The Science of the Total Environment, 92 (1990) 13–28
Elsevier

THE RISE AND FALL OF LEADED GASOLINE

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(Received June 6th, 1989; accepted July 10th, 1989)

ABSTRACT

Leaded gasoline has become one of the few "environmentally unsafe" products to be forced out of the market place. The history of lead additives in gasoline is outlined, from the discovery of the antiknock properties of tetraethyllead in 1921 (the first gallon of leaded gasoline was sold on 2 February 1923 to a motorist in Dayton, Ohio), to recent measures to remove lead from the gasoline of the 1980s. This report provides an historical backdrop to the continuing debate on environmental lead pollution.

INTRODUCTION

In 1853, C. Lowig reacted a lead–sodium alloy with ethyl iodide and obtained an impure hexaethyldilead from which he prepared a few triethyllead salts [1,2]. For well over half a century, these compounds elicited little scientific or commercial interest until the detailed study of organolead chemistry was undertaken by Gruttner and Krause between 1915 and 1925 [3, 4]. It was during that time that the excellent antiknock property of organolead compounds was discovered, which immediately revolutionalized the automobile industry. The demand for gasoline with lead additives, "the product of American research" [5], grew sharply and about 25 years later the production of tetraethyllead in the United States used over 100 000 metric tonnes of lead per year and ranked among the top 10 industrial chemical enterprises in the country [5]. By 1970, when leaded gasoline was the "tiger in the tank of almost every car" (familiar Esso slogan of the 1960s), the consumption of gasoline lead exceeded 270 000 tonnes in the United States and 375 000 worldwide [6]. Assuming an average lead content of $0.52\,g\,l^{-1}$ ($2.0\,g\,gal^{-1}$) during this period, the worldwide production of plumbiferous gasoline exceeded 720 billion (10^9) liters per year, making it one of the largest volumes of organic chemicals being produced at the time. Today, however, this "gift of God" [7] has turned into a curse from the gods and lead additives have essentially been phased-out of gasolines in North America and the pressure continues to grow to remove them from motor fuels in other countries. As to be expected, the fight to censure a highly profitable product with multinational oil and automobile industries as key players was particularly acrimonious, but ultimately the concern for the risk to public health has outweighed any economic benefits. Leaded gasoline has thus become one of the first "environmentally unsafe" products to be forced out of the market place. This report outlines the history of leaded gasoline, from its discovery in 1923 to recent measures to curtail its use in the 1980s. It provides an historical backdrop to the continuing debate on the problems of environmental lead pollution.

ORIGIN OF ANTIKNOCK LEAD ADDITIVES

The internal combustion (piston) engine was conceived by William Barnett in 1838, but was successfully built by N.A. Otto in 1876 [8]. It works on the principle that when a homogeneous mixture of fuel and air is compressed and fired by an electric spark, the resulting energy from the combustion pushes the piston outwards and turns the drive shaft. The degree of compression of the fuel and air, known as the compression ratio, determines the efficiency of an engine; the higher the compression ratio, the better the fuel economy and power output. However, when the compression ratio for a given fuel is too high, part of the air–fuel mixture tends to detonate or explode (heard as a *knock* or "ping"), resulting in overheating, loss of power and damage to the engine components. The early development of the internal combustion engine with a high compression ratio was severely handicapped by the composition of the available fuel, which typically gave rise to a knock.

The annals of chemistry contain several lucid accounts on how Thomas Midgley and his colleagues at the General Motors Research Laboratory screened over 33 000 different compounds in a period of 6 years and were able to stumble onto the antiknock properties of organolead compounds on the morning of 9 December 1921 [5, 9, 10]. It has been noted that on the particular occasion, "the ear-splitting knock of their test engine turned to a smooth purr when only a small amount of the compound (tetraethyllead) was added to the fuel supply . . . and all the men danced a non-scientific jig around the laboratory" [5]. The importance of this discovery was nicely articulated by the following exerpt from the *New York Times* (9 January 1937) published on the day when Dr Midgley received the Perkin Medal: "Midgley's work resulted in the creation of the entire ethyl gasoline industry with all that it implies — use of higher compression engines, greater flexibility of automobile operation and other advances. Tetraethyllead in motor fuels adds fifty times as much horsepower annually to American civilization as that which will be supplied by Boulder Dam" (cited by ref. 11). Today, as in 1923, there is still no other octane-improver additive or process that competes economically with lead antiknock compounds.

It was later discovered that lead in the additives also serves as a valve lubricant by forming a protective coating on the exhaust valve seat. Without the lead, abrasive and adhesive wear on the valve seat resulted in what was known as "valve seat recession", which could cause major engine damage. This added benefit remained one of the arguments used by industrial lobbies to keep the lead in gasoline until 1971, when all vehicles built in North America were required to have hardened valve seats and other features designed to minimize valve wear.

Small-scale production of tetraethyllead (TEL) additives was started in April 1922 and, on 2 February 1923, the first gallon of leaded gasoline was sold to a venturesome motorist in Dayton, Ohio, by the Refiners Oil Company [5]. The Kraus–Callis process for large-scale production of Et_4Pb was patented in 1923. In this process, molten sodium is combined with molten lead to form a highly reactive alloy which is then autoclaved with either ethyl chloride or methyl chloride to form tetraethyllead or tetramethyllead (TML) according to the following reaction:

$$4PbNa + 4CH_3CH_2Cl \rightarrow 3Pb + 4NaCl + (CH_3CH_2)_4Pb$$

As Nickerson [5] has aptly noted, the Kraus–Callis reaction "was one of the few industrial chemical processes so fundamentally sound that it has not required drastic revision since it was first introduced". In 1924, General Motors and Dupont created Ethyl Corporation to produce and market leaded gasoline.

A major drawback in the early use of TEL was the shortening of the engine's life by the lead oxide deposited on the exhaust valves, spark plugs and combustion chamber. On the basis of the pioneering work by Earl Bartholomew, the composition of the antiknock fluid was changed in 1928 to include dichloroethane and dibromoethane, which served as scavengers by converting the lead oxides into the more volatile lead halogenides [5]. Once this problem was solved, the production of lead gasoline rose sharply and basically controlled any further development of the engine, and shaped the subsequent direction of the transportation industry throughout the world.

In fact, the early 1920s was a crossroad in the American automobile industry. It had the option of developing smaller, more efficient engines that use better grade gasoline, or the larger, more powerful engines that rely on TEL to boost the octane rating. This point was emphasized by Dr C.F. Kettering, then the president of Ethyl Gasoline Corporation, at the conference to discuss the public health question in the manufacture, distribution and use of TEL gasoline:

> "We have got to do one of two things: we must build motors which are more efficient — we must build motors of very much smaller size and sacrifice a great many factors which we now enjoy in the motor industry, or we must do something which will allow us to get more work out of the fuel unit. Now, in regard to the building of such motors, there is nothing of a patentable or unknown thing in the building of higher efficiency motors. Our neighbors on the other side [of the Atlantic] a few years ago built high compression, relatively high efficiency motors because we shipped to them a better grade of gasoline than we use in this country . . . the automobile art today knows enough to design motors to take a better fuel, but instead it is handicapped because it has not been able to do it" (ref. 7, p. 9).

Dr Kettering, however, enthusiastically supported Frank Howard's (of Ethyl Corporation) vision that TEL was a "gift from God", and that the continued development of the particular motor fuel was essential to American civilization [7]. The Europeans, and later the Japanese, however, continued to develop smaller engines that burn higher grade gasoline.

LEADED GASOLINE EVERYWHERE

From 1 February to 1 August 1923, there were only about 30 ethylizers (hand pumps attached to the customer's gasoline tank) in use. The number subsequently increased sharply to about 1200 in May 1924, and in October of the same year had exceeded 17 000. By 5 May 1925, well over 300 million gallons of leaded gasoline had been sold [7]. The rosy picture was clouded somewhat when production was halted in May 1925. In response to the public outcry about the outbreak of severe lead poisoning, the expert panel appointed by the Surgeon General of the United States Public Health Service recommended that "a statement as to the health hazards involved in the retail distribution and general use of tetraethyllead gasoline motor fluid (be prepared), and that until such a time, the distribution of this substance be discontinued" [7]. Production was resumed in June 1926 after the occupational hazards had been investigated and the measures for protecting the workers had been instituted [12].

From about 1930 onwards, the consumption of lead in gasoline increased steadily and peaked at over 270 000 metric tonnes in the early 1970s (Fig. 1). By summing the data in the figure, it is estimated that over seven million tonnes of lead was burned as lead additives in the United States between 1926 and 1985. Assuming an average lead concentration of $0.4\,g\,l^{-1}$, it is estimated that about 20 trillion (20×10^{12}) liters of leaded gasoline were produced during the 60-year period. In terms of the volume alone, leaded gasoline must be ranked among the top organic chemicals used by modern society. During the late

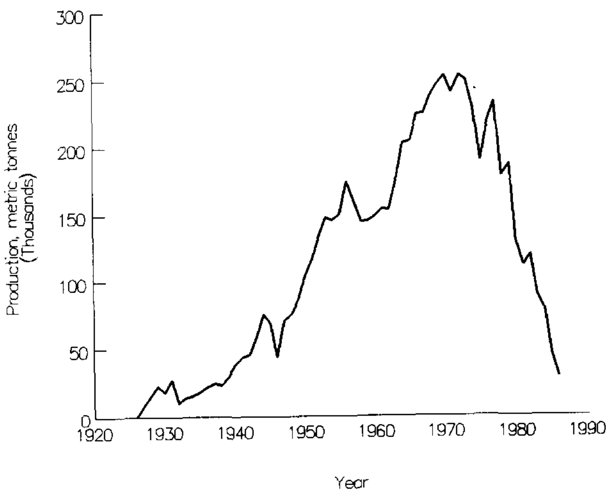

Fig. 1. Historical trends in the consumption of lead in gasoline in the United States compiled from refs 6 and 32, and R. Elias, personal communication, 1989.

1960s, leaded gasoline accounted for nearly 90% of all the automobile fuel sold in the United States [13].

Quantitative information on the worldwide consumption of leaded gasoline is hard to obtain. Since the Europeans and the Japanese used smaller, more efficient engines, it is not surprising that the United States accounted for over 80% of the leaded gasoline sold prior to 1970. Since then, the United States' share has declined considerably. The following is a comparison of the consumption of gasoline lead in the United States with that in the Western World (in thousand metric tonnes, see ref. 6):

Year	U.S.A.	Western World
1965	225	260
1966	247	283
1967	247	293
1968	262	310
1969	271	315
1970	279	326
1971	264	377
1974	250	375
1975	175	301

Although the quantity of leaded gasoline consumed in the United States has declined sharply since 1975, the reduction rate in the rest of the Western World has not been drastic and, in fact, the use of lead additives has gone up sharply in some developing countries. Today the United States accounts for less than 25% of the 150 000 tonnes of gasoline lead being consumed in the Western World (see below).

It should be emphasized that several developments in gasoline quality and engine configuration contributed to the ever increasing demand for leaded fuel. Among these were (a) the introduction of gas-guzzling V-8 engines in the 1940s; (b) the production, since 1960, of tetramethyllead as additives in gasoline with high aromatic content and for propeller-driven aircraft; (c) improvements in refinery technology to produce fuels with enhanced octane quality; and (d) the use of promoter compounds to enhance the antiknock quality and economic potential of the TEL and TML. For example, Ethyl Corporation's "TEL Motor 33 Mix", formerly used extensively in blending gasoline, contained about 57.5% tetraethyllead, 17.6% ethylene dichloride, 16.7% ethylene dibromide, 7.0% methylcyclopentadienyl manganese tricarbonyl, 1.2% dye, etc. [14]. Compounds such as lecithin or tertiary butyl phenols have also been used as stabilizers to prevent the oxidation of TEL during storage [14].

Changes in metallurgy and configuration of components also resulted in a marked increase in engine efficiency. In less than 20 years after TEL additives were introduced, the compression ratio and the engine efficiency doubled, the power per unit cyclinder increased by a factor of 3, and the octane of regular grade gasoline sold in the United States increased from 55 to 75. By the mid-1960s, when the automobile horsepower reached its peak, the compression ratio was about 10:1, the octanes reached 100, and the lead content of premium gasoline exceeded 0.78 $g\,l^{-1}$ [15, 16]. Leaded gasoline had become the main force driving the transportation industry.

EARLY CONCERNS ABOUT THE SAFETY OF LEAD ADDITIVES IN GASOLINE

Concern for the environmental health impacts of lead additives began shortly after the antiknock properties of TEL were announced. In October, 1922, William Mansfield Clark warned that "on busy thoroughfares it is highly probable that the lead oxide dust will remain in the lower (atmospheric) stratum", and can constitute a "serious menace to the public health" [17]. It was, however, the lead poisoning of gasoline handlers and a large number of workers in the TEL processing plant that kindled the public's concern about the deleterious effects of automotive lead exhausts. Dr Robert Wilson [10], who played a key role in the commercialization of TEL, provided a gist of the early concerns. "Before this (the organization of the first major company to take up the marketing of TEL) was underway, however, a serious outbreak of poisoning cases resulting from the manufacture of tetraethyllead was seized upon by labor agitators and publicity seekers in an attempt to convince the public that tetraethyllead was a major threat to public health. Ethyl gasoline was therefore temporarily withdrawn from the market pending a thorough investigation by a distinguished committee appointed by the Surgeon General". Among the agitators alluded to above was Dr Yandell Henderson, Yale Physiologist, who made the following anticipative and rather disconcerting observation about the possible public health consequences of exposing the general population to automotive lead:

> "I find two diametrically opposed conceptions. The men engaged in industry, chemists, and engineers, take it as a matter of course that a little thing like industrial poisoning should not be allowed to stand in the way of a great industrial advance. On the other hand, the sanitary experts take it as a matter of course that the first consideration is the health of the people . . . Lead poisoning today is comparable to typhoid fever. It is almost comparable to tuberculosis in its character as a disease. It is a form of poisoning of a peculiar type. It is cumulative. It is already common. We do not know what percentage of the population, how many tens of thousands of people in America, are carrying a greater or less quantity of lead in their bodies now. We have every reason to believe that it is a very considerable number" (ref. 7, p. 62).

In a private letter to R.R. Sayers of the United States Public Health Service, Dr Henderson noted poignantly that "in the past, the position taken by the authorities has been that nothing could be prohibited until it was proved to have killed a number of people. I trust that in future, especially in matters of this sort, the position will be that a substance like tetraethyllead cannot be introduced for general use until it is proved harmless" [17]. In his views on environmental toxicology, Dr Henderson was clearly well ahead of his time. Many other independent scientists, public health experts and labor activists across the country also questioned the safety of adding a known toxin to gasoline. Among these were Dr Alice Hamilton, a leading authority on lead poisoning, who believed that the environmental health issue should outweigh the occupational health and safety concerns, and the medical director of the Reconstruction Hospital in New York who opined that "perhaps a man may be poisoned from the tetraethyllead without showing clinical evidence and that therefore, there may be a considerable number of individuals so poisoned who have not come under observation" [7].

By contrast, DuPont and General Motors maintained that "the average street will probably be so free from lead that it will be impossible to detect it or its absorption" [17]. An intensive industrial lobby was mounted which effectively forestalled any government regulation on lead in gasoline. For example, in response to calls for more research on public health risks, the General Motors (GM) Research Corporation made an agreement with the United States Government to pay for the U.S. Bureau of Mines to undertake such studies. The agreement replaced "lead" with the trade name "ethyl" and included clauses that would bar press and progress reports during the study to ensure that public anxiety would not be aroused. Furthermore, Ethyl Corporation, which was formed by Dupont and GM to produce plumbiferous gasoline, was able to negotiate exclusive rights to comments, criticisms and approval of the results of the study before they were released (see ref. 17 for details). With the industry calling the shots, it was not surprising that leaded gasoline received a clean bill of health.

Dr Robert A. Kehoe, former director of the Medical Department of Ethyl Corporation and of the Kettering Laboratory in the Department of Preventive Medicine, University of Cincinnati, was generally regarded for many decades as the foremost authority on lead poisoning. His authoritative work on the human toxicology of lead was mostly responsible for rescinding the order banning the production and sale of leaded gasoline and he thus deserves much of the credit for saving the TEL industry [9, 10]. Although Dr Kehoe and his cohorts may be blamed for the large-scale lead contamination of the environment it should be noted that, at the time, the new, powerful antiknock agent was regarded as a milestone in the industrial progress of America. The accidental poisoning of workers was attributed to carelessness and failure to follow instructions. Great innovations involved some risk, the industrial lobby were quick to note. Objections to the widespread use of leaded gasoline on the basis of environmental and health risks that could not be documented by the science of the time were dismissed, more so because such suggestions were antipathetic to the economic and social conditions of the 1920s, which were tuned to the firm belief in industrial progress geared to the automobile.

For decades following the introduction of lead additives in gasoline, the study of lead poisoning was carried out primarily by industrial hygienists who continued to believe that the "potential health hazards in the use of leaded gasoline . . . while well worth investigating, were hypothetical in character" (Kehoe, cited in ref. 5; p. 567). The medical establishment and the medical texts commonly regarded lead poisoning as a disease acquired almost exclusively from industrial exposure or by children with pica. From the principle of dose–response relationships, it was felt that toxic chemicals such as lead could be produced safely by merely reducing the exposure dose to tolerable levels in the work place. Since the toxic material could not be eliminated completely to keep industrial workers safe, risk control prevailed as the philosophical basis of much of the industrial health program. Under such a climate, the few attempts to assess the sub-clinical effects of low-level exposure to lead in the ambient environment were generally dismissed using the armamentarium of clinical data obtained from adult male workers (some of whom were used as guinea pigs). Thus, the threat of gasoline lead to public health remained essentially neglected and unappreciated for well over 30 years.

THE FIGHT TO BAN LEAD ADDITIVES IN GASOLINE INTENSIFIED

In her book *The Silent Spring*, published in 1962, Rachel Carson [18] challenged the cherished belief that industrialization and peaceful application of science were invariably beneficial. She posed the disturbing question as to whether the benefits of comfort and convenience were worth the risk of a poisoned environment. Miss Carson's answer to the question marked the turning point in the fortune of leaded gasoline. Soon after *The Silent Spring*, Dr Clair Patterson [19] published a paper in which he charged that the average resident of the United States was being subjected to chronic lead insult (mainly from automobiles), that the atmosphere of the Northern Hemisphere had become severely contaminated with lead, and that the existing average body burdens of lead are about 100 times higher than the natural burdens. According to him, "it would be tragic if, many decades from now, it were recognized from accumulated evidence that large segments of populations in ours and other nations had suffered needless disability and torment because early warning signs like those recognized in this report went unheeded" [19]. It took less than a decade before Patterson's prophecy was realized.

The middle of the 1960s marked the onset of the environmental movement, and Patterson's [19] paper was just one of a number of influential reports which drew attention to the fact that the automobile tailpipe was the main source of environmental lead pollution and raised concern about the risks of long-term exposure to the large quantities of lead being discharged into the environment. Analysis of aerosol samples collected from June 1961 through May 1962 showed averaged lead concentrations to be $1.4\,\mu g\,m^{-3}$ in Cincinnati, $2.5\,\mu g\,m^{-3}$ in Los Angeles, and $1.6\,mg\,m^{-3}$ in Philadelphia, while the levels in freeway traffic generally exceeded $20\,\mu g\,m^{-3}$ [33]. Between 1953 and 1966, the concentrations of airborne lead in the United States averaged $1\text{–}3\,\mu g\,m^{-3}$ in urban areas, $0.1\text{–}5\,\mu g\,m^{-3}$ in rural and suburban locations, and $< 0.05\,\mu g\,m^{-3}$ in remote regions [34]. In a major paper published in 1970, Chow et al. [35] noted that "the lead aerosol concentration at San Diego is increasing at a rate of 5% per year. The isotopic composition of lead aerosols is similar to that of the lead additives isolated from gasoline, which are the largest contributors to atmospheric lead pollution". An authoritative report on lead, published by the U.S. National Academy of Sciences in 1972 [13], also strongly indicted the automobile as the major source of environmental lead pollution. Subsequently, there was a flood of papers on elevated levels of lead in many environmental compartments in every region of the world. In 1978 alone, well over 5000 papers and reports were published on every facet of lead in the environment. The research findings aroused considerable anxiety among the general public and put the legislators and public health officials under very intense pressure to minimize or eliminate the hazards associated with automotive lead pollution.

Medical and biochemical research on subclinical effects of long-term exposure to low levels of lead in the environment played the pivotal role in the lead-in-gasoline debate. Since the beginning of this century, there was a simmering concern in the United States regarding the health hazards associated with (a) the spray of lead arsenate pesticides on fruits and vegetable crops, and (b) lead paint and the epidemic of pica in inner-city children [20, 21]. By the late 1960s, mass screening programs for lead poisoning and undue exposure to lead were started among the children in the slum areas of some large, old cities. The community program was expanded when the United States government passed the Lead Based Paint Prevention Act in 1971. The early screening programs of the late 1960s and early 1970s unexpectedly uncovered the fact that undue lead exposure was not confined to children in the inner-city (or the "lead belts"), but was, in fact, a nationwide problem that affected middle class and rural children everywhere [20, 22]. The unexpected finding led to the realization that automobile lead had become a health hazard to the average citizen. An epidemiological study of blood lead (PbB) levels in the general population of the United States suggested the existence of a dose–response relationship: "It is clear that increased respiratory exposure within the range observed in community air pollution is capable of producing increased storage of lead in the body as reflected in the blood lead level, and that further increases in atmospheric level will result in higher blood lead levels in the population in a predictable relationship" [36]. A study of the PbB of about 2300 individuals in Cincinnati, Los Angeles and Philadelphia during the early 1960s found that "that levels of lead in the blood tend to increase gradually as the place of residence varies from rural to central urban areas. A second is related to increasing opportunity for occupational exposure to exhaust of automobiles . . . There appears to be an orderly progression in values (of PbB) according to the most likely concentrations of lead in the atmosphere to which these groups are exposed. For example, values are lowest for the suburban and rural groups, intermediate for downtown employees, and highest among those working with motor vehicles such as drivers of cars and parking attendants" [33].

The prevalence of undue exposure to environmental lead was dramatically demonstrated by the Second National Health and Nutritional Examination Survey (NHANES II) conducted between 1976 and 1980 and involving people of all ages in the United States. The NHANES data show that 2.3–3.9 million infants less than 5 years old had blood lead concentrations in excess of 250 $\mu g\, l^{-1}$, now recognized as the medical intervention threshold. About 13% of the population in the United States had PbB concentration $> 200\, \mu g\, l^{-1}$, and the distribution of PbB in the populations of other countries have since been shown to be similar to that of the United States [22, 23]. More importantly, NHANES II showed, rather conclusively, a causal relationship between gasoline lead and the prevalence of elevated PbB levels, a fact that was not lost on the legislators.

Until the early 1970s, it was generally assumed that increased lead absorption was of little clinical significance if there were no recognizable symptoms of *acute* poisoning (such as renal damage, peripheral neuropathy, anemia, neurological dysfunction, etc.), and the PbB levels were below 500 or 600 $\mu g\, l^{-1}$. From the mid-1970s, a large number of clinical and laboratory studies found that undue exposure in early life to low levels of lead (PbB $< 150\, \mu g\, l^{-1}$) is associated with a wide range of metabolic disorders, neuropsychological deficits, hearing loss, retardation in growth and development, etc. [22–25]. Not only that, low-level exposure to lead in the environment was strongly implicated in cardiovascular abnormalities in the adult male population [22, 26]. The effects of lead in many organ systems have no known threshold and have been detected at PbB concentrations as low as 60 $\mu g\, l^{-1}$ [22, 27]. These studies led to the conclusion that undue absorption of the automotive lead in the environment has become one of the most common preventable public health problems in our time. The "gift of God" has turned into a curse from the gods and the demand to get the lead out of gasoline therefore grew more strident.

In this brief outline, it is impossible to delve deeply into the long and heated battle between the environmentalists who wanted to get the lead out of gasoline and the strong industrial lobby which maintained that there was nothing to be alarmed about until the PbB levels of the general population reached the threshold at which acute and clinically recognizable lead poisoning occurs. The divergence of views is fairly well reflected in the proceedings of a 1965 symposium on environmental lead contamination sponsored by the United States Public Health Service [37], and in the June 1966 hearings of a U.S. Senate Committee on air and water pollution which was chaired by Senator Edmund Muskie [38]. In his book, *The Lead Scandal*, Des Wilson [28] has provided a good documentary of the "fight to save children from damage by lead in petrol" in Britain. He identified the three villains in the history of the lead-in-gasoline debate as (i) the "multi-national industries with enormous economic and political influence who have chosen to perpetuate a dangerous practice in order to protect profits; a practice they know threatens the health of the community, and particularly children; a practice they ruthlessly defend in the face of widespread concern"; (ii) the doctors and scientists "who consistently denied there was a problem until the evidence became overwhelming, and who, in many cases, even now prevaricate and delay while one generation of children after another become, in effect, guinea pigs for their research"; and (iii) the public health authorities who "failed to perform their role adequately, and when parents all over Britain combined together to fight for the health of their children, their main opponents became the very people who were appointed or elected to fulfil that public health role".

The so-called "scandal" simply demonstrates how difficult it is for science to resolve an issue with strong economic and social overtones. The contrasting strong opinion held by people on the opposing sides of the lead-in-gasoline debate is best illustrated using the following two excerpts:

> "For several years, controversy has surrounded the use of lead alkyl anti-knock additives in gasoline. Dozens of public hearings on the topic have been held across the country. A virtual army of scientists and technicians have studied the issue. Regulations have been proposed and debated. Yet, despite this tremendous amount of activity and research, the issues remain much what they were in the beginning. The search for a solid, factual, scientific basis for claims against lead has produced nothing of substance . . . Normally, attacks on lead have focused on charges that lead emissions from auto exhausts are a health hazard to the public, or that lead-free gasoline is necessary to meet automobile emissions requirements of the U.S. Clean Air Act of 1970. Neither charge is founded fact. Scientific evidence does not support the premise that lead in gasoline poses a health hazard to the public, either now or in the foreseeable future. Further, it has not been demonstrated that a non-leaded gasoline is essential to achieve a reduction of emissions from automobile exhausts" (J.F. Cole, ref. 29, p. 1).

> "From a vast mass of evidence the Administrator (of the U.S. Environmental Protection Agency) has concluded that the emission products of lead additives will endanger the public health . . . He reached his conclusion only after hearings spread over several months, considerations of thousands of pages of documents, publication of three health documents, three formal comments periods, and receipt of hundreds of comments. From the totality of the evidence the Administrator concluded that regulation was warranted. In tracking his path through the evidence, we, in our appellant role, have also considered separately each study and the objections petitioners make thereto. In no case have we found the Administrator's use of evidence to be arbitrary or capricious. Having rejected the individual objections we also reject the overall claim of error. We find the Administrator's analysis of the evidence and assessment of the risks to be well within the flexibility allowed by the "will danger" standard. Accordingly, we affirm his determination that lead emissions present a significant risk of harm to the health of urban populations, particularly to the health of city children" (*U.S. Court of Appeals ruling against the five anti-knock industries who wanted to overturn the reduction in lead content of gasoline*; cited in ref. 28, p. 3).

The debate on health risks and economic benefits of lead in gasoline remains as intense as ever. In the process, the concept of environmental health risk and even the definition of lead poisoning as a disease have undergone profound changes [39].

LEGISLATIVE MEASURES TO CURTAIL LEAD IN GASOLINE

It would now seem ironic that the first legislative effort to reduce the amount of lead in gasoline was not at all concerned with environmental lead pollution. As a result of smog problems in the Los Angeles valley, the Clean Air Act was passed in 1970 by the U.S. Congress which gave the Administrator of the

Environmental Protection Agency (EPA) the authority to control or prohibit any fuel or fuel additives that (a) causes or contributes to air pollution which may reasonably be anticipated to endanger the public health or welfare, or (b) will impair to a significant degree the performance of any emission control device or system which is in general use. On the basis of this statute, the EPA apparently could not impose a lead emission standard for motor vehicles because "research has not documented beyond reasonable doubt the levels of airborne lead in ambient air at which health effects in persons would be caused . . . " [30]. Instead, the EPA chose to address the problem of lead additives in gasoline by (a) requiring major gasoline retailers to sell at least one grade of unleaded gasoline beginning 1 July 1975 — this directive was aimed primarily at protecting the lead-intolerant catalytic converters that were to be installed on 1975 and later model cars; and (b) mandating a phase-down in average lead content of gasoline from about 0.52 to 0.28 g l^{-1} (2.0 to 1.1 g gal^{-1}) in 1982 and to 0.026 g l^{-1} effective January, 1986. The Administrator's directives were promptly challenged in court by the five antiknock companies (Ethyl Corporation, PPG Industries, E.I. DuPont de Nemours & Co., NALCO Chemical Co., and National Petroleum Refiners Association). Excerpt of the ruling by the Appellant reaffirming the Administrator's action has already been given above. Although dates for this directive were subsequently amended, the lead content of gasoline sold in the United States was reduced to 0.026 g l^{-1} (0.1 g gal^{-1}) since January, 1989. As a result of these legislative measures, the consumption of gasoline lead in the United States has plummetted from over 270 000 tonnes during the early 1970s to about 17 000 tonnes in 1988 (see Fig. 1). The reduction in the consumption of leaded gasoline is closely matched by the decline in

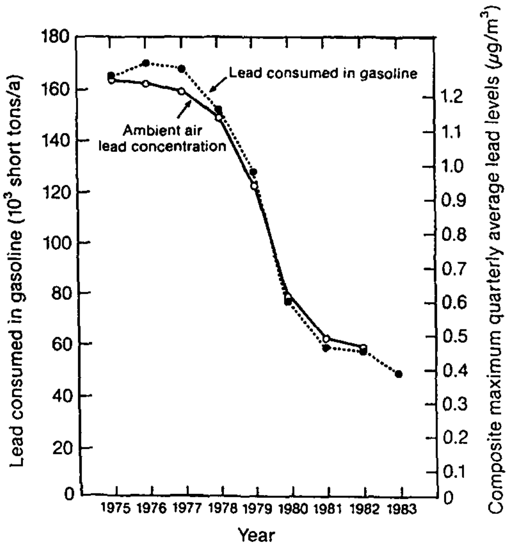

Fig. 2. Relationship between leaded gasoline consumption and airborne levels of lead in the United States; from ref. 22.

TABLE 1

Selected international limits on lead in gasoline (mainly from ref. 16)

Country	1984 Pb level ($g\,l^{-1}$)	Pb reduction schedule		Unleaded phase-in date
		Level	Date	
N. America				
U.S.A.	0.29	0.026[a]	1989	1975
Canada	< 0.77	0.29	1987	1975
Canada	< 0.77	0.026	1990	1975
CEC				
Denmark	0.15			1987
Germany	0.15	0.15		1987
Netherlands	0.40	0.15	1986	1987
U.K.	0.40	0.15	1986	1989
Belgium	0.40	0.15	1987	1989
Ireland	0.40	0.15	1989	1989
France	0.40	0.15	1989	1989
Italy	0.40	0.15	1989	1989
Greece	0.40	0.15	1989	1989
Athens	0.15			
Other European countries				
Austria	0.15			1987
Norway	0.15			1987
Sweden	0.15			1987
Switzerland	0.15			1986
East Germany	0.40	0.15	1989	1987
Czechoslovakia	0.40	0.15	1989	1987
Finland	0.40	0.15	1985	1989
Portugal	0.64	0.40	1986	1989
Spain	0.60	0.40	1986	1989
Yugoslavia	0.60	0.40	1989	1989
Asia Pacific/Latin America				
Taiwan	0.30			1985
Hong Kong	0.40	0.15	1987	
New Zealand	0.84	0.40	1987	1987
Singapore	0.40	0.15	1989	1989
Venezuela	0.84	0.29	1987	
South Africa	0.84	0.40	1986	1989
Malaysia	0.84	0.40	1989	
Argentina	0.84	0.40	1988	
Brazil	0.80	0.026	1989	
Australia				
Victoria	0.30			
New South Wales	0.40	(Australian jurisdictions are moving towards use of unleaded fuel)		
South Australia	0.65			
Western Australia, Queensland, Tasmania and Northern Territory	0.84			

[a] Concentration of $0.026\,g\,l^{-1}$ ($0.10\,g\,gal^{-1}$) is generally regarded as being "lead free".

airborne levels of lead in the urban areas of the United States (Fig. 2), and in the PbB concentrations in the human populations of that country [22, 23]. Because of the various "Auto Pacts" and the desire to attract vehicular tourists, changes made in the United States which affect automobile technology or fuel composition are generally adopted in Mexico and Canada. As to be expected, the consumption of leaded gasoline in these two countries has also declined sharply [31].

Actually, Japan was the first country to market lead-free gasoline, which became available from April, 1972. From 1975, all regular grade gasoline had become lead-free and the lead content of premium gasoline was reduced from 0.15 to 0.11 $g\,l^{-1}$. By 1981, < 3% of all the gasoline sold in Japan was leaded [15]. On the other hand, the European countries were reluctant to introduce any changes in the motor fuel system that would threaten their automobile industry by giving unfair advantage to the American and Japanese cars. Until recently, the member states of the European Economic Community (EEC) have only agreed on a maximum lead concentration of 0.4 $g\,l^{-1}$, although guidelines have been established stipulating that (i) starting 1 January 1986, any country can market lead-free gasoline on its own initiative; (ii) on 1 July 1989, lead-free gasoline must be available everywhere in the territory of member countries; and (iii) on 1 July 1989, the maximum level of lead in leaded gasoline will be 0.15 $g\,l^{-1}$ [31].

Current regulations in other European countries permitted average (total pool) lead contents ranging from 0.15 $g\,l^{-1}$ in Sweden, Switzerland, Norway and Austria to 0.64 in Portugal [31]. Many other countries have also established programs to reduce the lead content of their gasolines (Table 1). Unfortunately, few of the developing countries have established any regulations on lead levels in gasoline and, in fact, the unwanted lead additives made in Europe and North America are being dumped on these countries. The fight to curtail the lead in gasoline sold in the developing countries has yet to begin. Nevertheless, the worldwide consumption of gasoline lead continues to decline and one can only expect that leaded gasoline will soon become a rare commodity, thereby becoming the first major environmentally unsafe product to be forced out of the market place.

ACKNOWLEDGEMENTS

I would like to thank Mr. J.M. Azcue for his assistance with various aspects of the report, and Dr. Rob Elias for providing me with some unpublished data on gasoline consumption in the United States.

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