Methylcyclopentadienyl Manganese Tricarbonyl (MMT): A Science and Policy Review

January 2009

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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Acknowledgements

The authors would like to thank the William and Flora Hewlett Foundation for making this report possible through their generous support. Thank you to the government staff members who responded to our inquiries and to the academic researchers who shared their insights. Thank you also to Lauren Phillips for her help formatting the document.

Reviewers

We would like to thank the following ICCT participants who took the time to review and comment on the document.
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Executive Summary

Methylcyclopentadienyl Manganese Tricarbonyl (MMT) is a manganese-based fuel additive used to increase gasoline octane. It was widely introduced in the United States in the 1970s by the Ethyl Corporation when regulations restricting the use of tetraethyl lead first came into force. Today health scientists and automobile manufacturers are strongly opposed to its use. Combustion of MMT releases manganese, a potent neurotoxin when inhaled. In vehicles it can leave deposits that degrade the performance of pollution control systems. Similar concerns regarding tetraethyl lead have led to a near global ban on its use. Alternatives to MMT are in widespread use and can cost-effectively achieve similar octane levels without the associated health risk.

An employee of the General Motors Chemical Corporation discovered the importance of octane and tetraethyl lead as an octane booster in the 1920s. U.S. public health officials at the time warned that widespread emissions of lead particles would cause serious harm, but a review of the evidence sponsored by the U.S. Surgeon General allowed the lead additive to go forward. By the 1970s mounting evidence linked widespread inhalation and digestion of lead particles to neurological toxicity in children. At the same time, vehicle engineers warned that lead particles disabled catalytic devices necessary to meet newly passed vehicle emission standards. A regulatory ban on leaded gasoline was finally initiated in the U.S. in 1973. Leaded gasoline was widespread in the global gasoline supply, but by 2007 about 92 percent of this was lead free, and a global partnership has made completely eliminating lead its highest priority.

Soon after the ban of tetraethyl lead in the U.S., the Ethyl Corporation, successor to the General Motors Chemical Corporation, began marketing the lead alternative MMT. About 25 percent of the molecular weight of MMT is manganese, a silver-colored metal that forms compounds with oxygen, sulfur, and chlorine. The combustion of MMT releases manganese compounds into the air that are associated with neurological disorders akin to Parkinson's disease. As with lead, this additive raises concerns with regard to the public health risk of raising ambient concentrations of heavy metals and the disabling effect these metals may have on advanced emission control devices on vehicles. Scientists and automakers are encouraging action against MMT that is similar to the action being taken on lead, but the Afton Chemical Corporation which succeeded the Ethyl Corporation in 2004, vigorously defends its product as safe and effective[1]. MMT is not widely used in developed nations, but is being marketed heavily in developing nations as a convenient and low-cost lead replacement.

Manganese is present in food and is a part of a balanced diet. However inhalation is potentially a more dangerous route of exposure than digestion. When taken orally, manganese passes through the digestive system, where the liver is able to regulate the concentration entering the bloodstream. When manganese is inhaled into the lungs, however, it bypasses the liver and can enter the bloodstream directly, where it travels unfiltered to the brain and can potentially accumulate to toxic levels.

Suspicions about the neurotoxic effects of manganese were first recorded in 1837. Occupational studies have verified this effect and others relating to the pulmonary and reproductive system. The progressive neurological damage it

[1] Over its 80 plus years of existence the company that manufactures MMT today has changed its name at least three times. Today it is called the Afton Chemical Corporation, but it was once known as the Ethyl Corporation.

produces in workers is called Manganism. As symptoms of Manganism progress, the chance of recovery diminishes. Given the state of the science there is as yet no known successful treatment or cure for Manganism.

The brain is the most vulnerable organ in the body to high concentrations of manganese. Manganese compounds can cross the blood-brain barrier and accumulate in regions responsible for motor control, cognition, emotions and learning. The manganese compounds emitted from the exhaust pipe of vehicles includes highly soluble manganese sulfates which mix into the bloodstream more rapidly and may be more hazardous than other forms of airborne manganese.

MMT raises the concentration of manganese in the air. In countries where MMT was used, traffic density correlated with higher manganese concentrations. Manganese was also higher in urban areas than in rural areas where traffic is lower. It is unlikely that widespread MMT use would produce concentrations of manganese as high as those seen in occupational studies, but a group of epidemiological studies have shown that even low levels of airborne manganese can increase the incidence of Parkinson's—like disorders.

There are some uncertainties in the basic toxicology and epidemiology of manganese exposure. This is due in large part to the absence of good epidemiological studies, particularly those that focus on MMT as a manganese source. Most research has focused on neurological effects, but there is also a need to explore potential respiratory and reproductive effects. Researchers have also faced technical difficulties showing that manganese in the body increases when concentrations in the air rise.

The variables of population exposure are poorly understood and make predictions of health risk difficult. For example, certain population groups will be exposed to higher concentrations in certain micro-environments. Ratios of young and old in a population may also determine risk since age can make an individual more or less sensitive. And certain pre-existing health conditions can make an individual more vulnerable to Manganism. These factors suggest that where regulations allow use of MMT in gasoline supplies, in addition to strong enforcement efforts, some level of monitoring and ambient air quality standards may be necessary , just as this was done for lead.

A consensus within the health community against the use of MMT has been forming since the 1990s and recent developments are renewing calls for action. The World Health Organization, the United States government, the Canadian government and others have adopted risk-based standards for airborne manganese compounds, recognizing that without regulation this pollutant poses a threat to health. In addition, the US EPA has listed manganese compounds as hazardous air pollutants.

The American Journal of Industrial Medicine in 2007 published the Brescia Declaration that calls for an immediate halt in all nations to the addition of organic manganese particles to gasoline. The American Academy of Pediatrics which advises pediatric physicians and which played an important role in the policy debate to phase out leaded gasoline stated in 2003, "to permit addition of MMT to the US gasoline supply would not be prudent," and recommended that, "prevention of exposure to the most toxic additives to gasoline, such as tetraethyl lead, MMT, [and others] is best achieved by government regulation or phasing out of these compounds." The Canadian and American governments share doubts about the ability of the available research to accurately predict the health outcomes of manganese exposure. Non-governmental entities have attempted their own analysis although their results have been mixed.

Environmental concerns have received less attention than health concerns, and this is reflected in the scientific literature. MMT was found in most samples of water and storm runoff collected along highways where MMT was in use. Roadside plants, soils and urban animal tissues have all shown elevated manganese levels related to traffic. Relatively few studies have been published on the environmental effects of human-induced manganese deposition.

There is more certainty about vehicle impacts from several recent studies, although they have not been independently confirmed. The 2006 Worldwide Fuel Charter, published by an international coalition of auto manufacturers, recommends elimination of metallic additives like MMT in gasoline to non-detectable levels. Most major auto manufacturers in their owner's manuals recommend against using MMT.

U.S.-funded studies showed as early as the 1970s that MMT produces an increase in vehicle emissions. EPA concluded that emissions controls used in the early 1990s were not damaged significantly by the then-allowable concentrations of MMT. But more stringent emission standards introduced after this assessment again raised concern regarding the potential for harm to emissions control equipment. A 2002 study of the impacts of MMT on low emission vehicles (LEVs), which use higher density cells in catalytic devices, found that MMT increased hydrocarbon emissions over 100,000 miles and caused seven of eight vehicles to exceed emission certification standards. A 2004 paper published by Ford Motor compared vehicles used in the 2002 study and found that reddish-brown deposits on the cylinder head, spark plugs, and the catalyst were responsible for the increase in emissions. A 2005 follow-up analysis of these deposits found that they were compounds of manganese and zinc.

In the more than thirty studies of MMT and its vehicle impacts published by the Society of Automotive Engineers, the authors are almost exclusively affiliated with automobile manufacturers or Afton Chemical and its predecessor the Ethyl Corporation. The studies are relatively evenly divided in their findings, with each interest group finding support for their respective positions on the issue. In the absence of independent confirmation and given the preponderance of emission impacts highlighted by the vehicle industry, we conclude that these studies provide reason enough to put an immediate halt to the use of MMT.

An increasing number of voluntary and regulatory bans on MMT have restricted its use in the developed world and many countries in the developing world. A ban has been in place in the U.S. State of California since 1976. Laws and regulations also ban the use of MMT in Brazil, the Czech Republic and in Germany. The European Parliament is moving to place limits on manganese stricter than in the U.S. and ultimately as strict as New Zealand standards. A national law in the U.S. bans MMT use in reformulated gasoline, which constitutes 39 percent of the fuel supply. A separate regulatory limit restricts manganese to no greater than 8.3 mg/L in the remainder of the nation's fuel, and as of 2007 a voluntary boycott by fuel suppliers restricted MMT to less than 1 percent of the supply. Similar boycotts are in place in other countries and regions including Canada, the European Union, and India. MMT is being used in China, but strict government controls came into force in Beijing in January 2008 that limit the concentration to 6 mg Mn/L. New Zealand effectively bans the additive with a regulatory limit of 2 mg/L. In South Africa the majority of fuel sold does not contain MMT. This trend shows that actions to restrict MMT use are increasing in number, not only in developed nations but also in developing nations.

The Canadian government agency Health Canada is revising its 1994 risk assessment for airborne manganese taking into account new evidence of its health effects. A draft of the new assessment released for public comment in 2008 calls for a tightening of the current health standard from 0.11 micrograms per cubic meter (ug/m^3) to 0.05 ug/m^3. The US Environmental Protection Agency (EPA) is overseeing new health studies to develop models that better explain the transport of manganese in the body. These conclusions may lead to a revision of their risk assessment as well.

There are alternative ways to boost octane that policy makers should consider. Refinery investments alone can boost the octane of fuel without the need for metallic additives. These types of investments also create opportunities to reduce sulfur and other contaminants that degrade the quality of fuel. According to the US EPA, "…**the oil industry in the United States has been able to provide very clean, high-quality and low-emission fuel which meets the performance requirements of the vehicle industry—including octane—without the use of MMT**."(Oge, 2007) Countries that cannot make changes for technological or economic reasons can choose to import high octane blending components or pre-blended fuels that do not contain MMT or other metallic additives.

Policy makers seeking guidance regarding the use of MMT and other metallic additives can find it in the precautionary principle. The precautionary principle suggests: taking action to prevent the use of a substance when a potentially large and irreversible threat of harm is present and uncertainties over the degree of harm still exist; pursuit of alternatives that do not pose the same threat and are not limited by scientific uncertainty, like refinery investments; and placement of the burden of proof on the manufacturers of such additives to resolve uncertainties and prove absence of a threat. The Clean Air Initiative for Asian Cities in 2008 released a *Road Map for Cleaner Fuels and Vehicles in Asia* that recommended use of the precautionary principle:

"Prominent health experts have raised serious concerns regarding the potential adverse health effects of metallic additives such as MMT and ferrocene, along with their potential adverse impacts on vehicle emissions and emission control system components. Therefore, the environmentally responsible approach for Asian countries is to apply the precautionary principle for these metallic additives and to not use them until and unless the scientific and health studies show that they are safe."

Application of the precautionary principle to all metallic fuel additives is a lesson of tetraethyl lead. Had the precautionary principle been applied before its introduction, the devastating health impacts of lead emissions perhaps could have been avoided. We encourage policy makers to take action to prevent the use of MMT while health research continues and significant uncertainties persist; to pursue alternative means to boost octane; to place the burden of proof on Afton Chemical to respond to scientific uncertainties over the safety of its product; and to call for independent verification of the evidence. It would be imprudent to heed any argument to the contrary, particularly from manufacturers and suppliers with a conflict of interest. The medical community is a more reliable and credible arbiter of the safety of this product.

As it did in 2004, the ICCT recommends that the use of MMT be banned unless and until the unlikely event that further health studies indicate it is safe for the most vulnerable members of the population and vehicle studies demonstrate that vehicle emission controls are not harmed over their full useful life. This position is supported by the ICCT mission to dramatically reduce emissions from the transport sector to protect both public health and the environment.

The lesson from lead and the recommendation from public health researchers caution us against the unnecessary and avoidable use of MMT and other metallic additives. Moving toward safer alternatives for achieving octane improvements can put jurisdictions on a path to cleaner fuel and cleaner air.

We urge policy makers at all levels of government to consider carefully this recommendation and to adopt a position that is in the interest of public health and welfare.

From Tetraethyl Lead to MMT

Fuels in a gasoline-powered vehicle are prone to ignite prematurely, which causes power loss and unnecessary wear to the engine. A common sign of this pre-ignition is a pinging or knocking sound. American chemists in the early 1920s discovered that this noise was a symptom of the activation energy, or octane of the fuel. By raising octane to a consistent level, they found that vehicles would operate more smoothly and with greater power. They also understood that higher octane would allow for greater compression ratios in vehicle engines, which could put more powerful and efficient automobiles on the road.

The octane-enhancing powers of tetraethyl lead were discovered in December 1921 (Robert, 1983). This gasoline additive could very affordably maintain a high and consistent octane level, so it was quickly put on the market in February 1923 (Kovarik, 2005). The prospect of widespread exposure to airborne lead particles generated a serious debate over whether lead emissions presented an unreasonable hazard to public health. In places like New York and New Jersey, tetraethyl lead was banned quickly after it was introduced. A high profile review by the surgeon general and other public health officials concluded at the time that the existing evidence was not sufficient to warrant a national ban. As a consequence, the bans in New York, New Jersey and elsewhere were lifted and tetraethyl lead quickly became widespread throughout the national fuel market.

Over a period of five decades, basic research into the health effects of lead slowly verified initial public health concerns. This research showed that severe neurological defects in children were associated with high blood lead levels (Needleman, Davidson, Sewell, & Shapiro, 1974). By the 1960s the health effects of leaded gasoline were clear, but technological and political barriers stalled any action. Finally in December 1970 the US Congress passed the Clean Air Act, which required a 90 percent reduction in carbon monoxide, nitrogen oxides and hydrocarbon emissions. To achieve these reductions the US EPA required installation of catalytic converters on all new vehicles. Leaded gasoline damaged the platinum surfaces of these devices, so its removal was necessary to allow the catalytic converters to work. In 1973, federal regulations required a gradual decline in the lead content of gasoline. At the time the average level was 2.2 grams per gallon. Over a five-year period federal regulations required this to fall to near zero. The primary manufacturer of tetraethyl lead was the Ethyl Corporation, who challenged these regulations. In 1976 the challenge reached the US Court of Appeals, but in an important ruling the court

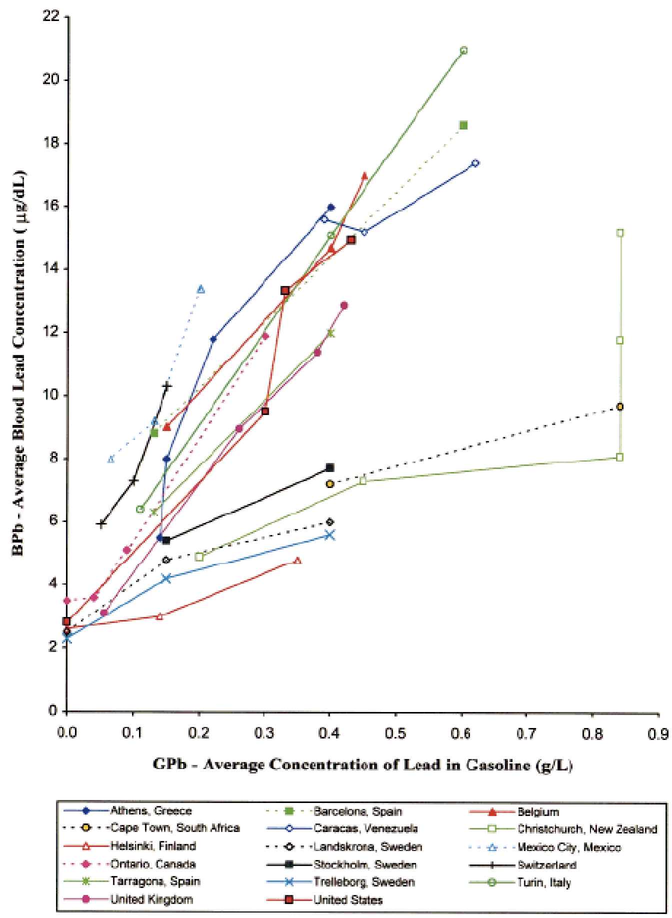

Figure 1: The relationship between blood lead concentrations and gasoline lead concentrations. Policies that lower gasoline lead content are an effective tool for reducing lead exposure (Thomas et. al, 1999)

allowed phase-out of lead to proceed. The court stated that the Clean Air Act was precautionary in nature and did not require actual proof of harm before regulation ("US Environmental Protection Agency vs Ethyl Corp., et al.,").

In addition to the primary objective of permitting proper functioning of catalytic converters, the transition to unleaded gasoline produced an important co-benefit: a dramatic decline in blood lead levels in children (Pirkle et al., 1994). The National Health and Nutrition Examination Survey (NHANES) found that between 1976 and 2002, the prevalence of blood lead levels greater than 10 μg/dL in children aged 1-5 years fell from 77.8 percent to 1.6 percent, a decline of nearly 98 percent (Berkelhamer, 2007). Many countries have experienced a similar decline after passing their own lead bans. A series of international studies verify a consistent linear relationship between gasoline lead levels and blood lead concentrations (Figure 1).

Leaded gasoline was eliminated in the United States in 1996. It has since been banned in a almost all other countries. However, despite global consensus on the dangers of lead use and the clear evidence of long-term harm to children, a handful of governments like Iraq and Afghanistan continue to permit leaded gasoline. The Ethyl Corporation has not voluntarily agreed to take its product off the market.

Fuel refiners responded to the lead ban with three alternative strategies for raising octane: a change in refinery processes, a shift to better quality crude, and adoption of alternative octane boosters (Newell & Rogers, 2004). New refinery processes like isomerization, alkylation, catalytic cracking and reforming provided the bulk—around 70 percent—of the lead octane deficit. New fuel additives provided most of the remainder. The demand for alternative additives to tetraethyl lead marked the beginning of efforts by the Ethyl Corporation to broadly market MMT.

Methylcyclopentadienyl Manganese Tricarbonyl ($C_9H_7MnO_3$, RN: 12108-13-3) was discovered in the United States in 1957 (Robert, 1983). It was first used as a combustion improver for fuel oil and turbine fuel (Ter Haar, Griffing, Brandt, Oberding, & Kapron, 1975). By 1975 it was being used to a small extent in gasoline. An amount equivalent to 0.018 grams of manganese (Mn) per liter of gasoline would produce a typical octane boost just under two octane numbers, but the actual octane level can vary with fuel composition. The U.S. ban on tetraethyl lead initially increased sales of MMT, but concerns over its health effects and its impact on vehicle emissions almost immediately created bans and restrictions on new sales.

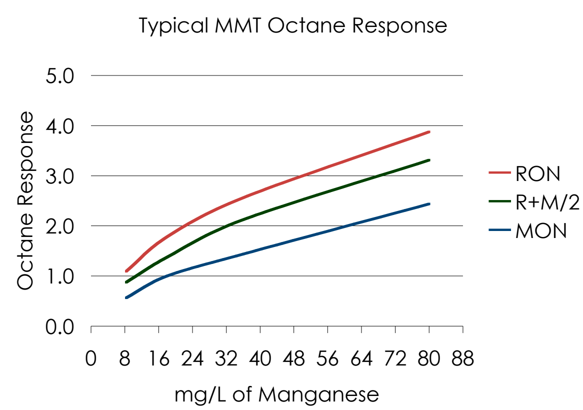

Figure 2: The relationship between octane gain and manganese concentrations in fuel when using MMT (Partnership for Clean Fuels and Vehicles, 2004).

The Status of MMT

There is little publicly accessible data on the amount of MMT consumed worldwide. Afton Chemical does not provide this data to the public and there are no government laws that compel Afton Chemical or fuel refiners to say whether they use MMT and in what amounts. Some independent fuel surveys have identified manganese in fuel, but this data is not comprehensive. It is also expensive to collect and in most cases it is proprietary. The most recent estimates we have are from 1995, which show a production rate of 1,800 tons per year (European Chemical News, 1995). Based on ICCT calculations using the levels recommend

MMT Legal Status in Selected Countries, 2008

Country	Action	Fuel	% of supply	Mn Maximum	Date Enforced	Law or Regulation
Laws in Place						
Germany						
	Statute	unleaded petrol	100	0 mg/L	n/a	Gasoline Lead Law
California						
	Regulation	unleaded petrol	100	0 mg/L	8/31/1977	Regulation 13 CCR 2254
United States						
	Regulation	reformulated petrol	39	0 mg/L	3/18/1994	40 CFR 80 Regulation of Fuels/ Fuel Additives
	Regulation	non-reformulated petrol	61	8.3 mg/L	7/11/1995	60 FR 36414
New Zealand						
	Regulation	unleaded petrol	100	2 mg/L	9/1/2002	2002 Petroleum Products Regulations
China						
Beijing	Regulation	unleaded petrol	100	6 mg/L	1/1/2008	n/a
National	Regulation	n/a	100	16 mg/L	1/1/2006	GB17830-2006
Brazil						
	Regulation	unleaded petrol	100	no limit-subject to EIA	n/a	n/a
Czech Republic						
	Regulation	petrol	100	0 mg/L	n/a	ČSN EN 228
South Africa						
	Regulation	metal-containing unleaded petrol	n/a	36 mg/L	na/	Government Gazette 23 Jun 2006 No. 28958
European Union						
	Resolution	n/a	100	6 mg/L	1/1/2011	2008 Fuel Quality Directive
	Resolution	n/a	100	2 mg/L	1/1/2014	2008 Fuel Quality Directive
Voluntary Actions						
United States		non-reformulated petrol	99	0 mg/L	1/1/1995	n/a
Canada			95	0 mg/L	1/1/2004	n/a
India			100	0 mg/L	3/1/2006	n/a
Indonesia			100	0 mg/L	n/a	n/a
Historical Laws						
United States						
	Regulation	unleaded petrol	100	0 mg/L	1977-1995	1977 Amendments to the Clean Air Act
Canada						
	Statute	unleaded petrol	100	0 mg/L	1997-1998	Bill C-29 Manganese-Based Fuel Additives Act

by Afton Chemical of 18 mg per liter of MMT, this is enough to treat 773 million barrels of gasoline. While MMT is used in less than one percent of gasoline sold in the U.S. today, between 1976 and 1998 there were over 70 million pounds sold (J.M. Davis, 1998). Today Afton Chemical says its product is used in 45 countries, but it does not name them (ACC, 2004-2006).

In developed nations MMT is used only sparsely due in part to the opposition of automakers and non-governmental organizations. Policy makers have placed intermittent bans on the product and major refiners have generally cooperated by voluntarily refusing to use it (Frumkin & Solomon, 1997).

In the United States there are overlapping state and federal laws. The state of California has banned manganese from fuel since 1977. At the national level, there are separate regulations for reformulated and non-reformulated fuel. MMT is banned from reformulated gasoline, which constitutes 39 percent of the fuel supply. Reformulated gasoline (RFG) is designed to reduce ozone-forming and toxic pollutants. RFG is required by the Clean Air Act to be used in cities with the worst smog pollution. It is used in the most populous regions of the U.S., i.e., throughout most of the East Coast; the Chicago region and some other major Midwestern cities; Dallas and Houston in the South; and California in the West (Energy Information Administration, 2008).

US EPA lost a legal challenge from Afton Chemical in 1995 (described in the next section), resulting in the federal ban on MMT use in non-reformulated gasoline being lifted. Maximum levels of MMT allowed are equivalent to 8.3 mg manganese per liter (mg/L). In 1996, following the overturn of the federal ban on MMT, the non-governmental organization Environmental Defense successfully urged all the nation's major refiners to voluntarily ban it (Halpert, 1996). Reportedly some independent refiners in the southwestern part of the country are using it, but sales of gasoline containing MMT account for less than one percent of the fuel consumed in the U.S. today (IFV, 2004; Oge, 2007).

MMT was widely used in Canada beginning in 1976, but in 2004 Canadian refiners followed the U.S. and instituted a voluntary ban. This was in response to concerns from automakers about the impact of MMT on vehicle emission controls. At least 95 percent of the fuel sold in Canada is now MMT-free. The Canadian General Standards Board (CGSB) has published

Why is Tetraethyl Lead Relevant to MMT?

For more than thirty years, policy makers and the public health community have expressed concerns over the health effects of MMT. For more than fifty years, public health officials voiced concern over the widespread introduction of lead. MMT shares physical characteristics that provide benefits and harms similar to tetraethyl lead: both are fuel additives that improve gasoline octane cheaply and affordably, yet both contain heavy metals associated with neurotoxicity and harm to emissions control technology. MMT shares a historical trajectory and certain physical characteristics that are relevant to the ongoing debate.

In the case of lead, public officials failed to avoid an international public health catastrophe, but MMT provides an opportunity to apply lessons from this tragedy. These officials learned that when a fuel additive provides public benefits but uncertain costs, policy makers should weigh risks and benefits in favor of the public interest. It is critical to be absolutely clear about known and potential risks to health and, when alternatives present themselves, consider those that provide similar benefit but minimize risk. Given the poor decisions that were made with lead, it would be foolish to ignore those lessons and make the same mistakes again.

a voluntarily standard of 18 mg Mn/L, but the Canadian government has no legally enforceable limit.

In Europe, member countries have relied on different mechanisms to restrict MMT. The Czech Republic has banned MMT, while in Germany the so-called Gasoline-Lead law requires producers of additives to demonstrate no additional health risk. Since Afton Chemical has not demonstrated this, MMT remains banned in Germany. In the rest of Europe refiners have avoided it voluntarily. The European Parliament is now taking steps to enact restrictions on MMT. Eight public health experts from the countries of Denmark, Italy, Sweden, Croatia, the Czech Republic, France, Poland, and the United Kingdom delivered a letter to all Ministers of Environment and Health in the EU calling for support of a proposal to ban the additive by 2010. In November 2008, the European Parliament, the Council of the European Union, and the European Commission agreed upon a proposal that would restrict manganese in fuel in 2011 to 6 mg/L by 2011 and in 2014 to 2 mg/L, or potentially zero depending on outcome of an environmental and health risk assessment. At the time of this writing the proposal had not been brought to a full vote.

In New Zealand, a 2002 fuel quality regulation set a cap on manganese at 2 mg/L. Since a minimum of 8 mg/L is typically necessary to increase octane by 1 RON, this effectively banned MMT. In Japan, where lead was banned in 1980, MMT is not in use (Menkes & Fawcett, 1997; Organization for Economic Cooperation and Development & United Nations Environment Programme, 1999). MMT is widely used in China, but in January 2008 the city of Beijing put into force an Mn standard of 6 mg/L.

In developing nations where lead use has been or is being phased out, Afton Chemical is leading a public relations and marketing campaign for MMT. Afton Chemical has engaged Hill & Knowlton to support its effort to “market MMT to the refining sector throughout Europe, the Middle East and Africa. This support entails an integrated public affairs and public relations effort aimed at creating understanding of MMT and its benefits across a broad range of government, commercial and related stakeholders” (Hill & Knowlton, 2008).

Legal History in the United States and Canada

Both the United States and Canadian governments have struggled unsuccessfully to ban MMT. Our review shows that as a consequence of this struggle, policy makers, fuel refiners and others have taken actions outside of the legal system to put in place a de facto ban on MMT in these countries. Indeed, while Afton Chemical promotes the fact that MMT is currently approved for use in these countries, MMT remains legal only as the result of lawsuits brought by its manufacturer to forestall restrictions or bans that would otherwise be in place (Afton Chemical, 2006).

The U.S. has been a battleground over MMT for the past thirty years. Beginning in 1975 just as lead rules were being implemented, the share of gasoline containing MMT grew over a period of three years from near zero to around 40 percent (AAP, 2003b). At the same time, new awareness of MMT spurred research into its effect on catalysts, and this found declines in vehicle performance. EPA “approached cautiously” the use of MMT as a primary anti-knock replacement for lead (Moran, 1975).

In 1976, the California Air Resources Board (CARB), fearful of the effect of MMT on vehicle catalysts, adopted a regulation prohibiting the sale of unleaded gasoline containing manganese-based additives (Lloyd, 2004). The California regulation 13 CCR 2254 (a) subparagraph (b) states "no person shall add manganese or any manganese compound, including the compound methylcyclopentadienyl manganese tricarbonyl (MMT), to gasoline represented as unleaded intended to be sold, offered for sale, or delivered for sale at retail in the State of California." A waiver of this restriction would be needed for MMT to be legally used in California, but no waiver has been granted.

The 1977 amendments to the Clean Air Act passed by the US Congress included a provision banning MMT from unleaded fuel. The Act gave the EPA administrator the power to waive the ban if the additive was proven safe for vehicles. It permitted MMT to be sold only in leaded gasoline, which was being phased out. By 1983 only around 11 percent of gasoline sold in the United States contained MMT (Borenstein, Jan 1993; HDSB, 2007).[2]

In 1990 Congress passed additional amendments to the Clean Air Act banning manganese-based additives in all reformulated gasoline. The 1990 amendments also defined manganese compounds as a hazardous air pollutant "known or suspected to cause cancer or other serious health effects…" It gave the EPA new powers to test fuel additives and to regulate toxic emissions from fixed and mobile sources.

Between 1978 and 1991 the Ethyl Corporation submitted four requests for a waiver of the ban on MMT. The first two were denied due to evidence that MMT increased hydrocarbon emissions and damaged emission control devices. The third was withdrawn. In response to a fourth application submitted in 1991, the EPA concluded after a two-year review that MMT would not "cause or contribute" to a failure of emissions control devices in use at that time (EPA, 1995). Nevertheless the request was denied over concerns that airborne manganese particles pose a health risk. The Ethyl Corporation sued EPA on grounds that Congress did not grant it the power to take into account public health, and in 1995 the U.S. Court of Appeals agreed (National Round Table on the Environment and the Economy, 1999). The Court compelled the EPA to grant the waiver, which it did in July 1995 (EPA, 1995). The Ethyl Corporation published a full-page newspaper ad in March 1996 asserting the EPA "has no data showing MMT to be a [health] threat at low levels of exposure." EPA Administrator Carol Browner responded, "while it is true that EPA does not have data proving MMT is not a threat, the lack of data is exactly the problem… EPA believes that the American public should not be used as a laboratory to test the safety of MMT" (EPA, 1996).

The following year the Environmental Defense Fund, a non-governmental organization based in the United States, pleaded with all major oil companies to publicly state their MMT use and to adopt alternatives. Twelve of the 14 largest refiners in the country accounting for 75 percent of the fuel supply said they were not using MMT and had no plans to do so (Frumkin & Solomon, 1997; Halpert, 1996). They cited economic and health concerns, and they feared negative publicity.

Since then, MMT has remained legal in non-reformulated gasoline sold in the United States, but serious consideration of its health and environmental effects continues. Under the authority of the Clean Air Act that permits testing of the health effects of fuel additives, the EPA has requested ongoing studies from Afton Chemical. In 2000 the agency announced Tier II testing requirements, which outline an agenda of scientific research for "sub-chronic systemic and organic toxicity, as well as the assessment of specific health endpoints" associated with manganese compounds and specifically with MMT. Pharmacokinetic testing of manganese compounds and characterization of manganese emissions from vehicles has been completed. This data is now being used to create physiologically-based pharmacokinetic models with an expected completion date in 2008. It is expected that this testing will result in either a refined risk evaluation for MMT or a second stage of testing (J.M. Davis, 2004; Environmental Protection Agency, 2007).

[2] Based on estimates that 25 percent of leaded gasoline contained MMT and 45 percent of gasoline contained lead.

Distinguishing Between Approving and Allowing

The Afton Chemical Corporation says on its website that the "MMT fuel additive is approved and used in all regions of the world," but the company does not make public any information about the volume of MMT used or the names of the countries where it is actually in use.

It is easy to misinterpret the above statement to mean that broad support for MMT exists throughout the world; it fails to distinguish between approving and allowing that reveals how actively a country supports it. An approval certifies that a fuel additive meets certain performance criteria, whereas allowing its use simply means there is not a sufficient basis to disallow it. The distinction is important in places like the United States and Canada where MMT is allowed, but not approved. In these places MMT is almost completely absent from the fuel supply. The best indicator of approval and use of MMT is its volumetric sales by country. Until the Afton Chemical Corporation makes this information public in a verifiable way, there can be no certainty about how much support for MMT truly exists.

Twenty years after it was originally passed, the California Air Resources Board (CARB) reviewed its ban on MMT in response to an executive mandate. The agency reaffirmed its 1976 regulation, which remains in place today (California Air Resources Board, 1997, 1998). CARB continues to have no opinion regarding the health effects of MMT, however in 1993 under Assembly Bill 2728 it declared manganese to be a toxic air contaminant. Additional regulation may be pursued in the future should evidence show it poses a significant health risk (Lloyd, 2004).

Like the United States, Canada has struggled with MMT. This additive came into use in 1976 with the move away from leaded gasoline. A series of safety reviews, beginning in 1978, found no evidence that MMT constituted a public health hazard. In the absence of restrictions, the sales of the additive grew substantially. When the Canadian phase-out of leaded gasoline was completed in 1990, MMT was used as a replacement in 90 percent of gasoline (Blumberg & Walsh, 2004).

A 1994 risk assessment of manganese by Health Canada set a reference concentration for respirable manganese at a level above the concentration most Canadians were exposed to. In 1996, automakers petitioned the Canadian government to restrict MMT and safeguard the pollution control equipment of their vehicles. Environment Canada, the government's environmental agency, shared this concern and announced its intention to restrict the sale of MMT through an importation ban (bill C-29, the Manganese-based Fuel Additive Act). The Ethyl Corporation responded with a lawsuit claiming violation of the North American Free Trade Agreement (NAFTA) and damages of $251 million. In 1998 Environment Canada, seeing the likelihood of losing this legal battle, agreed to an out-of-court settlement. This removed the ban and transferred $13 million for "reasonable cost and profit" to the Ethyl Corporation (National Round Table on the Environment and the Economy, 1999).

Six years later all of the major Canadian oil refiners voluntarily removed MMT from the gasoline supply as a precaution against liability concerns (IFV, 2004). Canadian refiner Imperial Oil asked the Canadian government "to regulate [MMT's] usage or ban it completely" if MMT was found to increase vehicle emissions or damage vehicle components (Fisher, 2004). Canadian refiners say they will continue to avoid MMT pending the outcome of a government review.

In 2008 Health Canada released a draft risk assessment for airborne manganese to update the standard it set in 1994. The draft recommends tightening the current standard by more than fifty percent from 0.11 μg/m^3 to 0.05 μg/m^3. This value represents the concentration at which the general population and sensitive subgroups can be exposed for a lifetime without appreciable harm. The agency has not made public a timeline for formalizing this draft proposal.

As this review shows, both the United States and Canada are reviewing new findings on the health impacts of manganese and assessing the results of ongoing research on impacts on human health and vehicle components. New evidence can provide the basis for revision of existing policy toward manganese and MMT.

Health and Environmental Impacts

MMT is an organic manganese compound. In concentrated form it is a liquid that is highly toxic if inhaled, digested, or comes into contact with the skin (HDSB, 2007). It is so highly unstable under sunlight that in a matter of ten to fifteen seconds it decomposes rapidly into a mixture of manganese oxides.

The combustion of MMT releases manganese compounds into the air that are associated with neurological disorders akin to Parkinson's disease. Inhalation of high concentrations can rapidly produce symptoms in healthy individuals. At low levels these symptoms can develop over longer periods of time and may be subtle and difficult to detect; there is a significant lack of data on low-level chronic exposure (Environmental Protection Agency, 1994; Zayed, 2001). Low-level exposure may produce a slow rate of neurological damage that would delay diagnosis and treatment. Government studies in Canada and the U.S. during the 1990s established reference concentrations for safe levels of environmental exposure, but reviews now underway in both countries have put these levels in doubt. There remains a degree of uncertainty over what level of airborne manganese is safe to breathe and what amount of MMT puts the public health of vulnerable populations at unacceptable risk.

Emissions and Exposure

About 25 percent of the molecular weight of MMT is manganese, a silver-colored metal that forms compounds with oxygen, sulfur, and chlorine (Environmental Protection Agency, 2008c; HDSB, 2007). Manganese is an abundant element in the environment. In air it naturally occurs at a level between 0.01 and 0.03 μg/m^3, while in urban areas these levels can average as high as 0.07 μg/m^3 (World Health Organization Regional Office for Europe, 2000).

In Canada, where MMT was widely used for decades, studies show that widespread use in fuels does change the concentration of ambient manganese. In places that experienced large declines in industrial manganese emissions for example, ambient concentrations did not fall to background levels, with MMT in gasoline as the only remaining source (Bankovitch et al., 2003; Zayed, Guessous, Lambert, Carrier, & Philippe, 2003). In addition, concentrations of ambient manganese were higher in urban zones of Montreal than they were in rural areas (Bolté, Normandin, Kennedy, & Zayed, 2004). Other studies have concluded from the Canadian experience that when traffic density rises, ambient concentrations of manganese rise too (Boudia et al., 2006; Loranger & Zayed, 1997).

Measures of ambient concentrations of manganese have been taken in a variety of locations in Canada. At two urban locations in Montreal the average airborne concentration from 1993 to 2000 was between 0.025 μg/m^3 and 0.029 μg/m^3 (Finkelstein & Jerrett, 2007). Manganese concentrations were in the range of 0.02–0.06 μg/m^3 near roadways and 0.02–0.15 μg/m^3 at several Canadian gas stations (Loranger & Zayed, 1997; Thibault, Kennedy, Gareau, & Zayed, 2002). Concentrations in two underground car parks averaged 0.068 μg/m^3 (0.014-0.128) and 0.026 μg/m^3 (0.015-0.048) respectively. (Thibault et al., 2002). In these micro environments certain sub-populations are likely to have higher risk of exposure and may require targeted interventions. The average concentration of MMT in gasoline ranged between 6.3 and 10.8 mg Mn/L, but the maximum allowable limit was 18 mg Mn/L. Had the concentration in fuel been higher, the ambient concentration of manganese would likely have been higher too.

The US EPA conducted an exposure assessment for particulate manganese using the results of a probabilistic study conducted in Riverside, California in the fall of 1990 when MMT was still being used in leaded gasoline. Assuming a concentration of 8.3 mg Mn/L (the legal US limit), the US EPA estimated that approximately 5-10% of the population could experience personal exposures of particulate manganese at 0.1 $\mu g/m^3$ or higher (J. M. Davis, Jarabek, Mage, & Graham, 1999). Although this study was not extrapolated to the entire U.S., the results suggested that widespread use of MMT may push ambient concentrations above the reference concentration and increase the risk of disease in certain communities.

Health Effects

Manganese is an essential co-factor for certain enzymes (see "The dangers of inhaling manganese" below) (Barceloux, 1999). Most individuals consume 1 to 10 mg per day through food and water, although the body retains only 3 to 5 percent of this. Although it is rare to suffer manganese deficiency, too little manganese in the diet can produce changes in hair color, skin problems, and variations in cholesterol, metabolism, and blood clotting. A more likely concern is accumulation of manganese in the brain that produces unwanted changes in motor function and behavior.

The manganese produced from the exhaust pipe of vehicles has properties that differentiate it from other forms of ambient manganese. This exhaust contains fine particles of manganese phosphates (Mn5(PO4)2), highly soluble manganese sulfates (MnSO4) and manganese oxides (primarily Mn3O4) (Moore, 2008; Zayed, Hong, & L'Esperance, 1999). Particle sizes range from as large as 10 microns to as small as 0.2 microns. These smaller particles can penetrate deep into the lung and deliver more manganese to the bloodstream. A study of animal exposures found that compounds with higher oxidation states delivered more manganese to the brain (Reaney, Bench, & Smith, 2006). Oxidative stress may also have a role in the progression of neurological disorder and in brain cell death (Dobson et al., 2004; Kitazawa, Wagner, Kirby, Anantharam, & Kanthasamy, 2002).

When taken orally, manganese passes through the digestive system. Here the liver regulates the concentration of the metal entering the bloodstream to protect the brain from toxic levels. When manganese is inhaled into the lungs, however, it bypasses the liver and enters the bloodstream directly where it can travel unfiltered to the brain. Certain manganese sulfate particles are highly soluble, so they can dissolve and travel more rapidly through blood to the brain (Dobson, Erikson, & Aschner, 2004). Inhaled manganese can also bypass the circulatory system and enter the brain directly through the nose. An animal study showed delivery of manganese along a group of nerves in the nasal passage that connects directly to the brain (Tjalve, Henriksson, Tallkvist, Larsson, & Lindquist, 1996). These mechanisms demonstrate that inhalation of manganese is potentially more dangerous than digestion, and it is the source of concern about large releases of manganese into the ambient environment (Teeguarden, 2007).

The brain is more vulnerable than other organs to high concentrations of manganese. One potential defense against neurotoxins is the blood-brain barrier, but Yokel and Cossgrove have shown that manganese compounds can cross this barrier. They have also shown that manganese enters the brain more rapidly than it leaves, which identifies a mechanism for accumulation over time (Yokel & Crossgrove, 2004). Studies in animals show that manganese will accumulate in other organs as well, including the blood, liver, lungs, and testes, but with a mechanism for accumulation, the brain is potentially more vulnerable than other organs

The Dangers of Inhaling Manganese

Manganese is a nutrient that is necessary for the proper function of the human body. It helps to produce enzymes like hexokinase, superoxide dismutase and xanthine oxidase for processing blood sugars into energy and for preventing diseases like cancer and renal failure. But it also falls into a category of neurotoxic heavy metals like cadmium, lead and mercury. The body must have manganese to function properly, but must regulate concentrations carefully.

The body absorbs manganese in food, and it has developed a way for taking only as much as it needs. When food makes its way from the digestive system to the circulatory system, it passes through the liver, which is well adapted to filter out high levels of manganese. It does this so well that instances of poisoning are rare in healthy individuals, although children may still be at risk (Wasserman et al., 2006). Individuals who are sick with liver disease or malnutrition cannot perform this function properly, so excessively high amounts of manganese in food and water can poison them.

The human body is less able to guard against manganese that travels through the air. When it enters the body, it penetrates deep into the lungs where it transfers into the bloodstream, bypassing the liver and making its way unfiltered to the brain. When airborne manganese passes through the nose, neurological pathways can transport it directly to the brain. These mechanisms explain why airborne manganese is much more dangerous than food borne. Manganese is safe only when filtered through a healthy digestive system, not when inhaled through the air.

(Drown, Oberg, & Sharma, 1986; Newland, Cox, Hamada, Oberdorster, & Weiss, 2002; Salehi et al., 2001; Salehi et al., 2003; Vitarella, Wong, Moss, & Dorman, 2000). Once in the brain, significant manganese accumulation and cell death occurs in the olfactory bulb and the basal ganglia (Dobson et al., 2004). The olfactory bulb is responsible for smell while the basal ganglia is responsible for motor control, cognition, emotions and learning. This research shows how vulnerable the brain is to high concentrations of manganese.

Suspicions about the neurotoxic effects of manganese were recorded in 1837 when workers breathing manganese dust experienced a decline in motor function, muscle weakness, tremors, a bent posture, soft speech and hypersalivation (Couper, 1837). Since then a group of occupational studies of high exposures have confirmed the development of Parkinsons-like symptoms. For example, a study of Belgian workers found that exposure to a mean integrated dust concentration of 793 $\mu g/m^3$ (40 $\mu g/m^3$ - 4933 $\mu g/m^3$) produced significantly worse performance on tests of visual reaction time, hand-eye coordination and hand steadiness (Roels, 1987; Roels, Ghyselen, Buchet, Ceulemans, & Lauwerys, 1992). A Canadian study of workers exposed to manganese at an average respirable concentration of 35 mg/m^3 found a significant effect on ability to keep hands steady, alternate hands rapidly, and display fine motor control. Swedish occupational studies have shown similar results (Iregren, 1990; Mergler et al., 1999; Mergler et al., 1994; Wennberg, Hagman, & Johansson, 1992; Wennberg et al., 1991).

The progressive neurological disorder seen in these workers is called Manganism, and it is often confused with Parkinson's disease. Both produce a decline in motor function and loss of coordination, but Manganism also produces changes in behavior. This can include nervousness, hyperirritability, memory loss, ability to think, bizarre behaviors and hallucinations (Health Effects Institute, 2004; McMillan, 1999). In severe forms of Manganism the individual falls victim to dramatic behavior changes like aggression, destructiveness, and compulsive and uncontrollable behavior. Occupational studies have verified this effect and others relating to the pulmonary and reproductive system (Hauser, Zesiewicz, Martinez, Rosemurgy, & Olanow, 1996; Iregren, 1990; Lucchini et al., 2000; Mergler et al., 1994; Roels, 1987; Roels et al., 1992).

As symptoms of Manganism progress, the chance of recovery diminishes. The administration of L-Dopa, a drug commonly given to Parkinsons patients, has no effect in patients with Manganism. A few small studies have administered edetate calcium disodium (EDTA) and para-aminosalcyclic acid (PAS Sodium) with some limited effect, but large-scale studies are still lacking (Discalzi et al., 2000; Ky, Deng, Xie, & Hu, 1992). Given the state of the science, there is no known successful treatment or cure for Manganism.

In Brescia, Italian researcher Roberto Lucchini has studied the prevalence of Parkinson's–related symptoms in stable communities downwind of industrial sources of manganese dust (Lucchini et al., 2007). Here the average standardized prevalence rate was 407 per 100,000, compared with 158 throughout Italy and a maximum 257 for all of Europe. Men displayed symptoms of disease at a below-average age, a sign that the effect of manganese is not age-related. In areas where concentrations of manganese in dust were highest, prevalence of Parkinson's was highest as well, suggesting a strong correlation between disease and concentrations of manganese. Outside of one ferroalloy plant the average ambient manganese concentration was 0.7 $\mu g/m^3$. Just 50 km downwind in the town of Brescia, the average concentration of manganese was 0.08 $\mu g/m^3$.

A study in Sauda, Norway, former location of the world's largest ferroalloy plant, found a prevalence rate for Parkinsons of 247 per 100,000, compared to the Scandinavian crude rate of 115 (Fall et al., 1996; Øygard, Riise, Moen, & Engelsen, 1992). In a study of a manganese mining village in Mexico, mean ambient concentrations of manganese were 0.1 $\mu g/m^3$. Here researchers found changes in cognitive and motor function associated with the manganese exposure of study participants (Rodriguez-Agudelo et al., 2006).

Researchers have had difficulty directly studying the effect of low-level ambient manganese exposure. The relative absence of widespread international experience with MMT has required researchers to focus mainly on industrial manganese emissions. Nearly all studies use Parkinson's disease as a proxy since doctors are likely to misdiagnose more rare manganese overexposures. Canada is the only country where MMT was widely used for any significant period of time and where accurate health records are accessible. Most ambient studies of MMT have taken place here.

Unfortunately, only one general population epidemiological study has successfully evaluated the association between MMT and health outcomes. Researchers based in the United States and Canada published a study in 2007 that looked at health records and ambient concentrations of manganese in two Canadian cities - Hamilton, Ontario, where a ferroalloy plant was the dominant manganese emission source; and Toronto, Ontario, where vehicles were the dominant source (Finkelstein & Jerrett, 2007). In Hamilton, researchers found a significant association between airborne manganese and incidence of Parkinsons disease at an odds ratio of 1.034 (1.00-1.07) per .01 $\mu g/m^3$ of Mn. In Toronto, where historical measurements of manganese were unavailable, researchers were unable to see an association between Parkinsons and total suspended particles, a proxy measure for manganese. With such low contrast between exposure levels and a small sampling period, the study may not have been sensitive enough to detect a relationship. A follow-up study is being planned.

Environmental Concerns

Environmental concerns have received less attention than health concerns, and this is reflected in the scientific literature.

Research shows that MMT can remain present in both air and water. For example, MMT was found in most samples of water and storm runoff collected along highways where MMT was in use (Yang & Chau, 1999). These results are unusual since they contradict our current understanding of MMT, which tells us that this chemical breaks down rapidly in the environment, particularly when exposed to sunlight. This raises questions about how completely MMT's environmental fate is understood (Zayed, 2001).

Roadside plants, soils and urban animal tissues have all shown elevated manganese levels related to traffic (Zayed, 2001). A handful of other environmental studies have contradicted this finding and show limited or no Mn deposition. One American study showed that MMT in gasoline will produce a slow increase in Mn concentrations in soil near a busy Canadian intersection, but a doubling of this concentration would take 95 to 256 years (Bhuie, Ogunseitan, White, Sain, & Roy, 2005).

Health-Based Regulations

Several jurisdictions including the United States, Canada, and the World Health Organization have conducted health assessments of airborne manganese. They universally establish that manganese compounds are dangerous and toxic substances. In the United States manganese compounds are classified as hazardous air pollutants known or suspected to cause serious health problems. In the state of California manganese compounds are listed as toxic air contaminants. Safety standards for ambient manganese exposure set by these agencies typically refer to a level of lifetime exposure below which no increase in risk for adverse health effects is expected to occur in the general population.

The US EPA has set a reference concentration (RfC) at 0.05 $\mu g/m^3$ (48, 101,102)(Environmental Protection Agency, 2008b; National Round Table on the Environment and the Economy, 1999). The reference concentration (RfC) is an estimate of daily inhalation exposure over a lifetime that is unlikely to pose an appreciable risk to the general population.. The Agency for Toxic Substance and Disease Registry (ATSDR), another US government agency, has established a minimal risk level (MRL) for chronic inhalation at 0.04 $\mu g/m^3$ (Agency for Toxic Substances and Disease Registry, 2000; Environmental Protection Agency, 2008b; National Round Table on the Environment and the Economy, 1999). The World Health Organization has established a guideline annual average airborne manganese concentration of 0.15 $\mu g/m^3$ (World Health Organization Regional Office for Europe, 2000). And the California Office of Environmental Health Hazard Assessment is set to lower its chronic inhalation reference dose from 0.2 $\mu g/m^3$ to 0.09 $\mu g/m^3$ based on an updated methodology for risk assessments (Office of Environmental Health Hazard Assessment, 2008). In 2008 the agency Health Canada published a draft assessment that proposes to cut in half the current Canadian standard for chronic inhalation from 0.11 to 0.05 $\mu g/m^3$. The California and Canadian proposals have not been formally adopted.

Uncertainties

Sources of uncertainty in the health effects of manganese are the dose, duration, and method of exposure, as well as the age of the individual and the presence of other chemicals.

Other uncertainties stem from unknown concentrations of MMT in use in gasoline and the difficulty in capturing the relationship between this and the concentration of ambient manganese. In Canada the average gasoline concentration ranged between 6.3 and 10.8 mg Mn/L, while in Montreal the background ambient manganese concentration varied between .02 and .03 $\mu g/m^3$, although this reached higher levels in certain micro-environments. In 2006 the concentration of manganese in Chinese gasoline reached 34 mg/L, well above the regulatory limit of 16 mg/L (Takei 2007). In Lithuania a recent survey showed concentrations up to 55 mg/L, even though octane benefits are limited to 2.5 R + M/2 at this level. (Environment Canada, 2003; Schindler, 2004). It is uncertain how these high MMT concentrations relate to the concentrations recorded in Canada since we have no ambient measurements to compare. The specific atmospheric conditions and geographic features of a region will certainly modify this relationship, just as it does for other pollutants. The higher than expected concentrations of manganese found in China and Lithuania suggest that both strong regulations and consistent enforcement are needed to protect against dangerous levels of exposure. In addition, it may be necessary to regularly monitor and regulate airborne concentrations to protect against adverse health effects, just as this was done for lead in the United States.

Additional uncertainty stems from the composition of the vehicle fleet. One study showed that when MMT was used, as low as 4 percent and as high as 41 percent of the manganese in gasoline was emitted (Environmental Protection Agency, 2006; Ardeleanu, Loranger, Kennedy, L'Espérance, & Zayed, 1999). Vehicle fleets are also growing, and as they grow the aggregate emissions from the fleet will increase. Emissions of manganese will vary with the composition of different vehicle types and drive cycles. These factors would add variation in the estimates for different countries.

Certain population groups would be exposed to higher concentrations in micro-environments. In two underground car parks in Burlington-Hamilton, Ontario, researchers recorded average concentrations between 0.16-0.20 $\mu g/m^3$ for total manganese and 0.04-0.10 $\mu g/m^3$ for respirable manganese (Thibault et al., 2002). A study of garage mechanic exposure recorded concentrations of 0.42 $\mu g/m^3$ Mn. Concentrations averaged over the mechanics' working and non-working hours were 0.25 $\mu g/m^3$ Mn (Zayed, Pitre, Rivard, & Loranger, 1999). These levels are higher than background levels in Canada, which suggests that workers who spend long hours in exposed environments may experience greater health risk.

The young and old are another set of high-risk population groups. Children spend more time outdoors, spend three times as much time engaged in sports and vigorous activities, and have a higher breathing rate in relation to their body size and lung surface area compared to adults. They are likely to have higher exposures to ambient manganese (American Lung Association, 2000; Committee on Environmental Health, 2004). The elderly are more vulnerable to neurological damage from manganese, which inhibits dopamine uptake (Watson, 2001).

Certain health conditions can make an individual more vulnerable. Adults with pre-Parkinson's syndrome may experience enhanced motor dysfunction (Gwiazda, Lee, Sheridan, & Smith, 2002). Individuals with iron deficiencies have shown elevated blood manganese levels, which may reflect how manganese and iron ions use the same proteins to cross the blood-brain barrier (Kaiser, 2003; Mena, Horiuchi, Burke, & Cotzias, 1969). Because an impoverished diet and lack of nourishment can cause iron deficiencies, this could be especially important if MMT is used in countries where malnourishment is a problem. And individuals with chronic liver disease are at increased risk of hepatic encephalopathy, a brain disorder similar to Manganism that may be caused by the liver's inability to filter manganese and other toxins from the blood before reaching the brain (Butterworth, 2003). Other evidence shows that even between healthy individuals, the metabolism of manganese may vary (Davidsson, Cederblad, Lonnerdal, & Sandstrom, 1991; Rodier, 1955). These show that the biological response of each individual to manganese exposure will vary.

Uncertainties remain in the basic toxicology and epidemiology of manganese exposure. For example, our understanding of the impact of low-level, chronic exposure to airborne manganese is rudimentary due to the few studies available on this topic, particularly those that focus on MMT as a manganese source. Research suggests that the neurological symptoms of overexposure to manganese may not become apparent until years after the exposure has occurred. Few attempts have been made to develop and fund long-term studies (Cotzias, Horiuchi, Fuenzalida, & Mena, 1968; Rodier, 1955). Such a review would need to look particularly at the effects on sensitive populations such as infants, pregnant women, the elderly, and people with preexisting conditions like liver disease and Parkinson's. This also includes people who live or work near major vehicle emissions sources like garages or major urban centers. And while most research has focused on neurological effects, there is a need to explore respiratory and reproductive effects as well.

One methodological difficulty is the reliability of certain biomarkers of manganese exposure. In a set of Canadian and Mexican studies there was no association between ambient manganese concentrations and blood concentrations (Bolté et al., 2004; Rodriguez-Agudelo et al., 2006). However the opposite was true of another Canadian study (Baldwin et al., 1999). The World Health Organization has expressed doubt that blood concentrations are a useful biomarker (World Health Organization Regional Office for Europe, 2000). A 2007 review found that not only blood samples but also urine samples fail to accurately predict manganese exposure (Smith et al., 2007). One researcher has proposed using a combination of blood concentrations, MRI scans and neurobehavioral tests, but this may prove burdensome (Greger, 1999). An accurate biomarker for manganese that can relate levels of exposure to the brain is needed.

The Scientific Consensus

The Canadian and American governments share doubts about the ability of the available research to accurately predict the health outcomes of manganese exposure. For example the US Environmental Protection Agency continues to demand research from the Afton Corporation to establish a pharmacokinetic model for manganese. This would fill a research gap in our understanding of how manganese interacts with the brain and other organs. The government agency Health Canada has developed a draft risk assessment for inhaled manganese that proposes a new reference concentration. The draft released for public comment in Spring 2008 updates an assessment completed in 1994.

Non-governmental entities have attempted their own analysis. In 1998 the American Medical Association Council on Scientific Affairs reviewed population-level exposures to manganese from MMT in gasoline and found a low risk of exposure. But this review was unable to evaluate long-term, low-dose exposures due to the absence of research (lyznicki, Karlan, & Khan, 1999). An effort by the American Chemistry Council Petroleum Additives Panel, in cooperation with the US EPA, submitted a screening level hazard characterization for MMT under the High Production Volume Challenge Program. The December 2007 screening found that the potential health hazard based is high for both acute inhalation and repeat-dose inhalation (High Production Volume Chemicals Branch, 2007).

Two health entities have taken a position on the use of manganese fuel additives. The American Academy of Pediatrics (AAP) in its 2003 practice guidelines to pediatricians on environmental health titled *Pediatric Environmental Health* makes recommendations on MMT (AAP, 2003a). The guidelines state that "to permit addition of MMT to the US gasoline supply would not be prudent" and recommend that, "Prevention of exposure to the most toxic additives to gasoline, such as tetraethyl lead, MMT, MTBE, or benzene, is best achieved by government regulation or phasing out of these compounds." The APP was founded in 1930 to establish an independent forum for pediatricians to respond to the special developmental and health needs of children. The organization based in the United States today has 60,000 members.

And in June 2006 the International Commission on Occupational Health convened a workshop at the University of Brescia entitled *Neurotoxic Metals: Lead, Mercury and Manganese – From Research to Prevention (NTOXMET)*. The conference participants, including researchers and physicians from 27 countries, adopted a consensus declaration on the prevention of the neurotoxicity of mercury, lead and manganese (Landrigan et al., 2006). The declaration made the following statement:

"The addition of organic manganese compounds to gasoline should be halted immediately in all nations. The data presented at the Brescia Workshop raise grave concerns about the likelihood that addition of manganese to gasoline could cause widespread developmental toxicity similar to that caused by the worldwide addition of tetraalkyl lead to gasoline. In light of this information, it would be extremely unwise to add manganese to gasoline."

Vehicle and Emissions Impacts

Aside from the health concerns outlined above, metallic fuel additives are problematic for air quality regulators because they tend to interfere with emission control devices on vehicles. Tetraethyl lead was eliminated primarily to allow catalytic devices to perform optimally. Manganese has posed a similar obstacle and it was on this basis that the state of California and the United States both banned manganese-based fuel additives in the 1970s. In the early 1990s the US Court of Appeals ordered the US EPA to rescind its ban, but the California ban remains in place.

Since the US Court of Appeals ruling in the early 1990s, major automobile manufacturers have sponsored ongoing tests of MMT and its effects on vehicle emissions, emission control system durability, and customer satisfaction. In light of the court action, automobile manufacturers are concerned that fuel containing manganese will cause vehicles—particularly low emission vehicles—to exceed increasingly stringent vehicle emissions standards. New emission control devices with higher cell densities may be more prone to clogging (Schindler, 2004). And at the same time, stringent standards leave little tolerance for emissions exceedances. In the absence of government research, private industry has funded its own vehicle emissions research.

Another reason for this concern comes from the experience in countries where MMT is or was used. In Canada, MMT has been blamed for higher warranty costs (Ghitter & Kenny, 1997). Customers there complained of blocked and ineffective catalysts (Schindler, 2004). In 2004 one automobile manufacturer experienced a dramatic increase in catalyst replacement rates in Canada where MMT was widely used, while the same vehicle model in the United States showed no such increase. In South Africa and China, use of MMT has lead to emissions deterioration and spark plug fouling (Schindler, 2004).

A variety of small-scale studies have been published since the 1970s on the emissions effects of MMT. The Society of Automotive Engineers (SAE) has published at least 30 studies on MMT beginning as early as 1975. The authors have been either affiliates of automobile manufacturers or the Afton Corporation and its predecessor, the Ethyl Corporation, and they each tend to produce results that support the positions of the organizations the authors represent. The distribution of studies is about even between the two and this distribution has produced little consensus over the vehicle emissions impacts of MMT.

A coalition of automobile manufacturers in 1996 launched a 6-year, eight million dollar study of MMT and its effect on vehicle emissions (Alliance of Automobile Manufacturers, 2008a). A total of 56 vehicles taken from 14 model types and 6 manufacturers were driven between 50,000 and 100,000 miles on fuel containing 31 mg Mn/L of MMT.

The first part of the study tested MMT on a selection of forty vehicles grouped to represent the 1996-1997 US vehicle fleet, including Tier 1 vehicles, transitional low emission vehicles (TLEVs), and a single low emission vehicle (LEV) (Alliance of Automobile Manufacturers, 2008c). The results showed that between 4,000 and

50,000 miles driven, MMT was associated with an average 13 percent increase in tailpipe HC emissions. Results that were statistically significant showed an approximate 6 percent increase in CO emissions, a 10 percent decrease in NO_x emissions, a 0.1 to 0.5 mpg decline in fuel economy, and a one percent or less increase in CO_2. One vehicle model experienced spark plug misfire and another experienced exhaust valve leakage. These results show that the use of MMT did indeed impact emissions of the vehicles, some of which would cause failure of emission certification standards.

The LEV model in Part 1 was driven up to 75,000 miles and showed a different suite of emission patterns. Not only did HC and CO emissions increase, but NO_x emissions increased as well. These results stimulated the creation of a second part to the study to continue exploring emission impacts on LEVs.

The second part of the study compared sixteen vehicles taken from three light-duty and one medium-duty California-certified low-emission vehicles from model years 1998 and 1999. The results showed that all light-duty LEV models failed to meet emission certification standards for HC, but met the NO_x and CO standards (Alliance of Automobile Manufacturers, 2008b). The single medium-duty LEV complied with all certification standards. Results for the full fleet of LEVs showed that between 4,000 and 100,000 miles, tailpipe emissions were on average 4 percent higher for HC and 1.4 percent for CO_2. CO and NO_x emissions were equivalent through 75,000 miles, but at 100,000 miles NO_x emissions were 24 percent higher and CO emissions were 14 percent higher. On-road fuel economy was 2 percent lower. The results showed that MMT in light-duty LEVs driven over 100,000 miles is associated with an increase in HC, CO and NO_x emissions, and as vehicles age the rate of increase in emissions rises.

What explains this difference in emissions between MMT and non-MMT fueled vehicles? The study authors theorize that the cause of the HC increase is the accumulation of MMT-related deposits on combustion chambers. The authors further explain that the increase in total hydrocarbons (THC), CO and CO_2 and the decrease in NO_x are consistent with both a fuel-rich bias and an increased throttle opening that causes additional fuel and air throughput. Both effects are expected to be additive over time. The increase in CO_2 is also explained by oxidation of engine-out CO. A degradation of catalytic converter performance over time explains the divergence in total emissions as the vehicles age.

In 2004 researchers affiliated with the Ford Motor Company undertook a follow-up study of two Ford Escort LEVs used in the AAM study (McCabe, DiCicco, Guo, & Hubbard, 2004). This was an effort to explain how MMT produced an increase in emissions. The researchers hypothesized that MMT changed the properties and the operation of specific vehicle components. They first leak-checked and inspected the vehicles for maintenance before emission testing. Then they removed the engine cylinder heads, spark plugs, oxygen sensors and catalysts from each. These parts were swapped individually, in groups and as a whole to determine the effects of specific components on the emissions of each vehicle. Back-to-back emission testing of the vehicles was performed for each configuration on a chassis dynamometer using fuel without MMT.

Results of emission tests reaffirmed the results of the AAM study. The complete swapping of the cylinder head, spark plugs, oxygen sensors and catalyst from an MMT-fueled vehicle into a non-MMT fueled vehicle produced the same emission characteristics within a 90 percent confidence interval. They caused a 118 percent increase in HC, 130 percent increase in CO, and 143 percent increase in NO_x in the vehicle that operated on non-MMT fuel in the original AAM study.

The authors related the causes of tailpipe emission increases to specific changes in vehicle component properties and performance. Increases in HC and CO emissions were associated with an increase in feedgas emissions and a shift in the air to fuel ratio caused by reddish brown deposits on the cylinder head.

Increases in NOx emissions were associated with deposits on the catalyst. A later study of these deposits found that they resembled manganese oxides and a combination of other manganese and zinc compounds (Boone, Hubbard, Soltis, Ding, & Chen, 2005).

Catalysts since the 1970s have been an essential technology to achieve emission reduction goals. Automobile manufacturers have expressed worry that technologies to continue reducing emissions, namely higher cell density and close-coupled placement of catalysts, will be even more susceptible to MMT deposits (Shimizu & Ohtaka, 2007).

Automaker Consensus

The Alliance of Automobile Manufacturers, the Engine Manufacturers Association, the Japan Automobile Manufacturers Association, and the European Automobile Manufacturers Association released a worldwide fuel charter in 2006 that sets standards to harmonize global fuel quality (ACEA, 2006). This charter recommends the removal of metallic fuel additives containing Mn to non-detectable levels for fuel used in catalyst-equipped vehicles.

Some automakers have expressly instructed vehicle owners not to use fuels containing MMT. In a 2004 user's manual Ford Motor says "Your engine was not designed to use fuel or fuel additives with metallic compounds, including manganese-based additives…. Repairs to correct the effects of using a fuel for which your vehicle was not designed may not be covered by your warranty" (Ford, 2003). Honda on its website for owners contains this statement: "Do not use gasoline containing MMT… this additive contaminates your engine components and exhaust emission control system, and can lead to a significant increase in emissions and a loss in performance and fuel economy. Damage caused by the use of fuels containing MMT may not be covered under warranty" (Honda, 2004).

Alternatives to MMT

There are many reliable and effective alternatives to raising octane. A country that imports its fuel can select a gasoline blend that does not use MMT, while a country that refines its fuel can make changes to its refinery process through new investments, new configurations, or importation of high octane blending components.

There are a variety of refining methods that can increase the octane of crude oil during processing. These include catalytic reforming, isomerization, catalytic cracking, alkylation, etherification, and hydrotreating. The type and configuration of each refinery will determine its ability to adopt any one of these methods and may require new investments and/or a reconfiguration. Consideration of new refinery investments should take into account ways to improve high quality fuel yield, increase the output of gasoline and diesel, reduce sulfur levels, and make other improvements in overall fuel quality.

In the absence of technical or economic resources to change refinery processes, there are high octane blending components on the market that refineries can incorporate into their final products. These are ethers like Methyl Tertiary Butyl Ether (MTBE) or alcohols like Ethanol. Ethers are high-octane organic compounds containing carbon, hydrogen and oxygen, while alcohols are a product of the fermentation of sugars in crops and other biological sources.

MTBE is an ether manufactured via a chemical reaction between methanol and isobutylene, both of which can be derived from natural gas. In the United States it is associated with large-scale contamination of groundwater supplies that affects the taste and odor of water. US refiners have largely removed this additive from their supply.

Ethyl Tertiary Butyl Ether is an ether produced by reacting ethanol and isobutylene with a catalyst under heat and pressure. It is widely used in Europe and Canada.

Tertiary-Amyl Methyl Ether (TAME) is an ether derived from C5 olefins and methanol over a catalyst and under heat and pressure. It has a relatively high octane rating that makes it a good blending agent. The United States produces 50,000 barrels of TAME per day. Production occurs in Europe, China, and Mexico as well.

Ethanol is an alcohol produced via the fermentation of sugars in crops like sugarcane, beets, and corn. It has been widely used in countries like Brazil and China and it largely replaced MTBE in the United States. While there is a great deal of debate regarding the social and environmental benefits of ethanol as a replacement for gasoline, use of smaller quantities as an additive is less likely to have a significant impact on food prices, availability of arable land and greenhouse emissions. Nonetheless, the type of feedstock and production methods used will impact the sustainability of the end product. Ethanol has a very high octane rating and used as a blending agent can bring up the octane rating of gasoline. Incorporation of ethanol allows refiners to produce lower aromatic and olefin content. It can be difficult to transport since water penetration renders it unusable. It can also increase vapor pressure, which requires removal of high volatility components from gasoline to accept ethanol.

The Argument for Precaution

We understand the precautionary principle to mean that when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically. A precautionary measure therefore is an action to protect health and the environment when there is cause for concern before any harm has appeared. Precaution encourages a thorough pursuit of alternatives to the proposed action and places a burden of proof on the proponent of the action.

This principle has been adopted in legislation by the governments of Sweden and Germany; forms the basis for the National Environmental Policy Act in the U.S., which requires environmental reviews of new construction; and informs international agreements like the UN Treaty on Biodiversity. But it also informs the actions of everyday life. As parents we teach our children to look both ways before crossing the street, and we tell them to think about what they say before they say it. Likewise policy makers have a duty to act proactively to prevent harm rather than reactively when the harm occurs.

In 2008 the Clean Air Initiative for Asian Cities, a coalition funded by the Asian Development Bank to promote and demonstrate innovative ways to improve air quality in Asia, released its report on fuel quality entitled *A Road Map for Cleaner Fuels and Vehicles in Asia*. It calls for the application of the precautionary principle with regard to metallic additives and states the following:

Prominent health experts have raised serious concerns regarding the potential adverse health effects of metallic additives such as MMT and ferrocene, along with their potential adverse impacts on vehicle emissions and emission control system components. Therefore, the environmentally responsible approach for Asian countries is to apply the precautionary principle for these metallic additives and to not use them until and unless the scientific and health studies show that they are safe (Asian Development Bank, 2008).

The precautionary principle was not applied to lead, and this failure yielded significant public health costs. As early as 1924 public health scientists including Yendell Henderson of Yale University stated that widespread use of tetraethyl lead constituted a "probable industrial and public health hazard" (D. L. Davis, 2002). Despite this awareness and the lack of scientific certainty on the matter, no restrictions were placed on tetraethyl lead. The cumulative mental health effects of lead exposure would have been avoided with the precautionary principle.

In the 1970s the US Court of Appeals applied the precautionary principle to a regulation on lead phase-out. It found that the EPA does not have to prove that a product is a public health hazard in order to prohibit its use. It merely should show that the product is likely dangerous. This finding allowed the phase-out and the eventual ban on leaded gasoline.

Today risk assessments are the tool many governments and scientific bodies use to assess the potential harm of new chemicals, new technologies and a variety of other vectors with unknown effects on human health and the environment. They have been useful in evaluating worker exposures and setting air quality standards. But risk assessments can only rely on available information and quantifiable risks. The first risk assessment for lead, for example, produced a safety standard that has since been revised multiple times in response to new research and a clearer understanding of its effects. The same is true for air quality standards for ozone and particulate matter. Risk assessments are an essential tool for policymaking, but they are limited by the peer-reviewed scientific research available. Risk assessments are not a proxy for precaution.

Scientific certainty is a high standard. The process of research coupled with the vetting, reviewing and consensus-building necessary to achieve it requires large amounts of time. But policy makers do not have the luxury of time to wait for a decision about the safety of a particular action or environmental exposure. In the case of MMT, what should the policy maker do in the absence of certainty?

The precautionary principle provides guidance. In the case of MMT, it advocates restrictions to protect human health and the environment Where the health of large numbers of people is at stake and the harm is potentially irreversible, it is far better to err on the side of caution than wait for scientific certainty. Therefore the precautionary principle advocates the type of action that is protective against harm.

The precautionary principle provides additional guidance. When an environmental exposure poses a threat, it suggests consideration of alternatives. In the case of MMT, this means consideration of alternative mechanisms to boost octane. A series of these have been highlighted in this report. The use of the precautionary principle is made easier in the case of MMT, where a range of effective alternatives are available to boost octane to the necessary levels. In other cases, the lack of alternatives can make implementation of the precautionary principle more difficult.

Finally, the precautionary principle advises that the proponent of a potential harm, in this case the Afton Chemical Corporation, bear the burden of allaying the concerns about the health effects and other impacts of its product, MMT. A number of uncertainties were highlighted above and these remain areas that impede full agreement about its effects.

Research on vehicle emissions impacts provides compelling evidence that use of MMT over the life of the cleanest vehicles will result in an increase in pollutant emissions, reduced fuel economy, and greater stress on vehicle components and pollution control systems. Research on ambient exposures to manganese shows that exposure to these emissions can produce accumulation of manganese in the brain. Taken together with what is already known about manganese neurotoxicity, this research offers a persuasive reminder of the potential for widespread harm. It does not make sense to experiment with the introduction of a potential human neurotoxin until and unless such concerns are definitively laid to rest.

The health costs in the U.S. alone due to elevated blood lead levels that were a consequence of adding tetraethyl lead to gasoline were estimated at $172 billion annually, approximately 300 times the costs of lead replacement (see Appendix A). The potential health impacts and costs associated with widespread MMT should account for direct manganese emissions and mitigation of emissions of HC, CO, NO_x, and PM. Additional vehicle-related costs may include reduced fuel economy and increased warranty and/or replacement costs of fouled spark plugs, plugged catalysts, poisoned sensors, and other vehicle components, as well as redesign and replacement of these components if possible.

The actual costs of not using MMT are quite low. The availability of reasonable, cost-effective alternatives suggests that policy makers should exercise caution with the risks of allowing MMT.

Conclusion

Metallic additives like manganese-based MMT, iron-based Ferrocene and lead-based Tetraethyl Lead all face similar constraints. Each is a cause of concern to automakers due to metallic deposits that shorten the lifetime of engine components and harm catalysts necessary to meet emissions regulations. The health impacts are likewise worrisome. The low cost of metallic additives does not reflect the high cost of health impacts nor the cost of repair and replacement of vehicle components. For all these reasons it makes sense to use the precautionary principle in setting regulations for use of metallic additives in gasoline.

Without a high degree of confidence that adverse impacts will not occur, the ICCT recommends that countries avoid use of manganese-based fuel additives like MMT in gasoline. Many cost-effective alternatives for boosting octane exist and each country and region can determine which alternative works best for them. . This action puts governments on a path to securing air quality improvements and enabling dramatic emission reductions to protect public health and the environment. The ICCT urges policy makers to pursue the course that is in the best interest of the public they serve.

Appendix A: Lessons from Tetraethyl Lead

Physicians and public health advocates were alarmed about the dangers of a leaded gasoline additive as early as 1922. In 1925, at a U.S. Surgeon General's conference on lead additives, Robert Kehoe, then a consultant to and later Medical Director of the Ethyl Corporation, predecessor to the Afton Corporation, argued that when it could be proven "that an actual danger to the public is had as a result of the treatment of gasoline with lead, the distribution of gasoline with lead in it will be discontinued from that moment" (Nriagu, 1998). Yet, despite absolutely conclusive evidence of the widespread harm associated with lead additives, the same company continues to market and sell them to this day.

Almost 50 years after tetraethyl lead was first approved for use as a gasoline additive, EPA announced that lead would be phased out of the gasoline supply. Rather than acting quickly to protect public health, the Ethyl Corporation sued the EPA and lobbied for almost ten years to overturn its rule (Kitman, 2000). Despite the Ethyl Corporation's efforts, the lead phase-down was completed in the U.S. and Canada in 1986 and 1990 respectively, and lead was banned completely in 1996 and 1993 (UNEP, 1999). At the same time, however, the Ethyl Corporation dramatically expanded tetraethyl lead sales overseas. Between 1964 and 1981, the Ethyl Corporation's overseas business grew by tenfold. According to its 2002 Annual Report, tetraethyl lead marketing agreements were still accounting for 65% of its operating profit (Ethyl Corporation, 2002)

Even now that the effects of gasoline lead additives are widely agreed upon, tetraethyl lead continues to be used in many developing countries. The primary intent of the initial phase-down by EPA was to allow the introduction of catalytic converters, which were rendered inactive by lead, in order to control conventional pollutant emissions from vehicles. At the same time, there was increasing agreement among the scientific

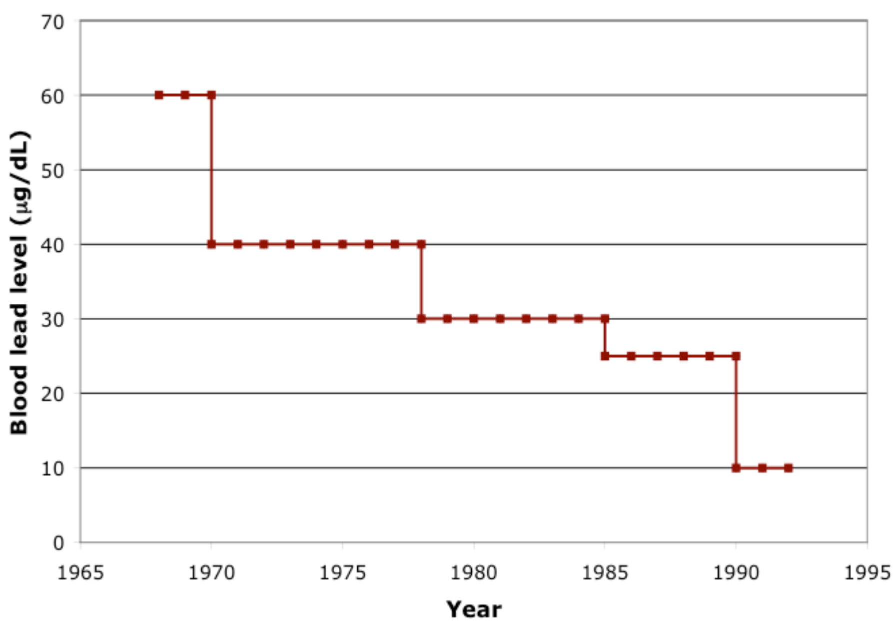

Figure A1: The change in the definition of blood lead toxicity over time. As recently as the 1970s the toxicity definition was six times higher than today's standard. At least fifty years of focused research informed that standard.

community that elevated blood lead levels were harming children and that lead additives to gasoline were an important contributor. Before the mid-1960s, a blood lead level of 60 µg/dL was considered toxic. By 1978, this level had been cut in half to 30 µg/dL (Centers for Disease Control and Prevention, 1991). In 1988, EPA concluded that some of lead's effects, "particularly changes in the levels of certain blood enzymes and in aspects of children's neurobehavioral development, may occur at blood lead levels so low as to be essentially without a threshold" (EPA, 2004). In 1990, the Centers for Disease Control (CDC) revised the definition of an elevated blood lead level downward to 10 µg/dL. More recent data demonstrates that there are adverse developmental effects at even lower blood lead levels, reinforcing EPA's earlier contention that there is no threshold for the negative impacts of lead (Bellinger, 2004; Chiodo, Jacobson, & Jacobson, 2004; Schwartz, 1994a). Figure A1 demonstrates how the federal definition of blood lead toxicity has changed over the years.

Lead affects virtually every system in the body and is particularly harmful to the developing brain and central nervous system of fetuses and young children. Very severe lead poisoning can result in coma, brain damage and death. Lower levels of exposure can result in kidney damage, hypertension and cardiovascular disease (Agency for Toxic Substances and Disease Registry, 1999; Centers for Disease Control and Prevention, 1991). Children are generally at greater risk from lead exposure than adults, and the impacts from low levels of exposure can be subtle and difficult to detect. The CDC states "Lead poisoning, for the most part, is silent: most poisoned children have no symptoms. The vast majority of cases, therefore, go undiagnosed and untreated" (Centers for Disease Control and Prevention, 1991). Even at subclinical levels (less than 10 µg/dL) elevated blood lead levels result in lowered IQs and can cause learning disabilities, impaired hearing, and developmental and behavioral problems (Centers for Disease Control and Prevention (CDC), 1991; Chiodo et al., 2004).

As lead was removed from gasoline, the mean blood lead level in the U.S. between 1976 and 1991 fell from 12.8 to 2.8 µg/dL, a 78 percent drop (Pirkle et al., 1994). Figure A2 shows blood lead and gasoline lead concentrations between the

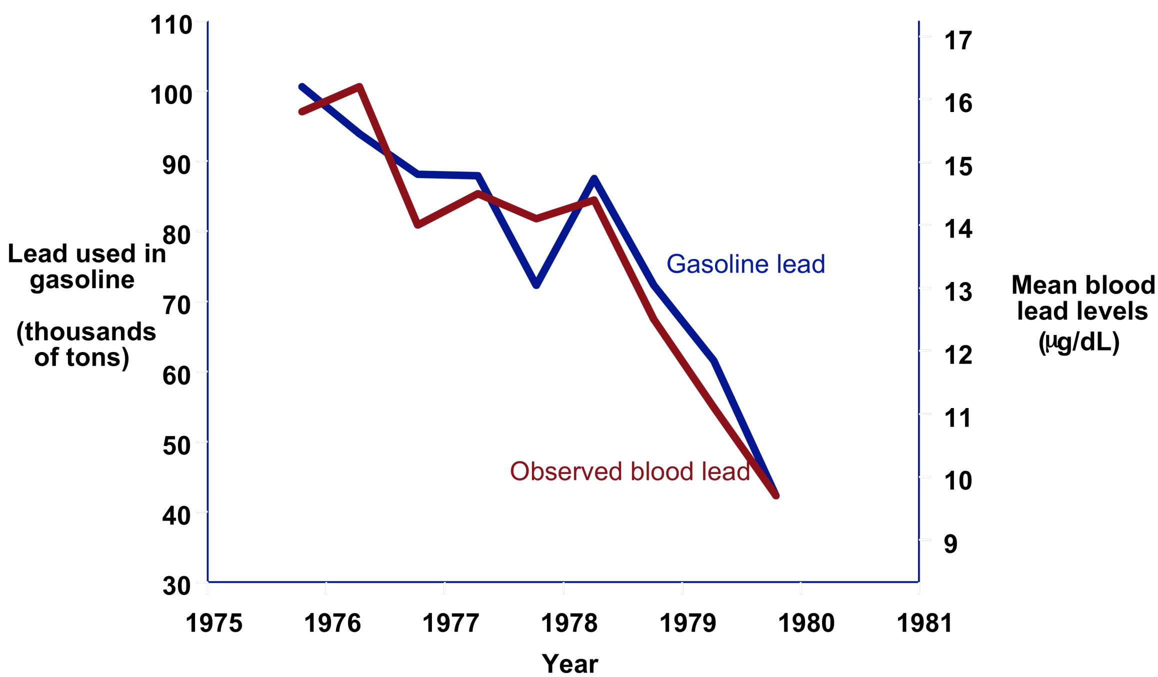

Figure A2: Change in observed blood lead levels and gasoline lead concentrations over time. Both followed a similar decline over a five-year period beginning in 1975 when regulations restricting leaded gasoline were first enforced.

late 1960s and the early 1990s. The two are closely linked. As gasoline lead concentrations fall in other countries, similar declines in blood lead concentrations have been found (World Bank, 2003).

An increase in ambient lead concentrations of 1 μg/m^3 would result in an increase in blood lead levels of 1.2 μg/dL in adults and 4.2 μg/dL in children. In adults, this increase in ambient lead concentrations is estimated to cause 45,000-97,000 cases of hypertension per 1 million males aged 20 to 70 and 200-650 premature deaths per 1 million males between the ages of 40 and 59 (Ostro, 1994). In children, the same increase in ambient lead would result in an average of 1 IQ point reduction. The total annual health benefit of reducing average U.S. blood lead levels by 1 μg/dL is estimated to be $17.2 billion (Schwartz, 1994a). By 1991, therefore, the U.S. was accruing $172 billion in annual benefits as a result of phasing out lead use from gasoline. This benefit is more than 300 times the predicted $500 million in annual costs attributed to lead elimination (Schwartz, 1994b).

The magnitude of predicted benefits for the U.S. suggests that removing lead from gasoline would produce a substantial economic benefit in other countries as well (Lovai, 1998).

Lead additives for gasoline are still in use in many parts of the world, and the health impacts from lead exposure continue to account for a significant share of the global burden of disease, especially in the developing world (Fewtrell, Pruss-Ustun, Landrigan, & Ayuso, 2004). Lead continues to be one of the most important environmental health problems for young children and, according to the CDC, it is also the most preventable (Centers for Disease Control and Prevention, 1991).

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