$). The poorer mean scores in the high-mercury group were largely attributable to the children of mothers with hair mercury above 10 ppm.

Among the 271 66 month-old subset of the Seychelles pilot cohort (Myers et al. 1995c) of 789, maternal-hair Hg concentrations (median, 7.1 ppm) were associated with significantly lower general cognitive index scores ($p=.024$), Preschool Language Scale scores ($p=.0019$), and perceptual-performance scale scores ($p=.013$). Because this study was for feasibility purposes, no information was collected on socioeconomic status, caregiver intelligence, or quality of home environment. The Sychelles main study did not report such associations. In the main Seychelles study (Davidson et al. 1998), the pattern of scores on six neurodevelopmental end point tests administered to the 66 month-olds did not suggest an adverse effect of either prenatal (mean: 6.8 ppm) or postnatal (mean: 6.5 ppm) Hg exposure.

Effects of mercury exposure were also observed in two smaller populations. A recent study indicated that the majority of hair mercury levels in Indian and non-Indian women and children within the Amazon Basin are in the range of 10-20 ug/g (ppm), within range of the threshold indicative of adverse effects to fetal development (Barbosa, Silva, and Dorea 1998; Clarkson 1992). Levels in general were higher in non-Indian subjects, which are estimated to consume more fish (contaminated by upstream gold-mining activities) than the Indian population (Barbosa, Silva, and Dorea 1998). Grandjean et al (1999) found that children's hair mercury concentrations were significantly associated with their scores on finger tapping, dexterity, and digit span tests. Also, in a French Guiana cohort, it was shown that maternal hair mercury was associated with low copying-design scores (more so in boys) (Cordier and Garel 1999).

Sensory, Neurophysiological, and Other End Points in Children

There is increasing evidence of adverse endpoints other than cognitive development in mercury-exposed children. During the 7-year evaluation of the Faroe Islands study (Grandjean et al. 1997), there were delays in some auditory-evoked potential peaks as a function of cord-blood mercury. Similar findings were reported in a cross-sectional study of 149 6- to 7-year old children living in a fishing village on Madiera (Murata et al. 1999). A relationship was also found between blood Hg concentrations and auditory function in the right ear at 3kHz in children and adults in Ecuador..

Comparison of Studies

Several epidemiological studies have evaluated subtle endpoints of neurotoxicity in an attempt to establish response relationships to low-dose MeHg exposure (see Table 16). These studies are important in that, unlike the acute poisoning episodes in Japan and Iraq, they relate more to levels of exposure in the United States and, therefore, are more appropriate for use in risk assessment.

The three largest and most comprehensive epidemiological studies were conducted in the Faroe Islands and the Seychelles Islands (main phase). The Faroe Island cohort examined the correlation between neurodevelopmental criteria in children and methylmercury exposure indicators, including maternal hair and placental cord blood. The setting for this study was the Faroe Islands (part of Denmark, located in the North Sea between Scotland and Iceland), a small Nordic community of approximately 45,000 inhabitants. Seafood consumption in this community is highly variable, and the population is socially homogenous. A major component of seafood consumption is the meat of the pilot whale. Deficits in speech, attention, and memory in seven-year olds were correlated with the methylmercury exposure indicators. Placental cord blood was the strongest predictor of these effects (Grandjean et al. 1997).

The Seychelles Island main cohort study examined the neurodevelopmental effects of pre- and post-natal methylmercury exposure in children. The setting for the study was the Republic of Seychelles, an archipelago in the Indian Ocean off the coast of East Africa, where 85 percent of the population consumes marine fish daily. A battery of five developmental tests was administered to 711 children in the cohort at 60 (+/- 6) months of age. Pre and post-natal exposure levels, as well as a number of other factors (diet, parental I.Q., sex, medical history, etc.) were analyzed to explain the outcomes of the developmental tests. No deficits were found resulting from Me-Hg exposure; the outcomes of the tests were explained largely in terms of the alternative factors. In some instances, performance on the tests improved at higher levels of Me-Hg exposure. The authors speculate that this may result from the beneficial aspects of fish consumption, including omega-3-fatty acids, and so the benefits of consuming fish may outweigh the health risks (Davidson et al. 1998).

Although the exposure in both studies was similar, different conclusions were reached. The Faroe Islands study found a range of adverse neuropsychological and neurophysiological effects associated with prenatal Hg exposure, but the Seychelles Island found none[4]. Explanations for these discrepant findings have been offered (see NRC 2000). In general, possible explanations include the following issues:

- **Influences of confounders and covariates**: Although neither the Faroe nor the Seychelles study controlled for all potential confounders, the NRC (2000) concluded that both evaluated most of the control variables that could have confounded associations observed between exposure and outcome. A few control variables that are sometimes modestly related to childhood neurobehavior were assessed in one study and not the other, including maternal age and birth order in the Seychelles study and obstetrical care in the Faroe Study, but the influences of those variables are probably too weak to account for any major inconsistencies between the two studies.

[4] An association was found between age at walking and maternal-hair mercury in boys (Myers et al. 1997), but was later found to be non-linear (Axtel et al. 1998).

Other possible confounding issues include place of Faroese residence (town versus country), test administration (examiner was not controlled for in the Seychelles study), age at testing, exclusion of Seychelles individuals with severe impairments, and PCB exposure in the Faroese population.

- **Population differences in susceptibility**: Susceptibility to effects of a toxicant can depend on predisposing factors, such as nutritional status, exposure to other agents, or genetic susceptibility. Genetic susceptibility is at issue here, because the Seychelles cohort was predominately African in descent and the Faroes cohort was Caucasian.
- **Timing, extent, and frequency of exposure**: Exposure to MeHg in the Seychelles is though daily consumption of fish (continuos exposure), as opposed to the Faroese whose significant source of MeHg is pilot whale meat consumed relatively infrequently (episodic exposure).
- **Biomarker differences**: To assess prenatal mercury exposure, cord blood and maternal hair concentrations were measured in the Faroe study and only maternal hair mercury in the Seychelles. Also, the maternal hair mercury samples collected in each study did not reflect the same period of pregnancy.
- **Differences in assessment batteries used**: Both studies used different neurobehavioral test batteries. In addition, the age of the children assessed in both studies was different; 7 year olds in the Faroe Islands and 5.5 years in the Seychelles.
- **Biostatistical issues**: Because the magnitude of the association between mercury exposure and expression of neurotoxicity is subtle, it is not likely that the association will be detected in every cohort studied. The differences between the two studies

could simply be due to sample variability in the expression of neurotoxictiy at low doses.

The completion and peer review of the New Zealand study helped to resolve some of the issues noted above. In the New Zealand study, the population's sources of MeHg were similar to those examined in the Seychelles. Children at 4 and 6 years of age who had been exposed in utero to MeHg were given a battery of neuropsychological and neurophysiological tests. As was the case for the Faroe study, decrements were reported in test performance at both ages in the children exposed prenatally to moderate high doses, including four endpoints that were found to be unrelated to MeHg (Crump 2000). Differences between the Fareo and Seychelles studies regarding the primary biomarker of Hg exposure, type of neuropsychological tests administered, age of testing, and sources of exposure (whale meat versus fish) no longer seemed determinative after the New Zealand study results were examined. Although exposure and research design were similar between the New Zealand and Seychelles studies, associations between MeHg exposure and and worse neurobehavioral test scores, as did the pilot phase of the Seychelles study (NRC 2000).

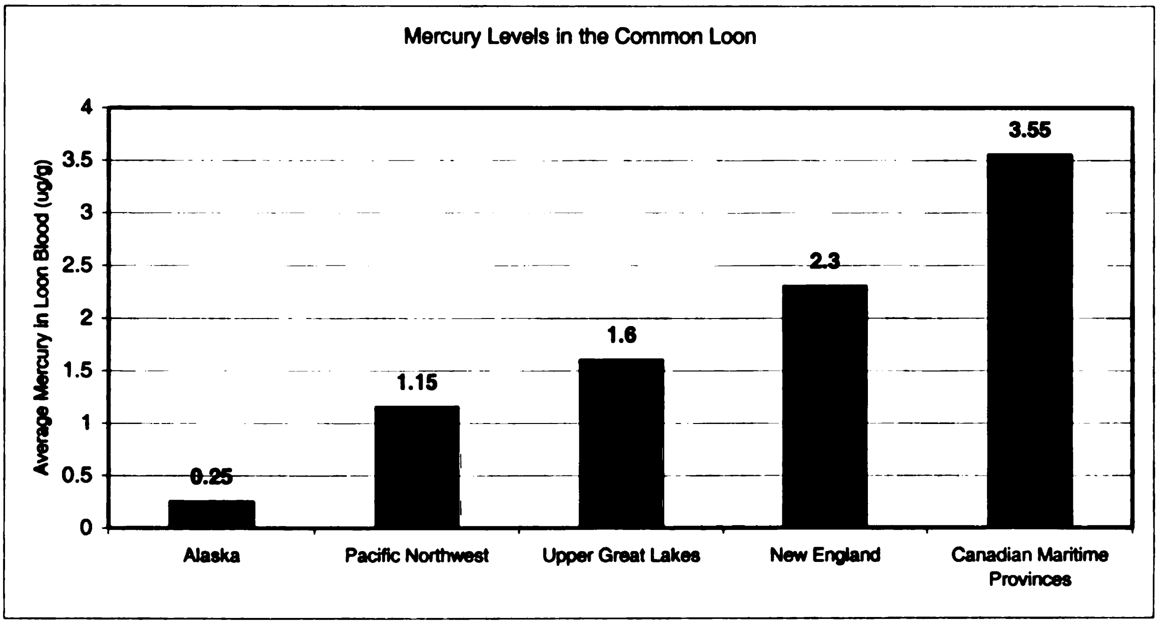
Tests preformed by Grandjean et al. (1997) to ascertain if the PCB and mercury effects among the Faroese could be separated revealed that it is not possible to determine the relative contribution of each. The NRC (2000) concluded that there is no empirical evidence or hypothesized mechanism to support the suggestion that PCB exposure might have enhanced the Faroese's vulnerability to MeHg. Statistical tests for interaction between PCB and mercury showed no interaction. It is unlikely that a difference in PCB exposure between the Faroes and Seychelles populations explains the lack of developmental neurotoxic effects in the Seychelles, where PCB body burdens are very low.

These are some of the factors that may account for the finding of adverse outcomes in the Faroes and New Zealand studies and the lack of them in the Seychelles, but non of them represent a critical flaw in any of the studies, nor do they adequately explain the differences (NRC 2000). After careful review, the NRC chose to recommend the study of neurotoxicity in 7 year old children in the Faroe Islands as the critical study on which to base MeHg exposure standards (RfD). The EPA has concurred with this finding. The advantages of this study over the others include a larger sample size, the use of two different biomarkers of exposure, and extensive peer review. The Seychelles study shares many of the strengths of the Faroes study, but the NRC (2000) concluded that a positive study is the strongest public health basis for and RfD. Disadvantages present in the New Zealand study included a small sample size and limited peer review.

ECOSYSTEM AND WILDLIFE IMPACTS

Mercury has a wide range of harmful effects on wildlife. Transported to ecosystems from a sources such as atmospheric transport (wet and dry deposition), runoff from storm events, and direct discharge to water bodies from industrial effluents, mercury is absorbed by organisms from the air, water, and soil, as they eat, drink and breathe. Mercury absorbed from food accumulates in the organism's body and damages the liver, kidneys, and especially the central nervous system. While much work in assessing the effects of environmental mercury to human health as centered on the issue of mercury as a neurotoxicant, studies in wildlife have focused on the reproductive effects of environmental mercury. Its effects are most devastating in embryos and the young, and mercury is suspected as an important cause of reproductive failure among loons, eagles, mink, turtles, river otters, and other wildlife across the U.S.

Figure 26: Mercury blood levels in common loon (Evers et al. 1998)



Since methylmercury is biomagnified throughout the food chain, animals at the high end of the food chain accumulate the highest levels of mercury. These animals include predatory fish, predatory mammals, marine mammals, and predatory birds. Predatory birds that consume fish such as loons and osprey are also at risk, because mercury is prevalent in aquatic ecosystems, and readily bioaccumulates in fish.

Researchers have found that mercury concentrations in loons tend to increase with age, and that mercury levels increase generally from west to east across North America (Evers, et al, 1998). Loons in Alaska, for instance, have only about 0.66 ppm of mercury in their blood compared to levels in the Pacific Northwest, which averaged 1.7 times higher (1.1 ppm), 2.4 times greater in the upper Great Lakes (1.58 ppm), 3.5 times greater in New England (2.3 ppm), and 5.3 times greater in the Canada's Maritime provinces, an extremely high 3.5 ppm. This trend reflects the U.S. EPA prediction model of total anthropogenic mercury deposition across the United States. (Evers et al. 1998).

In Maine, mercury poisoning in loons has caused reproductive problems and has limited their ability to fight off disease (Bradbury, D. 1997). Furthermore, acid rain appears to compound the mercury problem, since acidification increases the solubility and mobility of mercury and other toxic metals. Researchers in Wisconsin, for example, have found elevated levels of methylmercury in loons nesting on acidified lakes, as compared to those that nest on less acidified waters (Meyer, M.W 1995). Also, mercury levels associated with reproductive impairment and toxicity were recently reported for emaciated loons found dead or in a weakened state in eastern Canada, and these levels were higher than in apparently healthy loon (Scheuhammer, A. M., et al. 1998). Additional research has observed apparent mercury-related effects on behavior of young loons that may effect their survivability (Nocera, J. J. and P.D. Taylor 1998).

Other fish-eating waterfowl are affected as well. For example, moderately high levels of mercury have caused reduced hatching success and duckling survival in mallards and

American black ducks (Zillioux, E.J. 1993). Sampling and analysis of Great Lakes Herring Gull eggs between 1973 and 1992 revealed that in general, herring gull eggs mercury levels were highest in 1975 and 1982 (Koster, M.D. et al. 1996). Mercury burden in these eggs slowly declined and leveled off in the late 1980's and early 1990's. This finding indicates that mercury levels will likely not decrease further until anthropogenic mercury discharges to the environment are reduced.

During the 1970's, the mercury burden in Great Lakes Herring Gull eggs varied, with the highest levels being found in Lake Ontario and Lake Superior. This trend paralleled mercury levels observed in rainbow smelt, a common food source of the gulls. Spatial variation may indicate variation in loading to the lakes. The long retention time of Lake Superior may result in long retention times of toxins. By the early 1990's, mercury burdens were more evenly distributed across the Great Lakes. This may be the result of a shift from point source loading of mercury to diffuse, non-point sources (especially atmospheric deposition).

In addition, high mercury levels have been identified in free-roaming Florida panthers, especially those with a diet rich in raccoons, rabbits, armadillos, and alligators (Roelke, M.E. et al. 1991). Scientists now think that chronic exposure to mercury may be partly responsible for lower than expected population densities of panthers in much of their range and may actually be contributing to the extinction of these highly endangered animals.

APPENDIX II

PHASE I CONSENT FORM

Date

Name
Address
City, State Zip

Dear _______________:

The purpose of this letter is to ask for your participation in the study "Mercury Emissions from Coal-Fired Power Plants: A Critical Analysis of Reduction Strategies." This study is being conducted to address an important environmental policy issue (i.e. coal-fired utility mercury emissions) and to fulfil the thesis requirement of a Master of Science degree in Resource Development from Michigan State University.

Explanation of Research
Mercury emissions from the coal-fired utility sector pose a challenge for the condition our rivers, lakes and streams, as well as the health of people and wildlife that depend on these waterbodies for food, habitat, recreation, and enjoyment. This study will contribute to the ongoing public policy debate regarding whether mercury regulation for the coal-fired utility sector is needed, and if so, what emissions management strategies should be adopted..

Research Procedure
You are being asked to participate in this study because of your expertise and experience regarding the research problem. If you consent to participate, you will be contacted twice:

1. I will contact you by phone for a one-hour phone interview (please select a date and time that is convenient from the choices below). The telephone interview will cover the following topics (a) possible mercury reduction strategies, (b) criteria for evaluating these strategies, and (c) policy ideas for implementing these strategies.

2. Several weeks later you will be mailed a written survey based on the results of the telephone interviews. You will be asked to evaluate a number of alternative mercury reduction strategies, criteria, and goals. This survey will contain approximately 30 questions and should take no longer than one-hour to complete.

Assurance of Confidentiality
All data gathered during this study will be treated with strict confidence. Your confidentiality will be protected to the maximum extent allowable by law and, to ensure confidentiality, your identity will only be known to my advising professor and me. Any reports of research findings that result from this study will not associate your identity with specific responses or findings.

Consent to Participate
Participation in this study is voluntary. You may choose not to participate at all, may refuse to answer certain questions, or may discontinue participation at any time. **If you freely consent to participate, please sign below and mail this entire document to me** in the envelope provided.

____________________________ ____________________
Signature Date

____
Name

If you have any questions or concerns regarding your participation in this study, please contact:

Julie C. Metty
Principal Investigator
131 West South Street
Williamston, MI 48895
517/484-4954 (day)
517/655-6254 (evening)
mettyjul@msu.edu

If you have questions about your rights as a human subject of research, please contact:

David E. Wright, Chair
Committee on Research Involving Human Subjects
Administration Building University
Michigan State University
East Lansing, MI 48824-1046
517/355-2180

Thank you,

Julie C. Metty
Principal Investigator

APPENDIX III

PHASE II CONSENT FORM

IMPORTANT INFORMATION

PLEASE READ **BEFORE** ANSWERING THE QUESTIONNAIRE

The purpose of this survey is to identify priority strategies that could be used to control mercury emissions from coal-fired power plants, reflecting the perceptions and values of experts from diverse constituencies. I would appreciate your taking the next 30-45 minutes to complete the attached questionnaire.

Participation in this survey is **voluntary**. This means that you may choose not to participate at all, you may refuse to answer certain questions, or you may discontinue completing the questionnaire at any point.

Consent Statement: **You indicate your voluntary agreement to participate by completing and returning the questionnaire.**

Data gathered for this survey will be treated with strict confidence on the part of the research investigator. The names of subjects will not be linked to responses and subjects will remain anonymous in any report of research findings. Your privacy will be protected to the maximum extent allowable by law.

Should you have any questions or concerns about this study, please contact:

Julie C. Metty, Principal Research Investigator
Michigan State University
131 West South Street
Williamston, MI 48895
ph: 517/484-4954 (day), 517/655-6254 (evening)
mettyjul@msu.edu

Questions pertaining to a participant's rights as a human subject of research should be directed to:

Dr. David Wright, Chair
University Committee on Research Involving Human Subjects
Michigan State University, Administration Building
East Lansing, MI 48824-1046
ph: 517/355-2180

Your assistance in this research is very much appreciated.

Julie C. Metty
Principal Research Investigator

APPENDIX IV

PHASE II SURVEY INSTRUMENT

November 21, 2001

«Saluation» «First_Name» «Last_Name»
«Organization»
«Address1»
«Address2»
«City», «State» «Zip»

Dear «Saluation» «Last_Name»:

You have received this survey because you have been identified as an expert, who can provide valuable information for the study, "Mercury Emissions from Coal-Fired Power Plants: A Critical Analysis of Reduction Strategies." This study is being conducted to address an important environmental policy issue (i.e. emissions management of coal-fired utility mercury emissions) and to fulfil the thesis requirement of a Master of Science degree in Resource Development from Michigan State University.

Explanation of Research
Mercury emissions from coal-fired power plants pose a challenge for the condition of our rivers, lakes and streams, as well as the health of people and wildlife that depend on these waterbodies for food, habitat, recreation, and enjoyment. This study will contribute to the ongoing public policy debate regarding what type of emissions management strategy should be promulgated by the US Environmental Protection Agency to address mercury emissions from coal-fired power plants.

Over the past two months, experts from the utility sector, government agencies, and environmental organizations have been interviewed to explore the different strategies that can be used to control mercury emissions from coal-fired power plants, as well as the different criteria that can be applied to evaluate these strategies. These interviews revealed six alternative mercury emissions reduction strategies and nine possible evaluation criteria. These strategies and criteria h ave been incorporated into the attached survey and distributed to a broader group of experts from the same stakeholder groups, of which you are apart.

The purpose of this survey is to learn (a) your preferred strategy for controlling mercury emissions from coal-fired power plants, (b) the relative importance you place on each criteria when evaluating different mercury emissions reduction strategies, and (c) your preferred strategy with respect to each individual criteria. Once collected, this information will be analyzed to identify priority mercury emissions reduction strategies reflecting the perceptions and values of experts from diverse constituencies.

Please complete the attached survey and return it to me by April 17th, 2001 in the postage-paid envelope provided. Thank you in advance for your help with and support of my research endeavor.

Sincerely,

Julie Metty
M.S. Candidate/Principal Research Investigator
Michigan State University

Thank you for taking the time to complete this survey. Please indicate to which organization/sector you belong (check one):

☐ Utility Industry

☐ Government Agency

☐ Environmental Organization

SECTION A: Ranking of Alternative Strategies

1. Please rank the following six mercury emission reduction strategies, assigning 1 to your most preferred strategy and 6 to your least preferred strategy. Please assign a different number between 1and 6 to each strategy, using all numbers:

_____ **Maximum Achievable Control Technology (MACT) numerical emission limit**: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.

_____ **MACT technology regulation:** EPA determines MACT emissions limit and promulgates a technology standard for the utility industry.

_____ **MACT numerical emission limit plus emissions trading:** EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including emissions trading.

_____ **Multi-pollutant regulation:** EPA establishes and promulgates emission standards for multiple pollutants (e.g. NO_x, CO_2, SO_2, and Hg) at one time.

_____ **Receptor-based emissions limits**: EPA establishes and promulgates mercury emission standards for single plants based on their specific and identified pollution contributions.

_____ **Risk-based emissions limit**: EPA establishes and promulgates a mercury emission standard for the utility industry based on the estimated risks to the human population and ecosystems, i.e., the standard would provide an ample margin of safety to protect public health and ecosystems.

SECTION B: Criteria Importance Ratings

The following are nine criteria that might be used to evaluate the six alternative mercury reduction strategies described in Section A.

Criteria	Definition
Effectiveness	The ability of the reduction strategy to reduce mercury to target levels
Economic feasibility	Impact on business viability and power reliability, i.e. the reduction strategy's impact on utility operations, generation capability, company longevity, etc.
Technological feasibility	Need for new technology, i.e. the reduction strategy requires additional technological innovations.
Compliance flexibility	Amount of industry latitude in selecting a reduction method/ technology
Planning certainty	Level of certainty regarding future pollutant regulations and pollution control needs
Political feasibility	Level of political constraints in implementing the reduction strategy
Scientific defensibility	level of scientific certainty associated with the reduction strategy
Legal feasibility	Need for new or modified laws, i.e. the reduction strategy requires additional legal mechanisms.
Cost-benefit	Degree of benefit compared to cost

This section of the survey asks you to compare the **relative importance** of the above criteria in evaluating the alternative mercury reduction strategies. Using the importance scale provided, you will be asked to make a series of pairwise comparisons and indicate the relative importance of the nine criteria in evaluating the six alternative mercury reduction strategies.

The following is an example of a pairwise comparison using the hypothetical goal of purchasing a laptop. computer.

Example

Goal: Purchasing a laptop computer.

Evaluation criteria: *Criteria 1 - Price (cost of the laptop)*
Criteria 2 - Memory (size of hard drive)

*Pairwise comparison: Using the scale below indicate the relative importance of the **two criteria** (price and space) **with respect to the goal**: purchasing a laptop computer:*

Criteria 1	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	Criteria 2
Price	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Memory**

*In this example, the respondent is saying that **price** is **moderately to strongly** more important of a criteria than **memory** when purchasing a lap top computer.*

1. For each item below (i.e., a, b, c, etc.), using the scale provided please indicate which of the two **criteria** is more important **with respect to achieving the overall goal:** reducing mercury from coal-fired power plants. Circle the number that represents the relative importance of the criteria.

Note: For each pair of criteria (i.e. a, b, c, etc) below, only one scale value should be circled.

	Criteria 1	Extreme · Very Strong · Strong · Moderate · Equal · Moderate · Strong · Very Strong · Extreme	*Criteria 2*
a.	Effectiveness: the ability to reduce mercury to target levels	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Economic feasibility: impact on business viability and power reliability.
b.	Economic feasibility: impact on business viability and power reliability.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Technological feasibility: need for new technology
c.	Technological feasibility: need for new technology.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Compliance flexibility: amount of industry latitude in selecting a reduction method/ technology.
d.	Compliance flexibility: amount of industry latitude in selecting a reduction method/ technology.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Planning certainty: level of certainty regarding future pollutant regulations and pollution control needs.
e.	Planning certainty: level of certainty regarding future pollutant regulations and pollution control needs.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Political feasibility: level of political constraints.
f.	Political feasibility: level of political constraints.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Scientific defensibility: associated level of scientific certainty.
g.	Scientific defensibility: associated level of scientific certainty.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Legal feasibility: need for new or modified laws
h.	Legal feasibility: need for new or modified laws.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Cost-benefit: degree of benefit compared to cost.

SECTION C: Strategy Comparisons
In this section of the survey, for each evaluation criteria (e.g. effectiveness), you will be asked to indicate your preference between a pair of alternative mercury reduction strategies. As in the previous section, this will involve a series of pairwise comparisons.

1. Criteria: **Effectiveness**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **effectiveness** (the ability to reduce mercury to target levels). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	*Strategy 2*
a.	MACT numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
		Criteria: Effectiveness																	
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
		Criteria: Effectiveness																	
c.	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.
		Criteria: Effectiveness																	
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
		Criteria: Effectiveness																	
e.	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.
		Criteria: Effectiveness																	

2. Criteria: **Economic feasibility**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **economic feasibility** (impact on business viability and power reliability). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	*Strategy 2*
a.	Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
		Criteria: Economic feasibility																	
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
		Criteria: Economic feasibility																	
c.	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.
		Criteria: Economic feasibility																	
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
		Criteria: Economic feasibility																	
e.	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.
		Criteria: Economic feasibility																	

3. Citeria: **Technological feasibility**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **technological feasibility** (current technological availability). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme	*Strategy 2*
a.	Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Technological feasibility									MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Technological feasibility									MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
c.	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Technological feasibility									Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Technological feasibility									Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
e.	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Technological feasibility									Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.

4. Criteria: **Compliance flexibility**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **compliance flexibility** (amount of industry latitude in selecting a reduction method/ technology.). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme	*Strategy 2*
a.	Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Compliance flexibility									MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Compliance flexibility									MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
c.	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Compliance flexibility									Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Compliance flexibility									Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
e.	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Compliance flexibility									Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.

5. Criteria: **Planning certainty**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **planning certainty** (level of certainty regarding future pollutant regulations and pollution control needs). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme / Very Strong / Strong / Moderate / Equal / Moderate / Strong / Very Strong / Extreme	*Strategy 2*
a.	Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Planning certainty	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Planning certainty	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
c.	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Planning certainty	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Planning certainty	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
e.	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 Criteria: Planning certainty	Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.

6. Criteria: **Political feasibility**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **Political feasibility** (level of political constraints). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme		Very Strong		Strong		Moderate		Equal		Moderate		Strong		Very Strong		Extreme	*Strategy 2*
a.	Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
		Criteria: Political feasibility																	
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
		Criteria: Political feasibility																	
c.	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.
		Criteria: Political feasibility																	
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
		Criteria: Political feasibility																	
e.	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.
		Criteria: Political feasibility																	

7. Criteria: **Scientific defensibility**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **scientific defensibility** (associated level of scientific certainty). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme	*Strategy 2*
a	Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Scientific defensibility									MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Scientific defensibility									MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
c	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Scientific defensibility									Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Scientific defensibility									Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
e	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Scientific defensibility									Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.

8. Criteria: **Legal feasibility**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **legal feasibility** (need for new or modified laws). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme · Very Strong · Strong · Moderate · Equal · Moderate · Strong · Very Strong · Extreme	*Strategy 2*
a.	Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Legal feasibility	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Legal feasibility	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
c.	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Legal feasibility	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Legal feasibility	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
e.	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Legal feasibility	Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.

9. Criteria: **Cost-benefit**

For each pair of strategies, using the preference scale provided, please indicate which strategy is preferred with respect to the criteria **cost-benefit** (degree of benefit compared to cost). For each item below, circle the number that represents the level of relative preference with respect to the criteria. Note: For each pair of strategies, only one scale value should be circled.

	Strategy 1	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme	*Strategy 2*
a.	Maximum Achievable Control Technology (MACT) numerical emission limit: EPA determines MACT emission limit and leaves the choice of control technology to the utility industry.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Cost-benefit									MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.
b.	MACT technology regulation: EPA determines MACT emission limit and promulgates a technology standard for the utility industry.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Cost-benefit									MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.
c.	MACT numerical emission limit plus emissions trading: EPA determines MACT emission limit and leaves the strategy for compliance up to the utility industry including trading.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Cost-benefit									EPA establishes and promulgates emission standards for multiple pollutants (e.g. NOx, CO2, SO2, and Hg) at one time
d.	Multi-pollutant regulation: EPA establishes and promulgates emission standards for multiple pollutants at one time.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Cost-benefit									Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.
e.	Receptor-based standard: EPA establishes and promulgates emission standards for single plants based on specific pollution contributions.	9 8 7 6 5 4 3 2 **1** 2 3 4 5 6 7 8 9 Criteria: Cost-benefit									Risk-based standard: EPA establishes and promulgates an emission standard for the utility industry based on risk to human health and the environment.

Thank you for your participation in this study.

If you would like to make any additional comments, please use the space below:

APPENDIX V

REMINDER POSTCARD

Just a reminder…

You were recently mailed a questionnaire to identify your preferred strategy for controlling mercury emissions from coal-fired power plants. If you have already completed and returned the questionnaire, I would like to take this opportunity to thank you for your participation.

For those that have not yet returned the survey, please remember that the response deadline is **June 1, 2001**. Because you have been identified as an expert in this research area, I'm sure you understand the importance of the topic and how critical your participation is in helping me approach this issue in a comprehensive and informed manner.

Thank you in advance for your help with and support of my research endeavor.

Julie Metty, MS Candidate
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