THOMAS MIDGLEY, JR., AND THE INVENTION OF CHLOROFLUOROCARBON REFRIGERANTS: IT AIN'T NECESSARILY SO

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The 75th anniversary of the first public description of chlorofluorocarbon (CFC) refrigerants was observed in 2005. A symposium at a national meeting of the American Chemical Society (ACS) on CFCs from invention to phase-out (1) and an article on their invention and inventor in the *Chemical Educator* (2) marked the occasion. The story of CFCs—their obscure early days as laboratory curiosities, their commercial debut as refrigerants, their expansion into other applications, and the much later discovery of their deleterious effects on stratospheric ozone—is a fascinating one of science and society well worth telling. That is not the purpose of this article, though.

Thomas Midgley, Jr.
Courtesy Richard P. Scharchburg Archives, Kettering University

This paper is about contradictory sources, foggy memories, the propagation of error, and other obstacles to writing accurate historical narratives. It is about the digging, sifting, and weighing that historians do in order to piece together accounts that describe as accurately as possible a sequence of events, causes, and effects as they really happened. Professional historians, no doubt, can write numerous similar articles based on the path of their own researches; they will find nothing noteworthy in this article unless they find Midgley and the invention of CFC refrigerants interesting.

Critical readers are well aware of the importance of evaluating sources of information. For example, an article in *Nature* at the end of 2005 tested the accuracy of two encyclopedias' entries on a sample of topics about science and history of science (3). A thoughtful commentary published soon afterwards raised questions on just what should count as an error in assessing such articles: omissions? disagreements among generally reliable sources (4)? Readers of historical narratives who are neither practicing historians nor scholarly amateurs (the category to which I aspire) may find an account of a historical research process attractive. As a starting point, consider the following thumbnail summary of the invention.

Fatal accidents due to refrigeration leaks, including a disaster at a Cleveland hospital, placed refrigerants under the scrutiny of municipal health officials and the American Medical Association (AMA). Frigidaire needed a nontoxic, nonflammable refrigerant, and Charles Kettering asked Thomas Midgley, Jr., to find one (5). It didn't take Midgley and his associates Albert Henne and Robert

McNary long to focus on fluorine-containing compounds and to make dichlorofluoromethane ($CHCl_2F$) (6). Dichlorodifluoromethane (CCl_2F_2) was the compound that was eventually developed and announced as the first fluorinated refrigerant (7). The new refrigerant, dubbed Freon, took over the growing household refrigerant market during the 1930s, and closely related compounds were used widely in air conditioning.

Midgley was not a chemist by training, but a mechanical engineer, although the refrigerants were his second major chemical invention. He had led the team that discovered the knock-suppressing properties of tetraethyllead and developed leaded gasoline. Having contracted polio late in life, he applied his inventiveness to design a rope pulley or harness system that allowed him to move between his bed and wheelchair. An accident involving the system caused his death by strangulation in 1944 at the age of 55 (8).

These two brief paragraphs are not drawn from any single account, but some combination of these or similar statements can be found in popular and scholarly treatments of the subject in books, periodicals, and web pages. They contain several statements that are at least debatably if not demonstrably inaccurate. A series of fatalities related to refrigerant leaks in 1929 did receive national publicity and the scrutiny of the American Medical Association; however, Midgley and associates had already made and begun to test fluorinated refrigerants in 1928. A horrific fire and explosion causing over 100 fatalities, many of them from poisonous gases, did indeed strike the Cleveland Clinic in 1929; however, refrigerants were not involved. CCl_2F_2 was certainly the first fluorinated compound announced, developed, and manufactured as a refrigerant, but whether it or $CHCl_2F$ was the first compound made and tested for that purpose is unclear. Midgley was indeed a mechanical engineer by training, who became one of the most celebrated industrial chemists of his time. His associates publicly described his death in 1944 as an accident; however, contemporary death records and some private comments by associates assert that it was a case of suicide. Even the authorship of the obituary cited above is questionable: one of Midgley's colleagues, Thomas Boyd, wrote that he prepared several obituaries of Midgley published under the name of another associate, Kettering.

Clarifying the record on these points where possible is one purpose of this article; its other purpose, as already stated, is to describe the difficulties of unraveling a complicated story.

What Prompted the Search for Safe Refrigerants?

The erroneous assumption that highly publicized fatalities involving leaks of household refrigerants in 1929 prompted the invention of nontoxic, nonflammable refrigerants announced in 1930 is a combination of a mistaken chronology and the logical fallacy *post quam ergo propter quam* (literally "after it, therefore because of it"). To assume that the headlines about refrigerants in 1929 and 1930, detailed below, served as a spur to industry may be understandable, but it is not correct.

A cluster of deaths in Chicago in mid-1929 drew attention to the dangers of refrigerant leaks. In early July, a coroner's jury of pathologists and chemists found (9):

> At least fifteen and perhaps more persons died in recent months in Chicago from gases used in artificial refrigeration. ... Four persons have been victims of the gas [methyl chloride] in the last ten days in Chicago. Dr. Kegel [Health Commissioner] compiled a list of twelve persons who, he said, had been made ill by the gas, and a list of seven who had died from it in the last few weeks.

After the death of a couple and their one-year-old son two weeks later, Kegel ordered a local ban on the use of methyl chloride as a refrigerant. The Peerless Company, which manufactured the refrigerator, immediately announced that his company would stop making methyl chloride refrigerators until the cause of the deaths was determined (10).

The Chicago incidents were reported in newspapers across the country, albeit in relatively small stories on inside pages. Governmental, professional, and industrial groups were also taking notice. The US Public Health Service, Bureau of Standards, and Bureau of Mines issued a joint statement on July 31 intended to prevent "undue excitement." The statement explained basic principles of household refrigeration, and it explained that the three most important refrigerants in such machines were ammonia, sulfur dioxide, and methyl chloride (11):

> None of the three refrigerants ... can be breathed with impunity, but none are violent poisons when breathed for a short time in low concentrations.

It explained, correctly, that methyl chloride is the least poisonous; however, the others are so malodorous and irritating that "no one is likely to breathe much of them if escape is possible." The Bureau of Mines had recently investigated exposure to methyl and ethyl bromide and chloride in research pursued under a cooperative agreement with Dow Chemical Company. The idea behind this investigation was to mix the more toxic but fire-retarding bromides with the less toxic but more flammable chlorides to produce a refrigerant safe for homes, public buildings, and mines (12). The Bureau of Mines also explored the idea of introducing an odorant into methyl chloride to act as a warning agent (13).

Dr. Morris Fishbein, editor of the *Journal of the American Medical Association*, had headed the Chicago panel mentioned above. Later in the summer of 1929, the AMA appointed a committee to look into methyl chloride in domestic refrigeration (14). In 1930 the AMA Committee on Poisonous Gases published a report on household refrigeration. The report dwelt on methyl chloride at some length, rating it the most dangerous of six refrigerants for delayed toxic effects. Ammonia and sulfur dioxide were rated worst for immediate toxic effects. Warning agents might reduce the dangers associated with methyl chloride, but the report did not endorse adding toxic odorants to toxic refrigerants; in any event, warning agents can help only those who can escape, not infants or the physically or mentally disabled (15).

Manufacturers and advocates of methyl chloride as a refrigerant thought it was being unfairly criticized, and they maintained that it was safe when used properly. They emphasized the fact that when serious methyl chloride poisoning occurred, a central compressor employed to cool refrigeration units in multiple apartments leaked its large charge of refrigerant into the relatively confined space of one of those apartments. (Indeed, the government bureaus' statement and the AMA report also faulted large central refrigerators for their potential to deliver a large charge of harmful material.) During the next year, though, the AMA and advocates of methyl chloride traded polemics in their respective professional and trade journals (16).

A link between methyl chloride and a terrible explosion and fire at a Cleveland hospital, erroneously asserted in some accounts of the invention of CFCs, seems to be an odd artifact of AMA involvement in the methyl chloride controversy. As far as I have been able to determine, the link between methyl chloride and the Cleveland Clinic disaster was first made in 1954, in Williams Haynes' *American Chemical Industry* (17):

> A disastrous accident in a hospital in Cleveland gave methyl chloride a severe setback, and the American Medical Association went out of its way to wage war against it.

In May 1929, an explosion and fire at the Cleveland Clinic killed over 120 people, and most of the deaths were in fact due to breathing poisonous gases. The gases, however, were carbon monoxide and a mixture of nitrogen oxides formed from the burning of highly flammable nitrocellulose X-ray film—not methyl chloride. The explosion was traced to an unventilated storage room that housed X-ray film. On the day of the disaster, a leak had been detected in one of the high-pressure steam lines that ran through the room. Repairs were undertaken, insulation removed, and the steam line shut off, but not, apparently, before some decomposition of nitrocellulose began to trigger the disaster (18).

Naturally, this appalling tragedy was widely reported, investigated, and discussed. Initial reports included descriptions of people overcome by fumes (19) and comparisons to chemical warfare agents (20). Nitrogen oxides and carbon monoxide were soon identified as the compounds mainly responsible for the deaths and injuries caused by inhalation (21). A report released about a month later by a military panel working under Major General Harry Gilchrist, Chief of the Chemical Warfare Service, supported these conclusions. Gilchrist had arranged for tests involving the ignition of large quantities of nitrocellulose X-ray film at a Chemical Warfare Service facility. As the report pointed out, the armed forces had some experience with burning and igniting nitrocellulose (22).

I found no reference to methyl chloride in contemporary reporting on the Cleveland disaster, including reports of investigations, and I found no mention of the Cleveland accident in connection with the debate on the safety of methyl chloride in 1929 or the early 1930s. More telling than this negative evidence is an August 1929 editorial in the *Journal of the American Medical Association* that discussed the Cleveland Clinic disaster and the spate of methyl chloride poisonings in Chicago as two separate examples of dangers due to poisonous gases (23). It is clear, then, that no well informed sources at the time had any reason to believe that methyl chloride was implicated in any way in the Cleveland Clinic accident.

How Williams Haynes came to connect methyl chloride to the Cleveland Clinic fire decades later is not clear—if he was indeed the first to have forged the erroneous link. The relevant statement appeared in a section of *American Chemical Industry* that discussed refrigerating chemicals. None of the references provided in that section suggests any such connection. Perhaps Haynes saw and conflated or confused the two instances of hazardous gases in the AMA editorial; this is plausible, given that he mentioned the AMA in connection with methyl chloride and the Cleveland Clinic.

American Chemical Industry is a well researched and authoritative multi-volume reference work. It is a plausible but by no means definite source for the propagation of this phantom connection in later books and articles. *Science and Corporate Strategy: Du Pont R&D, 1902-1980* (24) and *Between Earth and Sky: How CFCs Changed Our World and Endangered the Ozone Layer* (25) are later well documented volumes that also blame methyl chloride for the Cleveland Clinic disaster. In both of these books, the only reference given for the statement is to a 1929 *New York Times* report that does not mention methyl chloride (Ref. 19 in this paper); however, *American Chemical Industry* is in the general bibliography of both. Both have been cited in still later publications as the source for similar statements.

Even without the Cleveland Clinic disaster, the string of fatal refrigeration accidents in Chicago and the publicity they generated around the deficiencies of household refrigerants make for a plausible motivation for seeking new and safer refrigerants. The accidents, however, took place after the research that some sources say they inspired.

The first public announcement of the invention of CFC refrigerants took place in April 1930 in Atlanta at the 79th national meeting of ACS. It focused on the properties of CCl_2F_2; it did not include an account of the circumstances that led to the invention. A paper based on the conference presentation also appeared in 1930 (7). The patent application for CFC refrigerants was also filed in that year (26). 1930 is certainly the public birthday of CFC refrigerants.

The year of the actual invention, though, was 1928 according to archival sources and published accounts that cite such sources. Scholarly papers by Stuart Leslie (27) and Mohinder Bhatti (28) cite oral history interviews and correspondence involving several individuals in their accounts of the invention of CFC refrigerants. Most of these materials can be found in the Charles F. Kettering Collection in the Richard P. Scharchburg Archives at Kettering University (formerly the Alumni Foundation Collection of Industrial History at the General Motors Institute). I have also seen reports put together on the history of Frigidaire that set the date of the invention as 1928 (29). These archival materials generally date from the mid-1940s to mid-1960s. They are not, therefore, as definitive as dated laboratory notebooks, for example; however, they constitute a number of independent recollections that converge on the same date.

The Chicago methyl chloride accidents could not have been the spur to the invention of CFC refrigerants, then. To assume that an earlier event is the cause of a later one is dangerous—particularly if the purportedly later event actually preceded its putative cause! Assumptions can be dangerous even when the chronology is more or less correct. A fictionalized account of the invention of CFC refrigerants has one of its characters castigate Midgley's company for making and selling dangerous refrigerators even after discovering a safe refrigerant (30):

> Do you mean to say you know how to make a non-poisonous refrigerant, but you're still manufacturing new refrigerators that use methyl chloride, the same gas that poisoned all those people up in Cleveland last month?

While avoiding the error of asserting that methyl chloride leaks inspired the invention of CFC refrigerants, the question fails to recognize the time it takes to develop a practical product after discovery, time for testing and time to devise and build manufacturing facilities. (By the way, the refrigerator manufacturer connected to Midgley's research efforts, Frigidaire, actually made refrigerators that operated on sulfur dioxide, not methyl chloride.)

If dramatic refrigeration accidents were not the spur to invention, what was? Several other explanations have been offered, but there is no clear answer. The same sources that place the date of the invention in 1928 agree that in that year Charles Kettering, head of General Motors Research, asked Midgley to develop a safe refrigerant. Nonflammability and nontoxicity were two of the principal criteria.

The way Midgley recalled it, nearly a decade afterwards, was that Kettering and associates at Frigidaire (which was owned by General Motors) "came to the conclusion that the [household] refrigeration industry needs a new refrigerant if they ever expect to get anywhere." (6) Thomas A. Boyd, another GM research associate of Midgley and Kettering, said that a safe refrigerant would be necessary before air conditioning could take off (31). The subsequent development of automotive air conditioning in the 1930s also looks like a plausible incentive for a refrigeration concern owned by an auto company.

None of these reasons withstands critical examination as a sole or primary motivation, however. The 1920s were growth years for household refrigeration in general, Frigidaire included. Industry-wide sales increased from about 65,000 refrigerators in 1925 to 730,000 in 1929 without new refrigerants (24). Frigidaire had survived its beginnings as the undercapitalized Guardian Frigerator Company in 1916-18 and its subsequent overextension under General Motors in the early 1920s. After its move from Detroit to Dayton under the umbrella of the Delco-Light subsidiary of GM, Frigidaire turned around. It introduced a less bulky air-cooled machine in 1924, and by January 1928, it regained independence from Delco-Light. The millionth Frigidaire refrigerator came off the production line in 1929. That same year, Frigidaire introduced its first room cooler (29b). During this time of growth, Frigidaire used sulfur dioxide refrigerant.

The question of why Kettering put Midgley on the project of developing safe refrigerants when he did was one that Frigidaire chronicler Thomas Shellworth asked but did not have answered. Shellworth worked in the public relations department of Frigidaire when he wrote a history of the company during the late 1940s (29a). Kettering was one of the people he interviewed as part of the project, and he asked Kettering why a search for safe refrigerants was initiated at that time. According to Shellworth's notes, Kettering did not seem to like the question. Indeed, those notes suggest an uncomfortable interviewer and a rather impatient interviewee, not surprising, perhaps, in light of Kettering's high position as a Vice President of the corporate parent (General Motors) of Shellworth's employer (32).

A later in-house chronicler of Frigidaire, Daniel McCoy, suggested a less dramatic reason for the refrigerant research program. Frigidaire wanted to expand in household refrigeration, air conditioning, and supermarket refrigeration. For all the growth in the household sector during the late 1920s, a large majority of houses that had electricity still had iceboxes rather than refrigeration machines. Air conditioning was in its infancy, so it had great potential for growth. Frigidaire was also working on commercial projects, such as ice cream cabinets. When Clarence Birdseye test-marketed frozen foods in 1930, Frigidaire provided the display cases (29b). What these areas had in common was that they involved refrigeration machinery operated in the proximity of the general public. This was in contrast to industrial refrigeration in workplaces like breweries and meat packers where the machinery was run by trained operators in the presence of a restricted population of workers. Frigidaire entered these fields with sulfur dioxide machines, but a less noxious refrigerant would clearly have been more desirable.

In automotive air conditioning, the proximity of the machinery to the motor vehicle operator was even greater, as was the possibility of accidental discharge of the working fluid. The GM Research Laboratories certainly took advantage of their invention of safe refrigerants to develop a vapor compression automotive air-conditioning system using CCl_2F_2 as the working fluid. The idea surfaced in 1930, with a formal proposal following in 1932, and work beginning in 1933 (33).

Inferring causes for actions from incomplete or contradictory sources is part of the job of reconstructing events and telling their story. Identifying a single or primary reason for action makes for a satisfying tale, but there does not seem to be any such dramatic trigger for the development of a safe refrigerant. The deficiencies of existing refrigerants were generally known in the industry, although the extent of the danger was made dramatically apparent by the Chicago accidents of 1929. The refrigeration industry was already expanding into areas that brought it into closer contact with the general public, and it was growing even with the old refrigerants. Development of safe refrigerants seems to have been desirable, but not necessary. GM decided to invest in such development in 1928, and it paid off.

What was the First Fluorinated Compound Studied for Refrigeration?

There is no doubt that dichlorodifluoromethane (CCl_2F_2) was the first fluorinated refrigerant developed for commercial use. Whether or not it was the first compound made for the purpose of investigating possible fluorinated refrigerants is less clear. As mentioned above, the announcement of the invention of fluorinated refrigerants focused on the properties of CCl_2F_2, the compound the researchers had decided to develop. That announcement was not an account of the research process, and it was silent on whether or not other compounds had been examined in the course of the project (7).

Midgley gave a brief account of the discovery during his address on the occasion of being awarded the Perkin medal in 1937. He described some of the reasoning that led him and his associates to turn their attention to fluorinated compounds. The boiling point listed in the *International Critical Tables* for carbon tetrafluoride (CF_4) would make it a promising refrigerant candidate; however, that published data point did not seem to be consistent with those of the few other halomethanes listed. In his speech, as published in *Industrial and Engineering Chemistry*, he said, "We selected dichloromonofluoromethane [$CHCl_2F$] as the starting point for experimentation." (6) Albert Henne, Midgley's assistant at the time of the invention, later told interviewers that the first target compound was, in fact, the one that was eventually developed and marketed, CCl_2F_2 (20b, 34).

How does one choose between these statements, made by two principals of the invention? I first looked for corroboration for either statement, but found no other independent statements on the subject. Next I examined the statements for the possibility of a misprint or mis-statement. R. E. Banks and John Tatlow noted Midgley's mention of dichloromonofluoromethane in the Perkin Medal speech, but wrote that his previous and subsequent papers on the subject mention only dichlorodifluoromethane. They suspect that an "unfortunate printing error crept into this account." (35) I would consider it easy for a printer or transcriber to drop a prefix, turning dichlorodifluoromethane into dichlorofluoromethane; however, it would be much more difficult to inadvertently transform a "di" prefix to "mono," and the text says dichloro*mono*fluoromethane. (Is it possible to imagine, though, dropping a subscript in a chemical formula, turning CCl_2F_2 to CCl_2F, and having a transcriber unaware of the tetravalence of carbon write out dichloromonofluoromethane?) It is equally difficult to see any possibility of misunderstanding Henne's statements. Boyd asked him specifically, "The first compound you made, did it have any hydrogen in it or was it strictly carbon, chlorine, and fluorine?" McCoy wrote that when he interviewed Henne, the latter pointed out the error in the Perkin Medal address.

Knowledge of the chemistry involved does not help decide the question either. The reaction used to make fluorinated hydrocarbons was substitution for chlorine atoms by fluorine atoms from SbF_3 in the presence of a catalyst, a method pioneered by Frédéric Swarts. Carrying out the Swarts reaction on chloroform would produce $CHCl_2F$ (Swarts had done this himself) (36) and possibly also $CHClF_2$, depending on conditions. Carrying out the same reaction on carbon tetrachloride would produce a mixture of CCl_2F_2 and CCl_3F. Both possible chlorinated starting materials were readily available at the time.

Weighing fragmentary and contradictory evidence is part of the task of the historical researcher. In my judgment, Henne's accounts are more likely to be correct than Midgley's, mainly because Henne was the person who made these compounds. Henne was a Ph.D. chemist by training, and his dissertation work focused on halogenated derivatives of ethylene. He was the member of the research group who knew of the Swarts reaction. In addition, Henne's comments have the tone of someone speaking for the historical record, and his statements to two different researchers on this point were consistent. Midgley's comments appear to me to have been more casual. Others may legitimately come to a different conclusion by weighing the statements differently. After all, Henne's recollections were recorded only after the passage of decades while Midgley's were less than ten years old. In addition, Henne's interview with Boyd suggests that he was mistaken about the dates of the research: he invoked the Depression, which had not yet started at the time the refrigerant research began.

Midgley's Death: Accident or Suicide?

Midgley could neither corroborate nor contest Henne's memory, for he had been dead nearly 20 years at the time of Henne's statements. Obituaries and early biographical sketches of Midgley described his death as a tragic accident that prematurely ended the life of a prolific inventor and public-spirited citizen. Undoubtedly his death was premature and tragic: he was only 55 when he died, an invalid because of polio contracted after the age of 50. He was strangled by a harness he had devised to allow him to move between bed and wheelchair. At the time of his death in 1944, his two best known inventions, leaded gasoline and CFC refrigerants, were used widely with no hint of the environmental problems that would later become apparent (37). Some considered Midgley to be a public benefactor because of these inventions; in any event, his service on a wartime inventors' council, on the ACS board, and elsewhere displayed a civic orientation.

Some knew or suspected that Midgley's death was no accident even at the time. The death certificate signed on the date of his death lists the cause of death as suicide by strangulation. Henne, called to the scene by the newly widowed Carrie Midgley, confided to a colleague, "That was no accident." (38) Suicide carried a considerable stigma in 1944, arguably a much greater one than at present. It cannot be surprising, then, that close colleagues and family members did not speak of suicide in public, whether because of concern for Midgley's reputation or because they did not know or believe that it was a suicide. Thomas Midgley IV, for example, does not mention suicide in his biography of his grandfather (39).

Boyd was one of those colleagues who wrote quite a bit about Midgley in several different contexts, and there is no suggestion in these writings that Midgley's death was suicide. The most public of Boyd's writing about Midgley was a belated obituary published in the *Journal of the American Chemical Society* in 1953. In that piece, Boyd calls Midgley's death "unexpected." (31) In an unpublished typescript autobiography, Boyd recalls that Midgley concluded his ACS Presidential address "Accent on Youth" at the September 1944 ACS meeting with the following lines from a poem he had written,

> Let this epitaph be graven on my tomb in simple style,
>
> "This one did a lot of living in a mighty little while."

Boyd went on (40):

> Whether that ending had any significance as a portent of the future, I don't know. But less than two months later, on November 2, 1944, Midgley died.

On the question of suicide, Boyd is silent, whether writing explicitly for publication (41) or not (42).

The mention of suicide entered published works about Midgley only decades after his death (43). But now that the environmental side effects of his best known inventions are widely recognized, the story of accidental strangulation persists and provides a final irony in many short versions of the tale of Thomas Midgley, Jr. Several internet pages on Midgley take up the theme of unintended consequences, of double-edged inventions. Leaded gasoline and CFCs are examples writ large, and the harness that strangled its inventor is a personal example (44). Sometimes the irony is more heavy-handed than others. Joe Schwarcz, Professor of chemistry at McGill University, writes of seeing a play in which Midgley's death was characterized as a just reward for his harmful inventions (45).

I have no evidence that any of the sources mentioned here mischaracterized Midgley's death as accidental in deliberate contradiction of the facts. Certainly some at least did not know or believe that it was a suicide. Nonetheless, the accident story fits well with the overarching narratives of some, whether those narratives were admiring tributes to Midgley or cautionary tales of unintended consequences.

Conclusion

How ought one to rewrite the thumbnail summary of the invention of CFCs with which this paper began? One answer is to replace it with the content of this article from that point to this. Detailed accounts, replete with documentation from contemporary and archival sources, are the scholarly products of historical research. Such accounts are the means by which historical researchers communicate with each other and with other experts such as teachers or with the most interested and competent of lay readers. Such accounts are not, however, suitable for less expert or less interested readers. More condensed accounts are required in such publications as encyclopedias, textbooks, general interest magazines of history (or science or technology), and books with a broader historical or scientific scope.

Getting the facts correct would seem to be an uncontroversial prerequisite for writing history, whether for a scholarly or a general audience. Without factual accuracy, judgments and interpretations will be suspect; and even factual accuracy does not guarantee correct interpretation. What is one to do when the facts are complicated or uncertain? Many writers for a general audience are not expert historical researchers. They have little choice but to rely on the most reliable products of such researchers, distilling and condensing as appropriate.

Historical researchers writing for a general audience at least should know where the complications and uncertainties lie. Even so, avoiding oversimplification is not easy. In some cases, it may be preferable to omit a complex or uncertain point rather than to oversimplify it. After all, recognizing the important and leaving out the nonessential is a necessary skill in writing abridged accounts for a popular audience. For example, I would omit any reference to the Cleveland Clinic in an abridged account of the invention of CFCs; the tale of how it came to be erroneously associated with refrigerants is an interesting back story for aficionados of history, but not a part of the story of refrigeration. Another strategy is to avoid the language of cause and effect where such language is not appropriate, choosing instead to describe features of the milieu in which an event occurred. For example, fatal refrigerant leaks and the use of toxic refrigerants were features of the time during which CFC refrigerants were developed, even if they were not significant drags on the growth of household refrigeration or direct inspiration for the invention of CFC refrigerants.

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22. "Names Fatal Gases in Cleveland Clinic," *New York Times*, June 16, 1929, pp N1-2.
23. "Increasing Hazards from Poisonous Gases" (editorial), *J. Am. Med. Assoc.*, **1929**, *93*, 460-461. The editorial was unsigned, as is common practice. Recall, however, that the journal editor was intimately acquainted with the Chicago cases.
24. D. A. Hounshell and J. K. Smith, Jr., *Science and Corporate Strategy : Du Pont R&D, 1902-1980*, Cambridge University Press, Cambridge, 1988.
25. S. Cagin and P. Dray, *Between Earth and Sky: How CFCs Changed Our World and Endangered the Ozone Layer*, Pantheon Books, New York, 1993. The Cleveland Clinic disaster is mentioned on p 61. This book is the best researched and most complete account of CFCs from invention to scheduled phase out currently available. The Cleveland Clinic disaster represents one of remarkably few factual errors. In my opinion, the book's main shortcoming is a somewhat shaky scientific perspective. It fails to explain, for example, that sound reasons for skepticism of Sherwood Rowland's and Mario Molina's 1974 proposal that CFCs harmed the ozone layer co-existed with the better described stupidity and greed that also beset the proposal.
26. T. Midgley, Jr., A. L. Henne, and R. R. McNary, "Heat Transfer," US Patent 1,833,847, issued Nov. 24, 1931.
27. S. W. Leslie, "Thomas Midgley and the Politics of Industrial Research," *Bus. Hist. Rev.*, **1980**, *54*, 481-503.

28. M. S. Bhatti, "A Historical Look at Chlorofluorocarbon Refrigerants," *ASHRAE Transactions: Symposia*, **1999**, *105*, 1186-1206.
29. a) T. R. Shellworth, *The History of Frigidaire* (1949 typescript), Frigidaire Collection, Richard P. Scharchburg Archives, Kettering University; b) D. C. McCoy, *History of Frigidaire* (1964 typescript), Frigidaire Historical Collection, Wright State University Libraries Special Collections and Archives.
30. C. W. Yuzik, "Refrigerators, Freon, and the End of the Ice Man," http://www.fridgedoctor.com/fridge-doctor-book/refrigerators-freon-and-the-end-of-the-ice-man.html accessed January 13, 2006
31. T. A. Boyd, "Thomas Midgley, Jr." *J. Am. Chem. Soc.*, **1953**, *75*, 2791-2795.
32. Shellworth research materials: interviews, Frigidaire Collection, Richard P. Scharchburg Archives, Kettering University.
33. M. S. Bhatti, "Riding in Comfort: Part II," *ASHRAE Journal*, September **1999**, 44-50. This article also shows a photo of the first air-conditioned automobile, which was not a result of GM development. It was a Cadillac owned by John Hamman Jr. of Houston, Texas, equipped in 1930 with a Kelvinator refrigeration unit mounted on the rear of the car.
34. A. L. Henne, interview with Thomas A. Boyd, July 27, 1964; Kettering Oral History Project, Richard P. Scharchburg Archives, Kettering University.
35. R. E. Banks and J. C. Tatlow, "Synthesis of C–F bonds: the pioneering years, 1835-1940," in R. E. Banks, D. W. A. Sharp, and J. C. Tatlow, Ed., *Fluorine: the First Hundred Years (1886-1986)*, Elsevier Sequoia, Lausanne, 1986, 71-108.
36. F. Swarts, "Étude sur le fluochloroforme," *Bulletins de l'Académie royale des sciences, des lettres et des beaux-arts de Belgique*, **1892**, *24*, 474-484.
37. Some readers who know that the introduction of leaded gasoline was controversial may take exception to the statement that it was not regarded as harmful in 1944. Concerns about lead emitted by automobile exhaust were raised by public health officials in the 1920s, and sales of leaded gasoline were suspended shortly after they began, pending investigation. These concerns ultimately proved to be well founded. Leaded gasoline was not shown to be harmful at the time, though, and at the time of Midgley's death it was in widespread use and under no cloud.
38. Quoted in Cagin and Dray, Ref. 25, p 375.
39. T. Midgley IV, *From Periodic Table to Production: The Biography of Thomas Midgley, Jr.* Stargazer Publishers, Corona, CA, 2001. This book is amateurish in both laudatory and pejorative senses. Clearly the author has affection for his subject, and he includes important archival material. At the same time, the book depends slavishly on some of its sources and displays little or no critical judgment.
40. T. A. Boyd, "Looking Back at My Life after 30" (1966 typescript); Thomas Alvin Boyd papers, 1921-1982, Ohio State University Rare Books and Manuscripts Library.
41. In his typescript autobiographical memoir, Boyd states that he had prepared several pieces about Midgley for Kettering that were published under Kettering's name. These include "A Tribute to Thomas Midgley, Jr.," *Ind. Eng. Chem.*, **1944**, *36*, 1179-1182; "Thomas Midgley, Jr., An Appreciation," *Science*, **1944**, *100*, 562-564; and Midgley's biographical memoir for the National Academy of Sciences (Ref. 8).
42. It is worth noting that although Boyd's autobiographical typescript was not for publication, it is likely that he was writing in some sense "for the record." Boyd had already worked on oral history projects on both sides of the microphone. He had interviewed many associates of Charles Kettering (See Ref. 34). He had also been interviewed by Joseph Ermenc of Dartmouth College about the discovery of tetraethyllead as an antiknock agent. Ermenc would also interview Boyd in 1966 about his recollections of Midgley. Transcripts of Ermenc's interviews of Boyd are included among the Thomas Alvin Boyd papers, 1921-1982, Ohio State University Rare Books and Manuscripts Library.
43. See, for example, Cagin and Dray (Ref. 25); Kauffman (Ref. 2); S. W. Leslie, "Thomas Midgley, Jr.," in *American National Biography*, Oxford University Press, Oxford, 1999, Vol. 15; and S. B. McGrayne, "Leaded Gasoline, Safe Refrigeration, and Thomas Midgley, Jr.," *Prometheans in the Lab: Chemistry and the Making of the Modern World*, McGraw-Hill, New York, 2001, 79-105.
44. Kauffman's article (Ref. 2) contains many references to internet pages about Midgley of highly variable quality; most of them adopt the unintended consequences theme. Kauffman also makes perceptive comments about the description of Midgley's death over the years as accident, then suicide.
45. J. Schwarcz, *Radar, Hula Hoops, and Playful Pigs: 67 Digestible Commentaries on the Fascinating Chemistry of Everyday Life*, ECW Press, Toronto, 1999.

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