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RESEARCH ARTICLE

Getting the Lead Out: A Career-Long Perspective on Leaded Gasoline, Dust, Soil, and Proactive Pediatric Exposure Prevention

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"*The right to search for truth implies also a duty; one must not conceal any part of what one has recognized to be true.*" Albert Einstein. Engraved on a bench at the Albert Einstein Memorial, National Academy of Sciences, Washington, DC.

ABSTRACT:
This commentary considers the long arc of lead (Pb) poisoning from antiquity to the 21st century. While Pb exposure is commonly attributed to paint or water, this article aims to discuss the underrecognized impacts of air Pb and soil Pb and to address controversial misconceptions related to these exposure sources. The Roman Aristocracy experienced lead poisoning mainly from the ingestion of foods, lead cookware, and lead-contaminated water and wine, but by the 20th century, lead exposure occurred by ingestion and inhalation. The introduction of tetraethyl lead (TEL) additives in gasoline was approved in 1925 in the US and produced an exponential increase in inhalable air lead exhaust particles through the 1970s. These five decades of widespread lead aerosol exposure were enabled by the Lead Industries Association (LIA), which confounded pediatricians, healthcare providers, and government agencies by promoting lead-based paint as the primary agent of childhood lead exposure. Empirical evidence of lead poisoning, environmental exposures, and proactive lead prevention in the general population was impossible until analytical instruments became commonly available for clinical studies and environmental measurements in the 1960s and 1970s. Soil studies in Baltimore, Maryland, beginning in the mid-1970s, indicated that lead particles exhausted from vehicles fueled by leaded gasoline excessively contaminated urban soils compared with non-urban soils. The invisible lead-contaminated air fouled multiple exposure routes via inhalation and ingestion. In addition to misunderstandings about sources of lead exposure, misinformation currently abounds regarding the timeline of banning lead in gasoline. The US Center for Disease Control (CDC) lists the ban as beginning in 1996. The banning of leaded gasoline first occurred in Japan starting in 1972, and after a 1984 Senate Hearing, the US Congress agreed on a rapid phasedown. A US Environmental Protection Agency (EPA) timeline confirmed that most leaded gasoline was banned by the end of 1986. Banning leaded gasoline was associated with sharp declines in the US population's blood lead, which prompted global efforts to ban leaded gasoline. The eventual result was a complete global ban on highway use of leaded gasoline achieved in August 2021. Leaded gasoline is still used in piston-engine aircraft and the US EPA is proceeding to complete the ban on lead additives in fuel. Using precautionary principles to recover lead-contaminated urban environments and prevent new toxicant exposures are essential challenges and opportunities for present and future generations.

I. Introduction

Lead is a potent neurotoxin that affects IQ, learning, behavior, and is a leading cause of premature death worldwide[1]. Because of the neurotoxic effects and loss of mental facilities, Pb exposure has the potential to undermine the functioning of society[2]. A 2022 analysis of blood lead test results obtained from United States (US) children found that in 2015 over half the US population presented with blood lead (BPb) exposures of 5 µg/dL and higher at some time during their lifetimes in the period between 1950 and 1980[3]. United States medical and public health providers commonly focus on lead sources in paint and paint dust, soil, water, ceramics, and household objects. These sources of Pb exposure are then evaluated to consider their role in childhood lead poisoning.

This Proceedings of the National Academy of Sciences (PNAS) publication noted that in 2015 over 170 million (>53%) of the US population presented with a blood lead (BPb) exposure equal to or above 5 µg/dL in early life (±2.84 million, confidence interval (CI) 80%). Within the Pb exposed population, over 54 million (>17%) presented above 15 µg/dL, and over 4.5 million (>1%) presented above 30 µg/dL (±0.28 million, 80% CI)[3]. Among children born from 1951 to 1980, BPb exposures greater than 5 µg/dL were nearly universal (>90%). Since 2012 the US Center for Disease Control (CDC) established 5 µg/dL[3] as the reference value for elevated BPb (see Fig. 1). The reference value was reduced to 3.5 µg/dL on October 28, 2021 and the CDC currently states that there is "no known safe blood lead level"[4,5]. McFarland et al. (2022) translated what is known about the neurotoxic outcome of BPb exposure into the loss of Intelligence Quotient (IQ) points and concluded that lead exposure contributed to a total loss of 824,097,690 IQ points, and that IQ point loss was disproportionate among US citizens born in 1951 compared to 1980[3].

What Pb sources account for over half of the total US population in 2015 presenting with Pb exposure ≥ 5µg/dL at some point during their lifetimes? Although the usual focus is on Pb in paint or water, the purpose of this article is to discuss the impacts of air Pb and soil Pb, which are underrecognized Pb sources in the US. To illustrate these impacts, we trace the long arc of lead poisoning from antiquity to the 21st century and provide a critical analysis on the relationship between human activity and Pb exposure. We draw from a narrative review and a career-long perspective to articulate not only the tremendous impacts of air Pb and soil Pb on human health, but also the monumental efforts required to remove lead from gasoline. We offer these perspectives to ensure accurate information about environmental lead is more widely recognized and to promote further environmental remediation and primary prevention of lead exposure for vulnerable populations.

I.I Early lead poisoning from antiquity: ingestion of lead-contaminated food and drink

Lead poisoning is not a modern malady; it is as old as the history of mining and smelting which began at least 6 millennia before the Christian era in Southeast Asia, China, and the Middle East[6]. Although the medical details were unknown, the Greeks and Romans described symptoms of extreme lead poisoning such as colic, wrist drop, saturnine gout, anemia, mental deficits, behavioral issues, and child-bearing problems. Such symptoms were often attributed to laborers in mining and smelting occupations. However, lead poisoning was also common among the Aristocracy who exhibited similar symptoms of severe lead poisoning. Sources that account for lead poisoning among the Aristocracy included contaminated water drawn from lead pipes in the aqueduct systems, lead-contaminated wine, and cosmetics. When wine becomes sour and turns to acidic vinegar, ancient Greeks and Romans would store it in lead containers, and the acidic wine would dissolve lead to form lead acetate (sugar of lead) imparting a sweet flavor. One notoriously lead-tainted recipe, Sapa, is made by cooking and concentrating grape juice in a lead pot to make a sweet-tasting, thick syrup[7]. Lead-contaminated wine was common from antiquity to relatively recent times in many places and among a wide range of cultures[8,9].

Lead poisoning in colonial America was observed by Benjamin Franklin's recognition of workers who were employed to set lead type at his print shop. He noticed that workers developed wrist-drop because they were not washing their hands before eating sandwiches. In a letter dated 31 July 1786, Franklin concluded his letter with the statement, "You will see by it that the opinion of this mischievous effect from lead, is at least 60 years old; and you will observe with concern how long a useful truth may be known and exist before it is generally receiv'd and practic'd on"[10]. The mischievous effects of lead flourished long after Benjamin Franklin's 1786 letter, and indifference and ignorance continued during the 19th, 20th, and 21st centuries. It is now well known that lead exposure is related to multiple chronic health conditions, responsible for the calcification of the heart arteries, and approximately 412,000 deaths in the US each year[11].

I.II The ignored 20th-century warnings about inhalation of leaded gasoline

Tetraethyl lead (TEL), an organo-lead fluid, was used as a gasoline additive in the US beginning in 1925. At the time TEL was hailed as a "gift of God" for saving the automobile industry from a technical problem of explosive preignition[12]. There were major objections to using TEL in gasoline, as will be discussed below. But the value of profits was so high to the automobile, mining, and petrochemical industries that they fought for its use, and assured the public that it did not create serious health problems. Now TEL is regarded as "The mistake of the 20th Century"[13].

As Rosner and Markowitz (1985) show, public health experts, government officials, scientists, corporate leaders, labor, and the public were aware of the dangers posed by the introduction of lead into gasoline. Multiple spokespersons predicted that adding TEL to gasoline would result in lead poisoning. One important early warning in the 1920s was the lead poisoning tragedy among workers who suffered horrific symptoms of hallucinations and mental breakdown when they were manufacturing TEL "looney gas"[14]. Early objections included concern over the invisible characteristics of leaded gasoline and the difference in the physiology of ingestion compared to inhalation.

At a 1925 hearing, Yandell Henderson, Physiologist at Yale University, predicted that ordinary physicians would not be able to diagnose patients who were exposed to lead aerosols because inhalation resulted in distributing invisible lead particles throughout all organ systems. Henderson also predicted in 1925 "that the use of tetra-ethyl lead or the so-called 'looney gas' would cause a vast number of the population to suffer from slow lead poisoning with hardening of the arteries, rapidly decaying teeth, weakening of certain muscles, and other symptoms"[15]. Dr. Henderson expressed concern about the fate of medicine and public health when he stated, "…This is probably the greatest single question in…public health that has ever faced the American public…. The question whether…the action of the Government is guided by [scientific] advice; or whether commercial interests are allowed to subordinate every other consideration to that of profit"[15].

II. Present realities:

II.I Lead industry priorities

How was lead approved for use in leaded gasoline? In the 1920s, despite widespread knowledge of lead impacts on health and scientists providing testimony, how was this poison allowed to be emitted to environments worldwide? The influence of the lead industry and corporations were motivated by the desire for profits, progress, and the vision of building cars, with efficient high-compression engines, running on petrochemicals that did not have pre-ignition knocking[16]. The lead industry had mobilized against scientific documentation of lead's health impacts since at least 1894, when researchers in Australia reported childhood lead poisoning due to lead-based paint[17]. In addition to blocking bans against lead paint and lead pipes[18], the Lead Industries Association (LIA)'s "greatest triumph was in 1925, when it overrode opposition to the introduction of tetraethyl lead as a gasoline additive"[17].

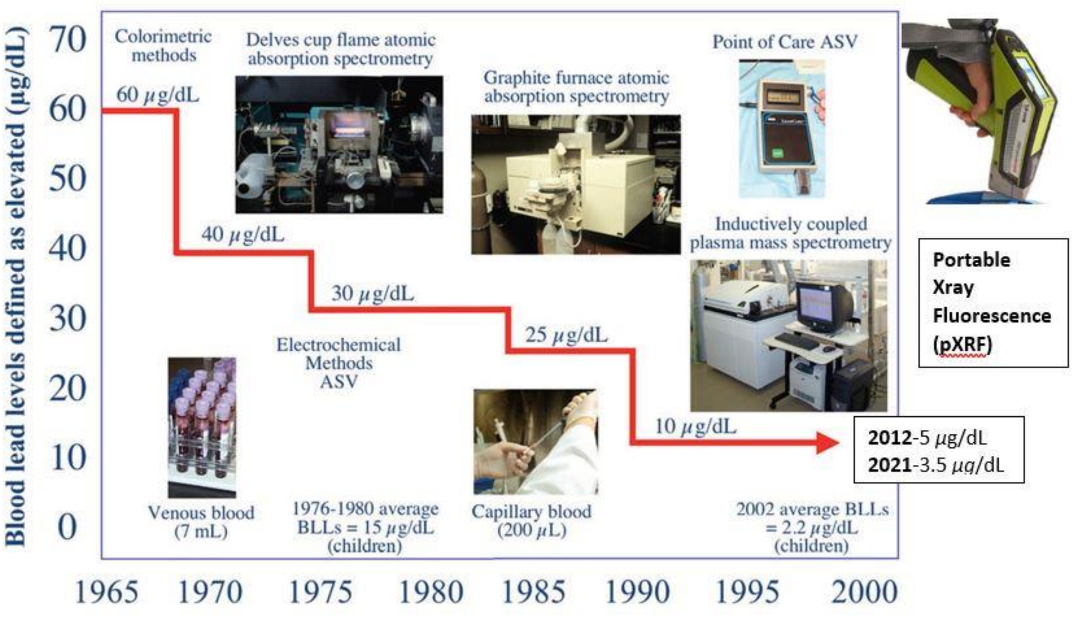
In past decades, it was assumed that the fiduciary responsibility of boards has been to enhance the corporation to maximize its value. Many chief executive officers (CEOs), directors, scholars, investors, asset managers, and others assumed, as a matter of fiduciary responsibility, that their responsibility was to protect the shareholders[19]. In this context it should not be surprising that the LIA made decisions to support the most lucrative money-making policies. Rosner and Markowtiz (1985) detail the ways in which corporations, government agencies, and scientists used a series of short-term studies to assert "that there is no danger of acquiring lead poisoning through even prolonged exposure to exhaust gases of cars using Ethyl Gas" (G. Edgar, General Motors director of research quoted in [12] p. 345). Despite such assurances, over 80% of 49 laborers in a tetraethyl lead processing plant died or were severely poisoned, which provoked controversy, and short-term banning of the sale of leaded gasoline in New York City, New York, and Philadelphia, Pennsylvania. Shortly after the last victim passed away, the Bureau of Mines released a study that The New York Times summarized with the headline: "No Peril to Public Seen in Ethyl Gas/ Bureau of Mines Reports after Long Experiments with Motor Exhausts/ More Deaths Unlikely." Scientists, public health experts, and activists questioned the validity of the study, which prompted proponents of leaded gasoline to escalate attempts to "sell" tetraethyl lead. Major arguments included that "leaded gasoline was essential to the industrial progress of America...that any innovation entails certain risks…[and] that the major reason that deaths and illnesses occurred at their plants was that the men who worked with the materials were careless and did not follow instructions"[12] (p. 347). Despite the warnings by Yandel Henderson about the Ethyl Gas Corporation providing funding for research, and issues with the conditions of the experiments, the industry managed to convince the US policymakers that there was no need to ban this gasoline additive "until definitive proof existed that it was a real danger"[12]. While people are presumed innocent until proven guilty in courts of law, should potentially lethal toxicants receive the same benefit of the doubt? Establishing the indisputable links between lead exposure and public health took decades of work and relied on advances in analytical instrumentation.

Although the LIA had initially advocated for the safety and use of lead-based paints, by the 1960s, the LIA asserted that lead-based paint was the dominant source of lead poisoning. On April 14, 1969, the board of directors of the LIA stated, "It should be a primary objective of any LIA program, or LIA participation in other programs, aimed at resolving the childhood lead poisoning problem to keep attention focused on old, leaded paint as its primary source and to make clear that other sources of lead are not significantly involved"[20] (p. 117). Several years later, employees of the Ethyl Corporation continued to publish research contending that ". . . it is clear that nearly all of the Pb in dirt around these houses is due to paint from the houses. Lead antiknock additives are therefore not a significant contributor to the lead content of dirt around houses where children usually play"[21]. The Ethyl corporation continued to fund research into the 21st century questioning the impacts of low-levels of lead exposure[22,23].

II.II The significance of analytical instruments

Appropriate analytical capabilities to detect trace quantities of lead were not commonly available until four decades after leaded gasoline was in widespread use around the world. Scientific understanding of lead poisoning became possible in the mid-20th century with the development of analytical instruments such as atomic absorption spectrometry, graphite furnace atomic absorption spectrometry, anodic stripping voltammetry, inductively coupled plasma spectrometers (ICP), and ICP mass spectrometers (ICPMS) that measure lead isotopes at high sensitivities[24]. An ordinary scientist was unable to analyze lead in air, water, and soil until after the new instruments were available in the 1960s and 1970s. The new instruments surpassed the abilities of established wet chemical techniques by orders of magnitude. The uses of new instruments were applied to measuring clinical outcomes and blood lead (Figure 1, after[24]). As the evolution of clinical effects of lead were learned, the exposure guidelines were gradually decreased.

Figure 1. The impact of Pb analysis advances on children's blood lead guidelines in the United States. The guidelines are now referred to as reference values, and they decreased with new findings. Currently, the CDC and World Health Organization state that for children there is no known safe level of Pb exposure.



Lead follows the same pathways in human systems as calcium. Once it enters the blood, the main storage is in bones, teeth, and arteries[25]. The new instruments gave the research community unlimited possibilities to study lead. For example, the ability to measure lead in food assisted in discovering that lead poisoning from soldered lead cans was a principal reason for the failure and total loss of the 1845 British Navy Franklin Expedition[26]. The risks posed by lead-soldered cans contaminating food during the canning process continued for over a century and were rediscovered in 1980 in the US population from the widespread use of lead-soldered cans[27]. Early measurements of metals in food products were further confounded by the fact that they were conducted in lead dust-contaminated labs. The Food and Drug industry scrutinized their own facilities along with the entire canning industry, and eventually required the renovation of their labs, scrapping their contaminated data sets, and eliminating lead-soldering in the food canning industry. In the early 1960s, observations of lead dust accumulating on plants growing near highways were also recognized[28].

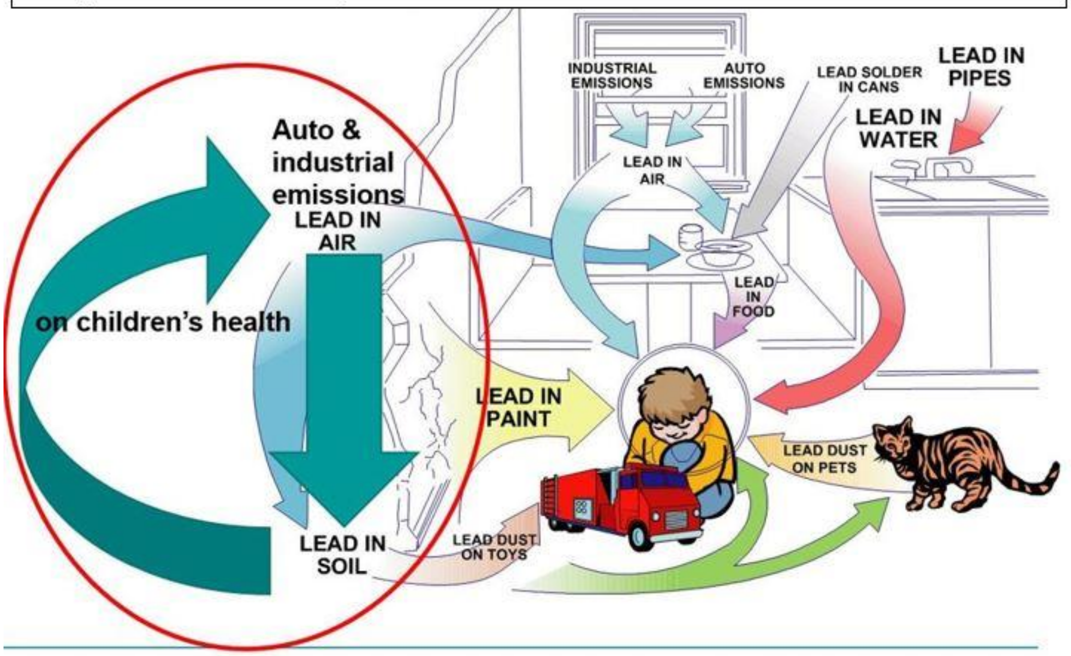
II.III Getting the lead out: soil research provided insights and recognition of the role that invisible lead (and other metals) played in the environment and human health

The innovations in scientific instrumentation enabled the analysis of lead in human tissues, as well as in historical and current environments. By the mid-1970s, these analytical techniques were applied to soil. At this time, researchers with the United States Department of Agriculture (USDA) in Baltimore, Maryland conducted the first city-wide survey of soil lead in the Baltimore Urban Garden Study[29]. The results of this study demonstrated that urban soils were highly lead contaminated. Soil lead was elevated around brick and stone buildings in communities with traffic-congested areas, and less elevated in areas where buildings contained lead paint but had low traffic congestion. This study highlights an urban design flaw: cars using leaded gasoline emitted lead exhaust in proportion to traffic congestion in the interior of the city and subsequent accumulation of lead dust in soil.

Replication of this soil study in the Twin Cities of Minnesota showed the same inner-city to outer-city accumulation of lead[30]. While the presence of lead in soil was indisputable, the health implications for children were unknown. As such, the legislature of Minnesota funded a project to collect soil samples and collect blood samples from children in the same census tracts across Minnesota. Studies were thus conducted by the Minnesota Department of Health in collaboration with the Pollution Control Agency which demonstrated that depending on city size and community location within cities, excessively high levels of lead were found in children's blood and in the soils of urban environments of Minnesota[30]. The results of this study demonstrated that soil lead was strongly associated with children's blood lead. While Minnesota was able to regulate relatively small sources of lead emissions by companies such as battery recyclers, it could not regulate and prevent lead exposure from the massive airborne emissions exhausted by motor vehicles using leaded gasoline.

While researchers funded by the Ethyl corporation argued that lead paint was the dominant source of soil lead and potential exposure for children[21], the research conducted in Minnesota, and subsequently corroborated in numerous other cities, demonstrate the strong correlation between traffic flow, leaded gasoline use, lead in soil, and lead in children's blood[31–33]. The causal mechanisms at play pertain to urban soils becoming dry, dusty, and being seasonally remobilized in the atmosphere. Seasonal cycles of lead dust, lead in the atmosphere, and elevations in children's blood lead have been shown to coincide in several cities[34,35]. Lead on the soil surface is therefore potentially remobilized back into the atmosphere, and both ingestion and inhalation are exposure pathways for children[36].

Figure 2. Child in a lead-contaminated environment. There are multiple pathways of lead exposure for children from air, water, and soil. The outdoor soil lead is readily tracked into the home and can be remobilized into the air where it becomes inhalable. From a CDC report to Physicians concerning Recommendations for Lead Poisoning Prevention of Refugee Children. Revised by HW Mielke.



The Minnesota legislature responded to the children's blood lead and soil lead results by attempting to ban the use of leaded gasoline in Minnesota. However, the Minnesota legislature discovered that it was illegal for the state to ban leaded gasoline. Gasoline additives are under the regulatory authority of the US federal government and cannot be altered by any other jurisdiction. Given this situation, the Minnesota Legislature petitioned Congress and the US Environmental Protection Agency (EPA) to enact a ban on leaded gasoline. This created further obstacles for limiting exposure to this widely used toxicant.

On June 22, 1984, the US Senate held a hearing on the Lead Reduction Act of 1984. The hearing was chaired by Senator Robert T. Stafford in response to the petition from the Minnesota legislature requesting Congress and the EPA to ban leaded gasoline. Senator Durenberger was a prominent questioner at the hearing, which was a dramatic event. The lead industry hired Cincinnati professor Robert Bornschein to help testify about the 60-year record of safety of leaded gasoline, the uncertainty about its environmental health effects, and lack of knowledge on children's exposure from TEL. Dr. Bornschein and Dr. Mielke were sharing papers up until the hearing.

From Dr. Mielke's perspective, he recalls:

> "There were thieves from the lead industry, turncoat colleagues to whom I entrusted my materials, and my Senator who shut down the hearing after my testimony to admonish me for daring to come to the hearing and talk against his bill. I think he raised a ruckus to bring the point home, but at the time it was crushing, and I spoke back to him that 10 more years of poisoning meant additional generations of children will be lead poisoned. Afterward, Senator Durenberger apologized, sent a photo of me during my testimony with the note "...with your help we're 'getting the lead out!'" and signed his name[37,38]. Senator David Durenberger (MN) recently died, and I now realize the need to memorialize him for his service to improve environmental health and his role in advancing the rapid phasedown of leaded gasoline. The rapid phasedown had national and international impact.
> Senator Durenberger's obituary in the NYT focused on negatives and didn't say much positive about him[39]. But I recall his positive words and his actions at the hearing that supported the US Senate to

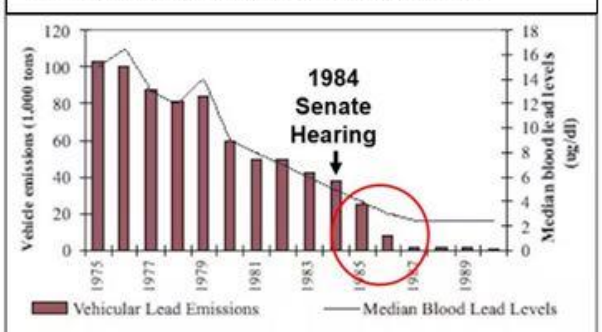
cooperate with the House of Representatives to encourage the EPA to pursue the early rapid phasedown of leaded gasoline. His insights into the childhood lead poisoning issue, his skills in questioning experts during their testimonies, and his ability to lay out the problem of airborne lead from gasoline in the context of children's environmental health were instrumental in the Congressional effort to ban leaded gasoline[40]. While I was an Assistant Professor at Macalester College, Senator Durenberger was a US Senator in the position of power to do what needed to be done to influence public policy for the good of the people of Minnesota and beyond.

A contentious issue at the hearing was the timing of when leaded gasoline should be banned. The EPA scheduled the banning of leaded gasoline for highway use in 1996, twelve years into the future of the hearing. The House of Representatives proposed banning leaded gasoline in 1986. The Minnesota Lead Coalition, which I represented, supported the House Bill. After my testimony and to my horror, Senator Durenberger shut down the hearing and went off the record.

When the hearing resumed, Bob McGowen from Ashland Oil Company of Minnesota testified and agreed with me that banning leaded gasoline was necessary to stay on track to shift to all unleaded gasoline and that the transition was possible by 1986. At the end of the day, Senator Durenberger persuaded the Senate to collaborate with the House of Representatives and press for the rapid phasedown in 1986. The EPA followed through with the rapid phasedown of leaded gasoline in 1985 which was completed by the end of 1986. The EPA created a figure showing the concurrent decline of leaded gasoline and children's blood lead (Figure 3)."

The banning of leaded gasoline started in Japan in 1972 and rapidly progressed in 1976 in the US with the requirement for controlling pollution with the addition of catalytic converters to new vehicles[41]. However, leaded gasoline decreases lagged in the mid-1980s. After the 1984 Senate Hearing, the rapid phasedown began in earnest and, except for a small proportion of leaded gasoline, was completed by the end of 1986 (Figure 3). As such, the rapid phasedown took place in 1985 and 1986. By 1994, the effect of the ban of leaded gasoline and of eliminating lead solder in the canning industry were confirmed. It was realized that children's blood lead decreased by 90 percent throughout the US[42]. By 1996, lead was eliminated from road use of gasoline, with exceptions for non-road vehicles such as race cars, boats, etc., and small airplanes, as described below.

Figure 3. US EPA figure showing the median blood lead decline taking place concurrently with the decrease of leaded gasoline.



Source: USEPA.

The US experience with banning leaded gasoline, along with support from the World Bank[43] and the UN enabled nation after nation to ban the use of leaded gasoline. Minnesota citizens played a key role, with the help of Senator Durenberger in persuading the US Senate to collaborate with the House of Representatives to mandate the EPA to rapidly phase down the use of leaded gasoline in the US. This generated impetus for getting the lead out of gasoline in all nations of the world. Leaded gasoline for highway use was finally eliminated worldwide, when Algeria banned its use in August 2021[44].

After the rapid phasedown of leaded gasoline in the US in the mid-1980s, there was a large US capacity for producing TEL, and the lead industry promoted leaded gasoline and exported TEL for use in nations around the world (Figure 4)[45]. During the late 1970s to 1990s, the promotion was successful in European nations, the Middle East, Africa, and especially in China, during its booming industrial manufacturing of automobiles, road construction, and the need for high-octane fuel, which was met with leaded gasoline.

When leaded gasoline exhausts enter the atmosphere, they eventually land in soil. Soil holds the legacy of environmental conditions and a range of human-induced impacts. Numerous cities throughout the world have been mapped by researchers to show soil lead (Figure 5). Several European governments have also been actively engaged in mapping the chemical environments of urban areas[46].

Figure 4. As US use of leaded gasoline declined, excess supplies of Alkyl lead (i.e.TEL) were exported around the world[41].

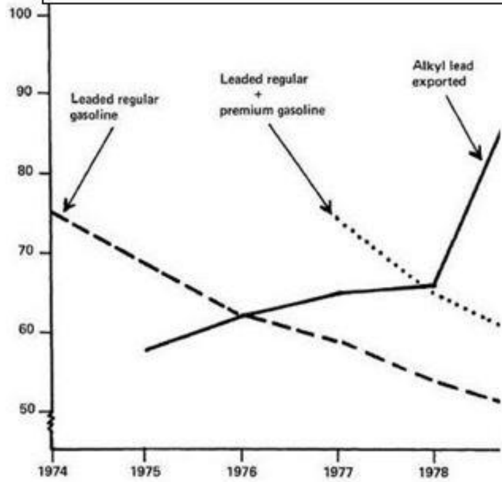
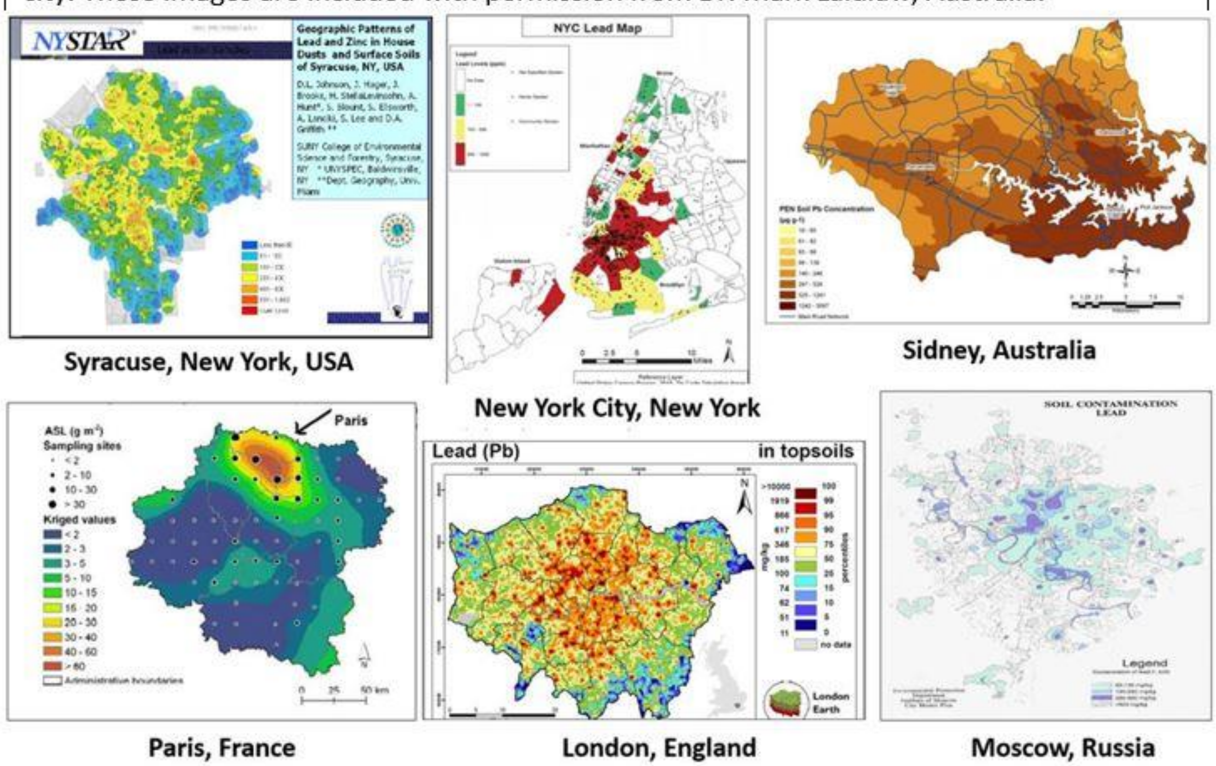


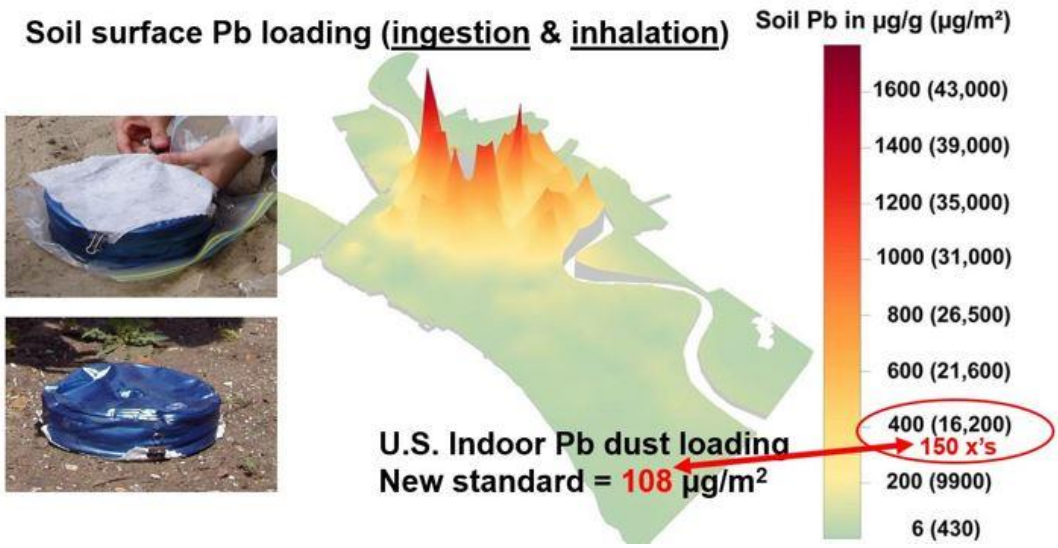
Figure 5. Maps of cities around the world. Each of the cities has a similar pattern as identified in Baltimore, Maryland, i.e., high lead interior and low lead in outer areas of the city. These images are included with permission from Dr. Mark Laidlaw, Australia.



II.IV The relationship between soil lead content and lead loading of the soil surface

Soil lead should be measured in two different ways to gain perspective on its exposure potency. Along with maps of the lead content in urban soil surfaces, it is important to understand the relationship between the lead content of soil, measured in µg/g, and the amount of lead loading on the soil surface, measured in µg/m^2. The tool developed for measuring lead loading of the soil surface is called the "potential lead on play surfaces," or PLOPS sampler[38]. The city of New Orleans, Louisiana has been mapped for both soil lead content of the top ~2.5 cm (µg/g) and soil lead surface loading with the PLOPS sampler (µg/m^2). The map of soil lead content and soil lead loading of the surface soil is illustrated in figure 6. We call attention to the fact that the US EPA soil screening level of 400 µg/g is equivalent to 16,200 µg/m^2. This represents a 150-fold larger amount of lead deemed acceptable on the soil surface than the standard permitted on the surface of interior floors (108 µg/m^2). The massive amount of lead being observed on the soil surface compared with the surface loading permitted in the interior of homes, that is necessary to protect children, illustrates a critical aspect of the magnitude of the soil lead problem.

Figure 6. Lead loading of soil compared with lead loading permitted on interior floors[38]. The US soil lead content standard is 400 µg/g, and the lead loading of soils meeting the soil lead content standard is 16,200 µg/m^2, or 150 times more lead than allowed by the housing interior surface dust standard of 108µg/m^2. Based on this comparison, the US soil lead standard requires a major reduction to protect children.



While the major source of air Pb landing in soil from automobile exhaust has been banned worldwide, the use of TEL in gasoline has not ended. TEL is in avgas, the fuel which is used to power piston engine airplanes. The children living within 1 km of small general aviation airports have higher blood lead levels than children living at further distances from these airports[47,48]. To protect the youngest members of our population, the era of TEL additives in gasoline must be totally ended because lead dust from TEL has known effects on the learning abilities and behaviors of lead-exposed children, and as they grow into adults the effects remain[49]. The research conducted in Baltimore that demonstrated the importance of legacy lead remaining in soil is still relevant[29]. Lead in soil is a continuing issue and to regain the environmental health of urban areas, the surfaces of urban soil must be remediated to create lead-safe play conditions for children.

III. Potential for recovery of pediatric lead-safe environments

Leaded gasoline emissions that have settled in the soil are being remobilized to the atmosphere and pose continuing risks to populations[34,36]. While monumental efforts have been undertaken to ban leaded gasoline, the historical effects can still be linked to population-wide blood level elevations in countries throughout the world[50]. It is imperative that governing bodies address these risks by ensuring urban environments are safe for humans to live in. Norway has shown precedence for primary prevention with the passage of a national action clean soil plan for mapping and remediating soils at childcare centers, children's elementary school playgrounds, and parks[51]. The steps required for mapping and contaminant mitigation have been evaluated by numerous researchers, and either removing or covering contaminated soil with imported substrates have been shown to be the most effective methods for limiting exposure to legacy lead[52]. Low-lead soils have been shown to exist outside of urban areas throughout the US[53] and the use of excavated subsoils, composts, and clean available materials have been shown to be effective for building new soils in a range of environments around the world[54–56]. New York City, New York, has a Clean Soil Bank, the first municipally run clean soil distribution system in the country, which can serve as a model for other locations to prioritize clean soil construction, distribution, and recovery of lead-contaminated environments[57,58].

Concerned citizens and researchers have been seeking to address these issues from a variety of perspectives, in countries throughout the world. As discussed by Walls et al., (2022), community-engaged projects to test and mitigate exposure to contaminated soils have been filling in the gaps of the environmental regulatory systems in the US. These regulatory systems are not addressing the needs of people who are contending with toxicants in soil[59]. These authors interviewed 30 community-engaged researchers and elucidate several obstacles to addressing these gaps. Some of the most crucial issues include the focus of the regulatory system on taking legal action against polluters instead of taking steps to protect public health. The authors further show that taking such preventative action is feasible, and only requires minimal funding and maintenance. Taking such steps for primary prevention may seem like a paradigm shift, but it can be accomplished with policy interventions. If the goal is to recover contaminated environments and protect public health, mandatory testing, placing new clean soil covers, and providing ongoing maintenance can be accomplished with funding, and can offer important green jobs.

While leaded gasoline emissions and lead dust in soil lead are invisible, sufficient research has been conducted to clearly elucidate this toxicant's presence and ongoing harm. The analytical tools have advanced to the point that metal measurements can be done by a handheld instrument. A comparison between common methods of analyzing soil lead shows strong agreement between the results of inductively coupled plasma spectrometers and x-ray fluorescence analyzers[60]. Creating policies to fund soil emplacement in cities worldwide is a necessary and feasible next step. As Dr. Mielke asked in his 1984 testimony, how many more years will children be allowed to be poisoned?

IV. Future warnings and precautionary principles

For over half a century, researchers have hypothesized that the fall of Rome may have occurred because of subtle but ongoing learning and behavioral issues within the lead-poisoned Aristocracy. Authors such as Gilfillan (1965) argue that the failures of critical management skills within the Aristocracy tore the society apart and resulted in the fall of Rome[61,62]. Lead poisoning and neurotoxicity continues to be a global and inequitable health issue[1], and soil lead exposure and all of its subsequent health issues has been shown to disproportionally impact low-income communities and communities of color[63,64]. Because lead follows pathways of calcium in human physiological systems, lead exposure has a serious neurotoxic effect on nerve conduction, especially in the prefrontal cortex which is the executive center of the brain associated with impulse control and behavior[65]. The implications are dire because the era of leaded gasoline, especially between the 1950s and 1980s, was a time when virtually all urban children were exposed to excessive amounts of lead[,3,42].

Lead is only one substance of a long list of toxicants commonly used in commercial products. Many other products that contribute to pediatric health issues have received research attention. Examples include products that disrupt estrogen production such as parabens and phthalates[66,67]. Fluorides from the environment or added to drinking water (and thus in foods or baby formula prepared with fluorinated water) are especially concerning neurotoxicants[68–71], as are perfluoroalkyl substances (PFAS)[72]. Unfortunately, the products of US corporations are legally protected by US law. Once in the marketplace, corporate products are considered safe until they are found to be unsafe beyond any reasonable doubt. Historians note that this approach came about in the 1920s when lead additives were being considered for gasoline[12].

An alternative regulatory approach is the precautionary principle. Simply put, the precautionary principle states, "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"[73]. European law is based on the Precautionary Principle, but it is not accepted in US law. One task ahead is to shift the rules governing the risks, responsibilities, and accountabilities of toxicant producers. The future of humanity depends on a wide range of issues, and the need to share truths and approaches for prioritizing health and sustainability has never been more important.

V. Conclusion

From historical accounts, empirical research, and public records, we observe the detrimental health effects of lead exposure on human societies from antiquity to the present. Lead exposures in antiquity were the result of the ingestion of lead. During the era from the industrial revolution to the present, the exposure pathways of lead in the population evolved to include both ingestion and the inhalation of aerosols from combustion. The increases in lead aerosols resulted from the exponential increase in vehicle manufacturing and leaded gasoline fuel production. The exogenous remnants of lead aerosol combustion products settled in soil and sediments, and the physiological remnants in bones and teeth result in endogenous lead exposure. In the appendix we articulate the timeline for the US removal of leaded gasoline in the mid-1980s and the role soil research played in influencing the deliberations of the Minnesota legislature, of US Congress, the US EPA, and ultimately the banning of leaded gasoline around the world. From the Lead Industry Association board meeting documents, we pinpoint deliberate efforts by the Lead Industry to suppress the truth on the impacts of leaded gasoline, by focusing only on lead-based paint and shielding leaded gasoline from scrutiny as a major source of children's lead exposure. We include these details to address the gap in other timelines, such as the one given by the US Center for Disease Control (CDC). This timeline does not report lead prevention actions taken in the 1980s at the community, state, and national level for preventing lead exposure from the dominant lead source of aerosols of leaded gasoline. Ultimately, rules of law govern issues concerning toxicants and these differ between the US and other nations. In the US, products are assumed to be safe until proven beyond reasonable doubt that they are unsafe. Europe and Canada use a framework of law based on the Precautionary Principle that places the responsibility and accountability on companies for the safety of their products. Our modern situation is presently faced with an enormous task of dealing with the truths about toxicants and their effects on pediatrics and society. We offer these perspectives to support researchers and advocates currently working to promote the health and safety of potentially vulnerable and exposed populations worldwide.

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Appendix of the timeline in the 1970s and 1980s and US actions to get the lead out. This timeline fills the time gap in the timeline of William J. (Bill) Kovarik, Ph.D. Dissertation, with updated revisions in Appendix 1. Chronology of leaded gasoline, University of Maryland. DAI 1994 55(4): 781-782-A. DA9425070 © 1993, 2013. See also, https://environmentalhistory.org/about/ethyl-leaded-gasoline/lead-history-timeline/ . The Environmental History Timeline has many similarities with Kovarik's timeline, but they have in common a lack of information about the US actions to ban leaded gasoline in the mid-1980s.

The process of "getting the lead out" required numerous developments and an evolution of understanding about the sources and effects of lead exposure.

- 1960s-1970 and beyond. Development of commercially available analytical instruments, appropriately sensitive for measuring small amounts of lead[24].
- 1960s to the present, subtle and chronic health conditions were clinically observed in multiple organ systems in association with lead exposure.
- 1962 Early measurements of roadway lead dust accumulation on plants[28].
- 1969 The Lead Industries Association board promotes the lead-based paint only scheme[75].
- 1971 Early study on plants and soils as indicators of metals in the air[76].
- 1972 Sayre observes children's hand-lead and floor dust disparities between houses in the inner city and outer city of Rochester and notes that paint is not the only source of lead dust[77].
- 1976 Application of an AAS analytical instrument to measure soil lead (and other metals) in a whole city study of Baltimore in Rufus Chaney's USDA Laboratory, Beltsville, MD. The research developed novel ways to rapidly analyze metals in batches of soil.
- 1979 Needleman observes an association between lead in baby teeth and classroom performance[78].
- 1979 The Baltimore soil metal data sets were moved to Minnesota, and publication was delayed several years.
- 1983 The Baltimore urban garden study was published in the American Journal of Public Health. The results indicated an urban design flaw whereby vehicle traffic using leaded gasoline emitted lead exhaust disproportionately between soils of the city interior and the outer areas of Baltimore. Chance alone does not explain the extreme statistical results[29].
- 1983 Replication of the Baltimore soil study in the Twin Cities of Minnesota showed the same inner-city to outer-city accumulation of lead and indicated that children living in the inner-city were being excessively poisoned[30].
- 1984 The legislature of Minnesota funded a project to collect soil samples and blood samples from children in the same census tracts across Minnesota. Soil lead was strongly associated with children's blood lead.
- 1984 The Minnesota Legislature, seeking to protect the children of Minnesota from learning, behavioral, and other health issues in the state attempted to ban leaded gasoline only to discover it is illegal to interfere with policies about additives in gasoline. The Minnesota legislature petitions the US Congress and the EPA to remedy the policy flaw regarding the state's rights to protect children. The policy flaw required Congressional attention[37].
- 1984 Senate Hearing chaired by Senator Stafford on the lead reduction act of 1984. Senator Durenberger is a prominent questioner at the hearing. The drama includes shutting down the hearing to scold Dr. Mielke for daring to testify against his Senate bill (allowing leaded gasoline to remain until 1996) and supporting the House bill (a rapid phasedown in 1986)[37].
- 1984 The lead industry's Jerome Cole and Cincinnati professor Robert Bornschein testify on behalf of the Lead Industry about the lack of certainty, the 60-year safety record of leaded gasoline, and that lead-based paint is the real problem[37].
- 1984 Bob McGowen of Ashland Oil company, a Minnesota refinery, testifies that Ashland Oil has an unused capacity of unleaded regular gasoline because of the allowance of small refiners to produce leaded regular gasoline without the expense of investing in the capacity to refine unleaded gasoline[37].

- 1984 Comments to the EPA about the findings in Minnesota and the need to ban leaded gasoline from the Minnesota Lead Coalition, Patrick L. Reagan, M.A. and Howard W. Mielke, Ph.D. Summarizes the Minnesota Lead Coalition research, community organizing, and coalition activities[79].
- 1984-1986 The rapid phasedown took place after the Senate Hearing and was completed, except for a small proportion of leaded gasoline (See Fig 3)[43].
- 1985 An EPA report summarizes the costs of reducing lead in gasoline compared with the benefits. It concludes that lead in gasoline has been shown to increase blood lead levels, which are linked to a variety of serious health effects (particularly in small children), lead impairs the effectiveness of pollution-control catalysts, and reducing lead in gasoline will reduce vehicle maintenance costs and improve fuel economy[80].
- 1994 Ten years after the Senate Hearing the US national reduction of blood lead was reported in a JAMA article. The remarkable blood lead reduction was attributed to the rapid phasedown of leaded gasoline and curtailing the use of lead solder in the canning process[42].
- In 1996 the EPA announced the near-completion of the elimination of leaded gasoline for highway use. However, TEL continued as an additive to fuels for piston engine airplanes which were exempt and are still fueled with leaded gasoline into 2023.
- August 2021 the last gallon of leaded gasoline was used in Algeria[44].
- 2023 The EPA sought comments on the listing of leaded avgas as endangering the health of citizens, and a step toward banning TEL in avgas. When the avgas ban is achieved it ends the era of TEL in fuel and this will benefit the US and the global population from lead aerosols derived from fuel additives.