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Benjamin D. Hutchins

"An Instinct for the Regrettable"

The Inventions and Legacy of Thomas Midgley, Jr.

To
Prof. STEPHEN M. MILLER,
who encouraged me to pursue the study of history;

Mr. MEL JOHNSON,
research librarian extraordinaire;
and

Prof. HOWARD P. SEGAL,
who always wanted a dedication page,

this paper is gratefully inscribed by the author.

On October 5, 1944, with the Second World War still raging and the technological might of the United States still fully dedicated to the war effort, a man delivered a short paper to a scientific-industrial gathering called the Silver Anniversary Forum on the Future of Industrial Research, which was held in New York under the auspices of a division of the Standard Oil Company. Speaking to the gathering by telephone, Thomas Midgley, Jr. described *his* view of the future of industrial research. Since Midgley was one of the most renowned and respected industrial chemists of his time – at the time of his speech, he was both President *and* Chairman of the Board of the American Chemical Society, an honor never bestowed on one person before or since – this was naturally subtitled "The Chemist's View".[1]

There are two especially notable things about Midgley's having presented a paper entitled *The Future of Industrial Research: The Chemist's View* by telephone. One is the fact that, though a prominent and respected figure in the chemical industry, Midgley was *not* a chemist by training. His degree, obtained from Cornell University in 1911, was in mechanical engineering.[2] The other is the reason *why* he delivered his speech by telephone. He was unable to attend the conference in New York, being confined to his bed in Ohio by paralysis – the consequence of an attack of polio he had suffered four years earlier, at the statistically improbable age of 51.[3] Within a month of his address to the Silver Anniversary Forum, he would be dead: strangled (either accidentally or deliberately,

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[1] Thomas Midgley, Jr., *The Future of Industrial Research* (New York: Standard Oil of New Jersey, 1944), 2-3.
[2] Thomas Midgley IV, *From the Periodic Table to Production* (Corona, Calif.: Stargazer, 2001), 5.
[3] Midgley IV, 65.

depending upon which account one credits) by an apparatus he had designed to hoist himself into and out of bed. [4]

Between those two dates – his engineering degree in 1911; his death in 1944 – Midgley pursued a career that saw him earn fame and respect in his chosen field of industrial chemistry by spearheading the invention of not one but *two* of the most eagerly-sought, widely-adopted, and world-changing chemicals of the 20th century. Both were hailed as marvels of science and answers to society's prayers. Both were credited with advancing the human condition, radically and in short order. And by the end of the century, both would be banned in the United States and much of the rest of the world, mentioned in the same breath not because of their shared inventor, but because they are the key chemical players in a textbook pair of anthropogenic environmental disasters.

As a result, their inventor's own reputation, once among the very highest in his field, has suffered considerably in the last few decades. By a careful examination of his works, their consequences, and where both factors intersect with his own life and times, it should be possible to determine just how much of the blame Midgley really deserves for the latter, and perhaps get an inkling of how he should justly be remembered today.

The first of Midgley's world-changing inventions came early in his career as an inventor and industrial chemist. In 1916, a few years after graduating from Cornell, he took a job at Delco (the future General Motors electronics subsidiary), where he worked for Charles F. Kettering, who had invented the electric self-starter for automobiles. Later that same year, Kettering founded a new company, Dayton Research Laboratories, to tackle

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[4] Sharon Bertsch McGrayne, *Prometheans in the Lab* (New York: McGraw-Hill, 2001), 104-105.

more purely research-oriented projects, and took Midgley with him.[5] There, he set Midgley the somewhat vague task of figuring out something to do about spark knock.

Spark knock (also known as detonation) is a condition that afflicts internal-combustion engines, in which the fuel-air mixture in the cylinders ignites when ignition isn't wanted, with disruptive and eventually destructive consequences. It frequently plagued the automobile and aircraft engines of the early 20th century, and at the time, no one knew why it happened, much less how to stop it. Midgley and Kettering developed experimental apparatus to study the workings of a small engine, in an attempt to solve the first part of the problem. In relatively short order, they did so, determining that knock is a function of overly-volatile fuel combusting both at the wrong stage in the process and too rapidly, in effect causing a small explosion where even combustion is wanted and a spike in cylinder pressure that can damage the engine.

Since petroleum combustion itself was so poorly understood at that time, there were no standard grades of gasoline, as we are accustomed to today. Instead, motorists and automobile designers gauged the usefulness of different types of gasoline based on where the crude oil they were made from originated (because different sources of crude had different proportions of various hydrocarbons, though no one yet knew that).[6] Unable to count on fuel from a particular source because of the cost and logistical difficulties of being so selective, Midgley and his team instead set out to find a plentiful and inexpensive additive that would, when mixed with any commercially available gasoline, retard or prevent knock.

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[5] In 1920, DRL would become part of GM as well, passing through various names until it ultimately became the General Motors Chemical Company.

[6] McGrayne, 85.

The search took several years and, at first, resembled the folkloric process by which Thomas Edison and his associates are said to have arrived at the tungsten light bulb filament – Midgley would simply get hold of various chemicals, pour them into the fuel supply of his test engine, and see what happened. Sometimes, as with compounds of iodine, selenium, and tellurium, what happened was a reduction in knock, but with unacceptable side effects. Iodine, for instance, destroyed engine parts with its corrosive nature, while aniline, the chemical that was the basis of the 19th-century artificial dye revolution, produced what Midgley deemed a commercially unacceptable exhaust odor. ("Humanity, even in doubling their fuel economy, will not put up with this smell,"[7] he remarked of the stench of aniline-doped exhaust.)

Eventually, Midgley adopted a more scientific method than what his boss, Charles Kettering, once proposed calling "the 'trial-and-success' method,"[8] basing his search more systematically on a study of the Periodic Table of the Elements.[9] In the early going, he and his team had discovered that adding things like nitrogen compounds and acids *increased* knock, and it occurred to him that such compounds are principally made up of lighter elements from the upper reaches of the Periodic Table (such as hydrogen and nitrogen). On the other hand, they'd had some success with selenium oxychloride, which is based on heavier selenium (element 34).

"With these facts before us, we profitably abandoned the Edisonian method in favor of a correlational procedure based on the Periodic Table," Midgley said in a speech delivered much later, for his acceptance of the Society of Chemical Industry's Perkin Medal

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[7] Midgley IV, 21.
[8] George B. Kauffmann, "Midgley: Saint or Serpent?" *Chemtech* 19 (1989), 718.
[9] See page 23.

in 1937. "What had seemed at times a hopeless quest, covering many years and costing a considerable amount of money, rapidly turned into a 'fox hunt.'"[10]

The hunt was not without its setbacks. After selenium, Midgley and his team tried compounds of the element below it on the Periodic Table, element 52, tellurium. With similar properties to its lighter cousin but greater atomic weight, tellurium made an even more effective antiknock agent than selenium had, but its similar drawbacks were magnified as well: like aniline, selenium and tellurium made a stink that no one involved in the research believed the buying public would tolerate, no matter *what* the advantages it conveyed. Midgley's wife is said to have banished him to the basement of their home for the duration of the tellurium investigation.[11] In his 1937 Perkin Medal speech, Midgley dryly remarked only, "There are, however, good reasons for not using tellurium compounds."[12]

In 1921, the breakthrough came in the form of a compound from still farther down the Periodic Table: one which was an extremely effective antiknock agent, did not produce a prohibitively offensive smell, and could be produced cheaply. Its principal constituent was element 82, a well-known, common material, easily obtained and easily worked, that was found in a wide range of commercial products at that time and had been part of humanity's arsenal of useful materials for centuries.

There was only one real problem: It was poisonous. The chemical in question was called lead tetraethyl, although, in an effort to downplay the part lead played in its makeup,

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[10] Thomas Midgley, Jr., "From the Periodic Table to Production" (1937), in Midgley IV (2001), 106-107.
[11] McGrayne, 86.
[12] Midgley Jr., "Periodic Table", in Midgley IV, 107.

Midgley's company soon redubbed it "tetraethyl lead" or TEL – sometimes blurring the matter further by leaving out the space, or even omitting the "lead" part altogether.

Lead's toxic properties were well-known by that time. Lead poisoning was a common affliction of painters, potters, plumbers (the "plumb" in "plumber" comes from the Latin name for lead, *plumbum*, which is also where its Periodic Table symbol *Pb* originates), and others whose jobs brought them into frequent contact with the substance. Its destructive effects are neatly summarized in Bill Bryson's *A Short History of Nearly Everything*: "Blindness, insomnia, kidney failure, hearing loss, cancer, palsies, and convulsions. In its most acute form [lead poisoning] produces abrupt and terrifying hallucinations, disturbing to victims and onlookers alike, which generally then give way to coma and death. You really don't want to get too much lead into your system."[13]

All that didn't stop lead from being employed in a wide range of different applications in the early 20th century. For instance, it was in most paints; many water pipes and tank linings were still made from it; and it was a key constituent of the solder used to make the cans for canned food, a use that wasn't banned in the US until 1995.[14] Most industrial uses of lead were considered safe on the consumer level because the element was in a non-volatile state (the flashing around the base of a chimney, for instance, is unlikely to inconvenience anyone once it's attached). However, lead tetraethyl, being an oil-soluble compound that vaporized easily (the exact qualities that made it useful as a fuel additive in the first place), was particularly dangerous to people trying to synthesize and work with large quantities.

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[13] Bill Bryson, *A Short History of Nearly Everything: Special Illustrated Edition* (New York: Broadway Books, 2005), 185.

[14] New York State Department of Health, "Sources of Lead", last modified April 2010. https://www.health.ny.gov/environmental/lead/sources.htm.

Midgley and his team knew all that, of course, and even if they hadn't, they soon had their own first-hand experiences with lead tetraethyl's toxicity. Chemist Carroll A. Hochwalt, one of Midgley's colleagues on the project, recalled decades later, "We all had lead poisoning. I had it. You could see the lines of lead in the bones, but it disappeared [in time]... Midgley had it, too."[15] Both then and later in the 1920s, Midgley and his team did continue to investigate other compounds that did not contain lead, most notably iron carbonyl (which had been tried with little success in Germany),[16] but none seemed likely to be as effective or as *cost*-effective as lead tetraethyl, and Kettering preferred the imperfect solution in hand to the possibility of a perfect one sometime later.[17]

By 1923, under the still-further-shortened, innocuous-sounding trademark "Ethyl" (Kettering's idea),[18] a lead-tetraethyl-based antiknock compound was being sold as an additive to gasoline at stations in the greater Dayton area, to be added during fill-up at the customer's request. It proved popular, and the following year General Motors and Standard Oil of New Jersey formed a new company, the Ethyl Gasoline Corporation, to produce and distribute it more widely.

With a cheap and reliable antiknock compound available, American automobile manufacturers could design more powerful engines and new types of cars and trucks that were dependent on that increased power. Aviation engines, too, developed ever greater horsepower with leaded gasoline to burn – a factor that was to become very significant in the early 1940s, when World War II called upon the aircraft industry to produce ever

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[15] Carroll A. Hochwalt, interview with Jeffrey L. Sturchio and Arnold Thackray, *The Beckman Center for the History of Chemistry Oral History Program* (July 12, 1985), 10.

[16] Joseph C. Robert, *Ethyl: A History of the Corporation and the People Who Made It* (Charlottesville: University Press of Virginia, 1983), 139-141.

[17] McGrayne, 85.

[18] Robert, 115.

bigger and more powerful planes for war. The 100-octane variant of leaded gasoline is still the standard aviation fuel today, long after lead disappeared from American automobile tanks, and the performance advantages it gave Allied aircraft during the war prompted one British government official to declare, "We wouldn't have won the Battle of Britain without 100-octane."[19]

Concerns over lead tetraethyl's toxicity, however, arose almost as soon as the product entered the market. At first, these concerns mainly had to do with the safety of the workers tasked with manufacturing the additive. Midgley and his team had already grappled with the reality of lead poisoning from their experiments, but for early production workers, the situation was even more grim. Workers in Ethyl's own Dayton plant, a DuPont manufacturing facility in Delaware, and Standard Oil's TEL plant in New Jersey all died in separate exposure incidents during 1924, prompting the cities of New York and Philadelphia to ban the substance's use.

Midgley and the Ethyl Corporation maintained that the chemical was only dangerous to manufacture – a problem that could be overcome with more research into the industrial safety procedures in use – and not in the form in which it ultimately reached the consumer. At one point, Midgley conducted a public demonstration in which he rubbed TEL on his hands and breathed its fumes, insisting, "I'm not taking any chance whatever,"[20] but never mentioning that he and several members of his team had taken extended leaves during the initial research because of lead poisoning.[21]

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[19] McGrayne, 103.
[20] McGrayne, 82.
[21] Hochwalt, 10.

As for the potential danger posed by the exhaust fumes of cars running on leaded gasoline, Midgley's investigations turned up no lead *in* said exhaust – a surprising conclusion given that part of the problem of preparing the product for market was figuring out a fixative *specifically for* carrying the lead out of the engine after combustion.[22] Meanwhile, the company commissioned a medical doctor and professor of physiology, Robert A. Kehoe, to determine whether the manufacture of TEL could be made safe for the workers,[23] and also requested a study by the U.S. Bureau of Mines into the matter, but no serious investigation was made into the potential threat to the public from leaded-gas exhaust.

As a result, as Sharon Bertsch McGrayne put it in *Prometheans in the Lab*, "Suddenly, tetraethyl lead had become an occupational, labor issue, not a broader, environmental one."[24] It would remain that way for decades. As late as 1966, the *Encyclopædia Britannica* was still blithely asserting that lead poisoning was "almost exclusively an occupational disease which is usually chronic in nature."[25]

Meanwhile, with the Bureau of Mines' study (paid for by General Motors) and Kehoe's positive findings in hand, Ethyl and its corporate parents were able to have the local bans on the product repealed, and gasoline containing TEL became the standard in the United States until the 1970s (it would not be banned outright there until 1996). The only concession to safety made at the time was that leaded gas would be prepared and distributed by its manufacturers that way, rather than treated at the point of sale, so that at

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[22] McGrayne, 89.
[23] Robert, 122.
[24] McGrayne, 91.
[25] "Lead poisoning," in *Encyclopædia Britannica* (Chicago: William Benton, 1966), 844.

least gas station attendants would no longer have to handle and look after large quantities of undiluted TEL.

Lead tetraethyl for gasoline, a dangerous poison that nevertheless enabled rapid advancement in internal combustion engine technology and may have contributed to the Allied victory in World War II, would be a double-edged enough legacy for any chemist, but for Midgley it was only the first of two such creations. The second came when, a few years after the TEL controversy had died down, Charles Kettering brought his restlessly inventive friend a new urgent problem to solve, pulling him away from some less pressing research into synthetic rubber compounds that had occupied most of his time since his part in the Ethyl business was concluded.

Spark knock had been one of the great engineering problems of the day when Midgley first tackled it in the second decade of the 20th century, and a chemical that could solve it was a sort of industrial chemist's Holy Grail. There were other Grails to be quested for in the 1920s, and one of them was the elusive, possibly mythical safe refrigerant.

Mechanical refrigeration had been around for some time by that point, but the machinery it required was cumbersome, complicated, expensive – and dangerous. A refrigeration machine is a kind of heat engine, using mechanical work to transfer heat from a cool area to a warm one (the work opposes heat's natural tendency to flow the other way), by way of a substance known as a "working fluid". It is the working fluid that actually carries the heat away from the area to be cooled, and upon which the mechanical work is done by the refrigerator's compressor. In the 1920s, most useful working fluids were substances like ammonia and sulfur dioxide, which, in addition to being only so-so refrigerants, tended to be highly toxic, flammable, or both. That was fine so long as they stayed inside the sealed workings of the machinery, but not so fine if they escaped.

Unfortunately, that happened a good deal, which was a problem when refrigerators were found mostly in large industrial settings, and became a greater one when home refrigerators started to become more widespread. Accidental poisonings from refrigerator leaks became unfortunately common occurrences, spurring calls from public health officials for investigations into safer alternatives (one such incident, and resultant call for change, was reported in the July 13, 1929 issue of the *Chicago Tribune*).

What Chicago Public Health Commissioner Kegel[26] evidently did not know in 1929 was that such an investigation was already under way. The previous year, while Midgley was still working on the synthetic rubber problem, Charles Kettering asked him to tackle that very problem on behalf of one of Ethyl Corporation's sister GM subsidiaries, Frigidaire.

Midgley had specific parameters that the new compound had to meet, particularly in terms of boiling temperature, and he had to find something that wasn't toxic, wasn't flammable, wouldn't corrode the machinery, and – a critical consideration in this project just as it had been for lead tetraethyl – was, or could be made, cheap to produce. Instead of starting with an Edisonian scavenger hunt, he turned to the Periodic Table immediately in his search for the new refrigerant.

"Flammability decreases from left to right," he explained later. "Toxicity (in general) decreases from the heavy elements at the bottom to the lighter elements at the top. These two desiderata focus on fluorine [element 9]."[27]

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[26] The *Tribune* seems to have assumed that its readers would know who this person was, since his first name is never specified in the 1929 article mentioning his call for safe refrigerant research.

[27] Midgley Jr., "Periodic Table", in Midgley IV, 111-112.

As anyone who has taken a high school chemistry course should know, fluorine is *far* from non-toxic, but its position on the Periodic Table suggested to Midgley that it might become so in certain compounds. That surmise proved correct, and the result, after a great deal of number-crunching involving the boiling points of various carbon compounds and how they might interact with fluorine and its neighbor chlorine, produced dichlorodifluoromethane: better known to the public at large, after its 1930 introduction to the marketplace, as Freon R-12.

Unlike TEL, Freon and its extended family, collectively known as the chlorofluorocarbons or CFCs, were not controversial when they were first invented. They were inarguably just what Midgley had been asked for: extremely capable refrigerants that were neither poisonous nor flammable. Eagerly embraced by the refrigeration industry and the public, they served as the working fluids in refrigerators and air conditioners by the millions for decades, making it possible to air-condition places that would never have been considered for it before (such as the passenger cabins of automobiles).

Moreover, CFCs were adapted for a wide range of *other* uses, not originally envisioned by Midgley or his employers. The same qualities that made them ideal refrigerants also made them useful as aerosol propellants ("blowing agents" in the parlance of the industry) and industrial solvents. They were used extensively in the production processes that made useful things out of polystyrene foam, for example, and in the 1950s and '60s there were a *lot* of useful things being made out of polystyrene foam.

Midgley had another 14 years to live when Freon hit the market, and he didn't spend them idly, but no subsequent invention of his would have the impact that TEL and Freon had – either when they were introduced, or decades after his untimely death. When he died in 1944, he may have had mixed feelings about his role in lead tetraethyl's advent, though he seems to have convinced himself that, as he put it in his 1937 Perkin Medal speech, "The toxic hazards had to be determined and controlled... and they have been controlled."[28] However he may have felt about TEL, he would have had no reason at all to think that his second great invention, CFCs, would ever be regarded as anything but the unalloyed boon to humanity he had been so lauded for creating.

Coincidentally, both legacies started to unravel in the same order in which they were created, and both falls were the result of investigations into matters that were not directly related to the chemicals themselves.

The story of the ultimately successful campaign against leaded gasoline is an epic of scientific activism all to itself, but the short version is this:

In 1948, four years after Thomas Midgley's death, a geology graduate student at the University of Chicago named Clair Patterson was assigned, as the topic of his doctoral dissertation, the rather sizeable task of determining the age of the Earth. His dissertation advisor, geology professor Harrison Brown, actually didn't think it would be that big a job – the phrase he used in pitching the idea to Patterson was "duck soup"[29] – since he, Brown, had recently developed a method for determining the age of rocks by measuring the amounts of the three stable isotopes of lead in them. He thought he was, in effect, just employing the time-honored technique of having one of his grad students do all the dreary math.

In the event, the calculation took Patterson seven years, not because the solution to the problem eluded him mathematically, but because he found it almost impossible to get

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[28] Midgley Jr., "Periodic Table", in Midgley IV, 109.
[29] Bryson, 193.

clean samples to work with – and keep them clean. Try as he might, his calculations kept getting fouled by mysterious, unaccounted-for quantities of lead. Only by developing precursors to today's fanatically meticulous cleanroom protocols was he finally able to perform the calculation to his satisfaction and announce that the Earth was 4.55 billion plus or minus 70 million years old. By then, Patterson himself was no longer that interested in the age of the planet; he was much more preoccupied, not to say obsessed, with where all that extraneous *lead* was coming from.

A decade and more of diligent investigation eventually turned up that the answer was, basically, "everywhere." The entire atmosphere, it seemed, was contaminated with lead, and some clever lateral thinking involving core samples of ancient glaciers showed that it had been, in increasing quantities, since – wait for it – 1923.[30] The lead Midgley had confidently "determined" wasn't in automobile exhaust had been there all along, undetected by the scientific instruments of the day, waiting for someone like Patterson to come along and stumble over it while trying to do something completely unrelated.

Patterson's response to this discovery, irrelevant to the topic of his research, was to *make* it the topic of his research. As Sam Kean put it in *The Disappearing Spoon*, "His horror over lead contamination turned him into an activist."[31] He spent the remaining four decades of his career (he died in 1995) campaigning against industrial lead, which – particularly in the 1950s and '60s – meant taking on some powerful business interests, notably the mighty Ethyl Corporation. In the process he weathered professional and personal attacks and smear campaigns, not only from corporate interests, but also from the

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[30] Bryson, 195.

[31] Sam Kean, *The Disappearing Spoon: And Other True Tales of Madness, Love, and the History of the World from the Periodic Table of the Elements* (New York: Little, Brown, 2010), 75.

government agencies that had failed to protect the public from them. In 1965, U.S. Public Health Service chief toxicologist Herbert E. Stockinger responded to one of Patterson's early papers on industrial lead contamination by comparing him to the decade's most notorious environmental gadfly, demanding rhetorically, "Is Patterson trying to be a second Rachel Carson?"[32]

The comparison was probably more apt than Stockinger intended, since, though longer and lonelier, Patterson's crusade against industrial lead was ultimately as successful as Carson's against the pesticide DDT. General Motors, one of the Ethyl Corporation's own chief backers, saw the handwriting as early as 1970, announcing that it would start fitting its cars with catalytic converters (which use platinum catalysts to reduce exhaust pollution). Since the catalysts are rendered useless by lead, cars fitted with catalytic converters can only run on unleaded fuel; in effect, GM was taking a major step toward obsoleting its own product by making its cars incompatible with TEL-infused gasoline, and other manufacturers soon followed suit. Leaded gas disappeared from American service stations in the mid-'80s, relegating pumps marked "Regular" and "Unleaded" to the same dusty corner of historical photography as saloons with hitching posts for horses outside. In fact, in 2014, "Regular" *means* "Unleaded" – just as it did before TEL went mainstream in the mid-'20s.[33]

CFCs took a little longer to be brought down, partly because they are less obviously dangerous than lead; in hindsight, as Kean notes, "It's common sense today that... cars

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[32] McGrayne, 185.

[33] Interestingly, the crusades against DDT and TEL have another parallel as well, in that today they are both being pushed back against in the Third World, where, it is claimed, only DDT can halt the rampancy of insect-borne diseases and only cars that need leaded gas can be built and run economically.

shouldn't vaporize lead for us to breathe."[34] The damage wrought by CFCs is harder to see, was harder to find, and – especially – is harder to explain to laypeople than the dangers of atmospheric lead. Partly, however, the fall of CFCs took longer simply because the happenstance that led to the discovery of how dangerous they were didn't come along until later.

James Lovelock wasn't trying to find evidence of atmospheric contamination *per se* when he discovered the unexpected persistence of CFCs in 1970; he was merely sampling the air over Ireland to see what a new generation of gas detectors could tell him about its composition. When the results of his tests showed an atmospheric concentration of about 60 parts per trillion of a popular CFC refrigerant, R-11, he wasn't particularly alarmed. In a subsequent investigation, he determined that the CFC concentration was the same everywhere from England to Antarctica; but like everyone else at that time, he believed the chemical was harmless, and merely found it interesting that it would be so persistent. (Some of the people above him in England's scientific food chain didn't even think it was interesting; in the words of a National Research Council article on the matter, one of the people who reviewed Lovelock's application for funding for the experiment "could not imagine a more useless bit of knowledge than finding the atmospheric concentration of CFC-11.")[35]

At around the same time, two scientists at the University of California, Irvine, heard about Lovelock's work and were intrigued by his findings. F. Sherwood Rowland and Mario Molina had no reason to believe that CFCs were a particular problem either, but wondered

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[34] Kean, 75.

[35] National Research Council, *The Ozone Depletion Phenomenon* (Washington, DC: The National Academies Press, 1996), 5.

what else could be determined about these peculiarly durable chemicals, and what effects such a worldwide infusion of a chemical that, after all, does not occur in nature might have.

What they discovered, to their increasing alarm, was that CFCs' durability enabled them to linger in the atmosphere for decades after being released, but *failed* when they ultimately reached the stratosphere. There, without the insulating bulk of the atmosphere to shield them, the long-inert CFC molecules are finally broken up by direct exposure to solar radiation, particularly in the ultraviolet. Again, Rowland and Molina found this interesting, but not necessarily important – until they took a look at what they break up *into*, and what those decay products do.

Simply put, what they do is destroy ozone, the allotrope of oxygen responsible for shielding the planet's surface from much of that very ultraviolet radiation. The breakup of CFCs by UV light releases lone chlorine atoms from the CFC molecules; each of these then reacts with two molecules of ozone, O3, in a reaction that ultimately produces three molecules of regular atmospheric oxygen, O2. At the end of this process, the chlorine atom remains free, so that, if there's more ozone around, the process can repeat indefinitely. The breakup of the CFC molecule is thus not the *end* of the trouble, but the *beginning*. Between the sturdiness of CFCs before they reach the stratosphere and the way the chlorine atoms are recycled in the destruction of ozone, Rowland and Molina realized that even if all CFCs were banned immediately, ozone levels would keep dropping for at least another hundred years.

As with TEL, removing CFCs from widespread usage took years and required a major worldwide effort. This took the form of the 1987 Montreal Protocol, an international agreement to phase out CFCs, which was modified in 1996 to impose quicker and more stringent bans on most such substances.[36] Thanks to the persistence of already-released CFCs and their chlorine by-products, it will take decades for ozone levels to recover, but the pace of harm has been curtailed. Unlike TEL's manufacturers, the makers of refrigerants participated, for the most part willingly, in the removal of their harmful products from the market, and fielded non-ozone-depleting replacements in fairly short order.

And here is the final twist in the story of Thomas Midgley, Jr., the man who gave the world not one but two heads of the chemical hydra fought by so many late-20th-century environmentalists. When industrial chemists of the 1980s returned to the lab to develop ozone-safe alternatives to CFC refrigerants, they looked in their archives and discovered that someone already had. A team of chemists working in the 1920s and '30s had developed an entire *range* of useful refrigerants, some based on chlorine-fluorine interactions with hydrocarbons (like dichlorodifluoromethane, the original R-12), but others relying only on hydrocarbons and fluorine. One of these, tetrafluoroethane (R-134a), became the *de facto* replacement for ozone-destroying R-12 in many applications.

The punch line: R-134a, and the other hydrofluorocarbon refrigerants currently replacing the CFCs, are *also* Midgley's inventions.[37]

The question of assessing Midgley's legacy, then, is not as simple as it may appear on its face. Indisputably, he led the way to the creation of two of the 20th century's most infamous chemicals, a fact that prompted Bill Bryson to lament, in *A Short History of Nearly Everything*, that Midgley had "an instinct for the regrettable that was almost uncanny."[38] Nearly four decades after unleaded gasoline started making its comeback, new deleterious

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[36] National Research Council, 8.
[37] McGrayne, 105.
[38] Bryson, 186.

effects of the atmospheric lead from a half-century of widespread TEL use are still being postulated, including a recent claim that it may have been responsible for an upsurge in violent criminality noted in the United States in the 1960s and '70s.[39]

Around the centenary of his birth in 1989, when the battles to rid the world of lead tetraethyl and CFCs were still fresh in many minds, the tendency was to demonize Midgley as a cavalier chemical cowboy, more showman than scientist, or a sloppy researcher. Some have gone so far as to imply that his death in 1944 was (if accidental) the just fate of a despoiler.[40]

It is true that Midgley's record is not unblemished, particularly when it comes to lead tetraethyl. His "taking no chance whatever" stunt with TEL was disingenuous at best, since he had first-hand knowledge of the dangers of what he was telling everyone was harmless. Although some reports claim that he was so shaken by the deaths at the Dayton TEL plant in 1924 that he considered abandoning the project,[41] another account has him coldly dismissing the deaths of workmen at the Standard plant in New Jersey the same year as the workers' own fault, a consequence of carelessness. "The minute a man shows signs of exhilaration [a common symptom of lead poisoning], he is laid off," he told a reporter for the *New York World*. "If he spills the stuff on himself he is fired. Because he doesn't want to lose his job, he doesn't spill it." As McGrayne puts it, "Apparently, Midgley's generosity and conviviality didn't extend to his workers."[42]

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[39] Kevin Drum, "America's Real Criminal Element: Lead," *Mother Jones* (April 2013), accessed December 9, 2014, http://www.motherjones.com/environment/2013/01/lead-crime-link-gasoline

[40] Carmen J. Giunta, "Thomas Midgley, Jr., and the Invention of Chlorofluorocarbon Refrigerants: It Ain't Necessarily So," *Bulletin for the History of Chemistry* (2006), 74.

[41] Midgley IV, 34.

[42] McGrayne, 92.

It should, however, perhaps be kept in mind that when he made those remarks, Midgley was just 35, under tremendous pressure from his corporate superiors to sell his invention to a concerned public, and had been working almost nonstop on the antiknock problem for nearly a decade. He had suffered lead poisoning himself and might still have been experiencing some of its symptoms – which include impaired judgment. At this remove, we can never be certain, but while the reckless showmanship of the TEL hand-washing stunt is in character based on what else is known about the ebullient inventor, such callous remarks about the safety of the workforce preparing his invention are not.

Regardless, Midgley believed, as did many other people in industry at the time, that TEL was necessary, and the empirical evidence – Midgley's favorite kind – of World War II seemed to bear him out. Furthermore, however cavalier his attitude toward the *industrial* safety concerns of the product, he seems to have been genuinely convinced that it posed no threat to the general public. True, he regarded public health officials as meddling amateurs ("fanatical health cranks" was the phrase he used for them),[43] but that is in keeping with the aforementioned conviction: He believed such people were making trouble over something he had already determined was a non-issue. As for CFCs, as previously noted, he can have had no inkling of the harm they would one day be found to wreak, for the simple reason that *no one* did until 1974, three decades after his death, when Rowland and Molina published their findings.[44]

Further, his surviving speeches and writings reveal a man who was, like many scientists and engineers of his time, firmly convinced of the power of science and technology to save the day. In his last address before his death, the October 1944 speech to

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[43] McGrayne, 89.

[44] National Research Council, 6.

the Assembly on the Future of Industrial Research, he spoke in highly positive terms of humanity's ambition and ingenuity, saying,

> We are the only species of living creatures that even conceives of exerting any control over the environment thrust upon it. Admittedly, this control is far from complete. Its extension is greatly to be desired. To accomplish this extension we need to increase our knowledge of the universe in which we live. The only fundamental tool at our command, for extending this knowledge, is the reproducible experiment.[45]

Both of Midgley's most infamous inventions were responses to problems created by previous technologies: the knocking of the early internal combustion engines and the inadequate safety of primitive refrigerants. Faced with the knowledge that his own solutions had become problems, it seems eminently likely, based on all we know of the sort of man he was (to use McGrayne's words, "a curious, compulsive, and creative problem-solver"),[46] that he would have gone in search of *new* solutions. Some nowadays may regard this as a vicious cycle, but to someone like Midgley, it was simply in the nature of progress.

In fact, the example of R-134a shows that he *did* go in search of new, or at least alternative, solutions, even at the time, without knowing that he was, in effect, solving a problem of his own creation. It is true that he can no more have known about this than about the dangers CFCs posed in the first place, but it says something significant about him that, even at the time, he didn't stop at the first dazzling success. He explored a variety of different options, and documented them all carefully in case they turned out to be useful to future generations of chemists – precisely as they did, more than four decades after his death.

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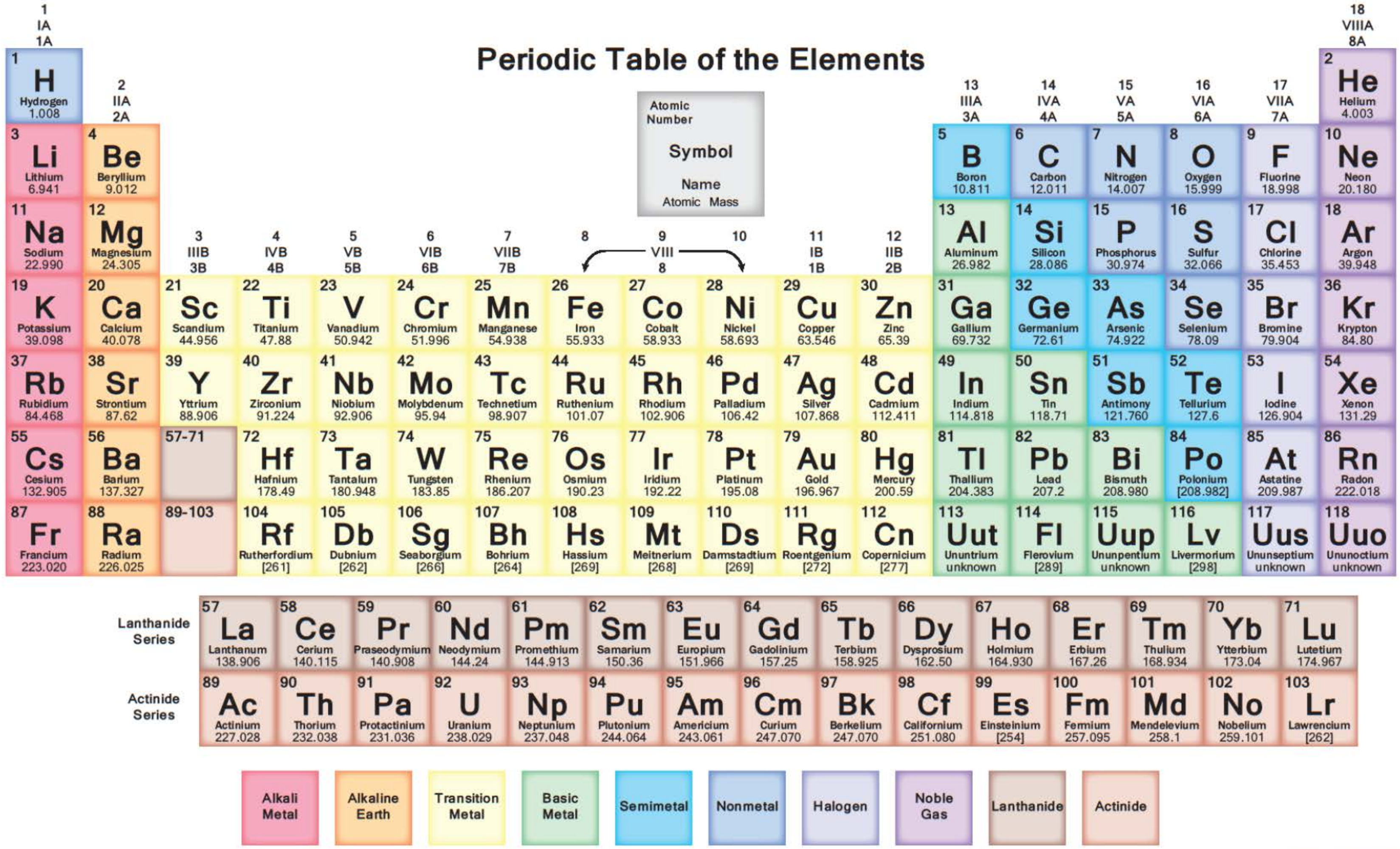
[45] Midgley Jr., *The Future of Industrial Research*, 5.
[46] McGrayne, 105.

It is, therefore, impossible to declare victory for either side of the argument George B. Kauffmann postulated with the title of his biographical article, "Midgley: Saint or Serpent?" which appeared in the journal *Chemtech* in 1989. Like all real people, Midgley was both those things and neither; but when one considers his views on the promise of science, his foresight in developing a range of different refrigerants based on different underlying chemistries, and all he could have known about his most notorious inventions, the picture becomes clearer. When all those factors are taken into account, they show that – however double-edged his legacy – the man himself was closer to the former than the latter.

Periodic Table of the Elements



Atomic Number
Symbol
Name
Atomic Mass

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide

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A note on sources: There may be some confusion over the fact that there are two items entitled "From the Periodic Table to Production" cited in the footnotes of this paper, both of them written by someone named Thomas Midgley. Midgley the chemist's grandson, Thomas Midgley IV, wrote a biography of his grandfather in 2001 and entitled it *From the Periodic Table to Production*, after the title of the speech Midgley (the elder) delivered when he accepted the 1937 Perkin Medal. Said speech is included in the appendix of Midgley IV's book, and both are cited in this work.