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The global search and commercialization of alternatives and substitutes for ozone-depleting substances[☆]

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ABSTRACT

The Montreal Protocol has halted 99% of global production of chemical substances that deplete stratospheric ozone, which protects life on earth from the harmful effects of ultraviolet (UVB) radiation. UVB causes skin cancer and cataracts, suppresses the human immune system, destroys plastics, and damages agricultural crops and natural ecosystems. Because ozone-depleting substances (ODSs) are powerful greenhouse gases, the Montreal Protocol also protects climate. From the authors' perspectives in multiple roles as environmental entrepreneurs, practitioners, and authorities, this paper explains how individuals, companies, and military organizations researched, developed, commercialized and implemented alternatives to ODSs that are also safer for climate. With the benefit of hindsight, the authors reflect on what was neglected or done badly under the Montreal Protocol and present lessons learned on how Montreal Protocol institutions can be renewed and revitalized to phase down hydrofluorocarbons (HFCs).
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[2] Dr. Nancy J. Sherman worked for the food packaging industry in the phaseout of ODSs, then for ExxonMobil as Program Officer for environmental, safety and health contributions, including the Save The Tiger Fund, then returned to graduate school to earn a Ph.D. at University of Virginia, Charlottesville. She now works for IGSD as Director of Technology Assessment.

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[4] Marco Gonzalez was the Executive Secretary of the Montreal Protocol Ozone Secretariat from 2002 until 2013 after being involved in energy and environmental issues over 20 years. He held senior positions in the Government of Costa Rica, including energy and telecommunication institutes, high technology centers, the Ministry of Environment and the National Congress, where he spearheaded the legislative ratification of the Ozone Treaties. He actively participated in the implementation of treaties at national and international levels, chaired meetings of the Vienna Convention and the Montreal Protocol, and served as Vice Chairman and Chairman of the Executive Committee of the Multilateral Fund of the Montreal Protocol.

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I dream of our vast deserts, of our forests, of all our great wildernesses.
We must never forget that it is our duty to protect this environment.
Nelson Mandela

1. Timeline of scientific, corporate and environmental leadership in ODS phaseout

"All truths are easy to understand once they are discovered;
The point is to discover them."
Galileo Galilei

1970–1971: Paul Crutzen warned that increasing the atmospheric concentration of nitrous oxide (N_2O) through fossil fuel combustion and increasing use of nitrogen fertilizers might deplete stratospheric ozone (Crutzen, 1970, 1972). Halstead Harrison and Harold Johnson warned that the proposed fleet of aircraft flying in the stratosphere faster than the speed of sound (supersonic transport—SST) would damage the ozone layer and climate from nitrogen oxides produced in exhaust emissions (Harrison, 1970; Johnston, 1971). Few scientists took the warning seriously enough to publicly support the warning, but Crutzen (1970) has 40 citations in the 1971–1974 period and Crutzen (1972) has 60 citations in the 1972–1974 period.

1972: E.I. du Pont de Nemours & Company (DuPont) invited global fluorocarbon manufacturers to a panel, *The Ecology of Fluorocarbons*, with an invitation proclaiming that:

> "Fluorocarbons are intentionally or accidentally vented to the atmosphere worldwide at a rate approaching one billion pounds per year. These compounds may be either accumulating in the atmosphere or returning to the surface, land or sea, in the pure form or as decomposition products. Under any of these alternatives, it is prudent that we investigate any effects which the compounds may produce on plants or animals now or in the future" (Glas, 1989).

As a result of that workshop, 19 companies formed the Chemical Manufacturers Association Fluorocarbon Program Panel, which eventually funded at least US$20 million in research at academic and government facilities worldwide. This private science funding was important for supplementing investigations of the hole in stratospheric ozone layer over the Antarctic, since private money moved at the speed of necessity.

1974: Mario Molina and F. Sherwood Rowland warned in an article published in Nature that chlorofluoromethanes (popularly known as chlorofluorocarbons – CFCs) would migrate to the stratosphere and deplete ozone that protects the earth against the harmful effects of ultraviolet (UV) radiation (Molina and Rowland, 1974). Increased UV radiation causes skin cancer, cataracts, suppression of the human immune system, and damage to agricultural and natural ecosystems. Few scientists took the warning seriously enough to publicly support the warning, but Molina and Rowland (1974) has 67 citations in the literature in 1975 alone, which is a substantial response. Industry did take notice, viewing the stratospheric ozone depletion warning as a threat to sales and profits, and ruthlessly organized science sceptics and economics exaggerators (Andersen and Sarma, 2002; Cagin and Dray, 1993; Dotto and Schiff, 1978; Oreskes and Conway, 2010).

With the collaboration of the Natural Resources Defense Council (NRDC), Molina and Rowland presented their findings at a meeting of the Chemical Manufacturers Association and held a press conference warning that "even a 10 percent depletion could cause as many as 80,000 additional cases of skin cancer each year in the United States (US) alone, along with genetic mutations, crop damage, and possibly even drastic changes in the world's climate" (Cagin and Dray, 1993). In the press conference, Molina and Rowland advocated the boycott and ban of CFC cosmetic and convenience aerosol products (hairspray, deodorants, and pesticides) (Brodeur, 1986; Cagin and Dray, 1993).

1975: The call for aerosol boycotts and bans unleashed a vicious response from the aerosol products industry, including personal attacks, blacklisting[5], and disparagement. CFC manufacturers paid for full-page newspaper advertisements questioning scientific findings, and many newspapers and trade journals covered the story.[6] According to the Los Angeles Times, the trade publication Aerosol Age suggested Rowland and Molina were agents of the Soviet Komitet Gosudarstvennoy Bezopasnosti (KGB).[7] Industry worked behind the scenes to discourage federal funding of ozone research that was likely to find fault with CFCs and to blacklist faculty and students who used science to advocate public policy (Andersen and Sarma, 2002; Brodeur, 1986; Cagin and Dray, 1993; Dotto and Schiff, 1978).[8]

US boycotts and bans in Oregon state and the cities of Berkeley, California, and Ann Arbor, Michigan, gained traction when SC Johnson and then Menon and Gillette broke with their industry, marketed ozone-safe alternatives[9], and advertised against CFC products so successfully

[5] "Blacklisting" attempts to harm adversaries by excluding them from employment, funding, and participation in policy making. A blacklist encourages discrimination and censorship.

[6] What Sherwood Rowland taught us about science, and the Earth. 2012. Los Angeles Times, 13 March 2012. http://opinion.latimes.com/opinionla/2012/03/sherwood-rowland-scientist-in-a-superhero-suit.html. (Accessed 7 March 2013).

[7] Today, being accused of being agents of the Soviet Union's KGB out to destroy capitalism may seem like rhetoric, but 1974 was just two decades after thousands of careers were damaged or destroyed and some people were imprisoned by McCarthyism and just one decade after the University of California regents and administrators first allowed free speech on college campuses.

[8] From 1975 to 1985, Dr. Rowland was not invited to any chemistry department to give a lecture despite the importance of his work. Dr. Donald Blake and Dr. Ralph Cicerone quoted by Felicity Barringer in "F. Sherwood Rowland, Cited Aerosols' Danger, is Dead at 84." New York Times, 12 March 2012. http://www.nytimes.com/2012/03/13/science/earth/f-sherwood-rowland-84-dies-raised-alarm-over-aerosols.html?pagewanted=all&_r=0. (Accessed 7 March 2013).

[9] Alternatives to CFC aerosol propellants include hydrocarbons, carbon dioxide, and compressed air, with not-in-kind alternatives including pumps, sprays, rollers, sticks, creams and more.

that almost every American company transitioned away from CFCs before the US Food and Drug Administration (FDA), Consumer Product Safety Commission (CPSC) and Environmental Protection Agency (EPA) in 1978 banned all non-essential uses of CFCs in food, drug and cosmetic products. Canada, Netherland, and Sweden also enacted bans, but the rest of Europe steadfastly continued run-away CFC aerosol product use (Andersen and Sarma, 2002; Brodeur, 1986; Cagin and Dray, 1993; Stoel et al., 1980). Citizens, leadership companies and some regulators were taking the warning seriously.

The price of the alternatives for cosmetic and convenience aerosol products was so much lower that Mexico undertook its own transition under the leadership of the aerosol product industry and with the support of government (Andersen and Sarma, 2002).[10]

1975: Veerabhadran Ramanathan was first to warn that CFCs are powerful greenhouse gases, adding significantly to the scientific justification to control CFCs (Ramanathan, 1975; Ramanathan et al., 1985). Few scientists and environmental authorities took the warning seriously enough to support the warning, but Ramanathan (1975) has 33 citations in the 1975–1979 period.

1975: The US National Academy of Sciences and Department of Transportation issued their 'Climate Impact Assessment Program (CIAP): Environmental Impacts of Stratospheric Flight: Biological and Climatic Effects of Aircraft Emissions in the Stratosphere' finding that:

- nitrogen oxides from SSTs were a threat;
- atmospheric levels of chlorine from CFCs would deplete the ozone layer six times more efficiently than oxides of nitrogen from SSTs;
- ozone depletion would increase the intensity of UV light at ground level;
- increases in ground level UV light would adversely impact plant growth and animal health.[11]

Influenced by the result of the CIAP studies and associated warnings, elaborate US plans to build fleets of SSTs were shelved, with production of only small numbers of the French/British Concorde and Soviet SST Tupolev (Andersen and Sarma, 2002). Policy makers were taking the warnings seriously.

1976–1988: Refrigeration and air conditioner stakeholders denied the ozone science, claimed that alternatives were unsafe or unavailable, and predicted dire economic, health, and safety consequences (Andersen and Sarma, 2002). In Europe, Imperial Chemical Industries (ICI) was skeptical, obstructionist, and slow to accept the science, even after the signing of the Montreal Protocol. European aerosol stakeholders questioned the science and denied that alternatives were available, despite the fact that European aerosol products sold in the United States had been CFC free after the US ban (Andersen and Sarma, 2002). Attacks on ozone science were largely the work of a few dedicated science sceptics and anti-environmental activists who had also campaigned to mislead the public and deny well-established science on the safety of tobacco, acid rain, and climate change (Oreskes and Conway, 2010). These science sceptics, cynics, and paid deniers were relatively ineffective in slowing ODS phaseout because the most credible and trustworthy scientists made extra efforts to translate complex atmospheric findings into reports suitable for corporate, military and government policy makers (Fahey and Hegglin, 2014).

Some science sceptics also claimed that multinational fluorocarbon producers contrived the ozone depletion concept in a plot to market HFC substitutes to ODSs with expiring patents, and that these corporations funded environmental non-governmental organizations (ENGOs) through their foundations to propagate the falsified theory (Andersen and Sarma, 2002; Moore, 1990; Robbins et al., 1992).

1981: Total ozone measurements using Dobson spectrophotometers at Japanese, British, and other Antarctic research stations recorded an approximate 20% reduction in stratospheric ozone levels (Chubachi, 1984; Farman et al., 1985). None of the Antarctic scientists published their 1981 results or consulted other stations to confirm their observations. In the Antarctic spring of 1982, Antarctic stations and the ozone-measuring devices aboard the Nimbus 7 satellite again registered low ozone levels. Two years later, the first report of seasonal ozone depletion over Antarctica was published by Japanese scientists, who failed to appreciate the significance of their findings and took no actions to bring them to the attention of policy makers (Andersen and Sarma, 2002; Chubachi, 1984). Because activist scientists more directly involved in policy on stratospheric ozone had not anticipated the Antarctic ozone hole, they were not carefully monitoring the Antarctic reports.

1985 (March): Thirty-four countries agreed on the Vienna Convention for the Protection of the Ozone Layer, which established the framework for a protocol. The obligations of the Parties to the Convention were to cooperate in research, atmospheric observations, and information exchange, and to adopt policies to control human activities that might modify the ozone layer and climate. The only mention of CFCs came in Annex 1 as one of the many substances 'thought to have the potential to modify the chemical and physical properties of the ozone layer' (Andersen and Sarma, 2002; Benedick, 1991, 1998). It is significant and visionary that the Vienna Convention addressed both stratospheric ozone and climate.

[10] The innovation by Mexican industry was to manufacture in open-air buildings where any hydrocarbon leak would be naturally disbursed by the wind and thermo-siphoning, in contrast to factories in the colder climates of US and Canada that required active safety systems to detect dangerous hydrocarbon concentrations and mechanically ventilate the closed buildings. The innovation by the Mexican government was an advertising campaign promoting ozone protection and explaining to customers that each aerosol product actually contained more active ingredients but weighed far less because hydrocarbons are more efficient per unit weight than CFCs; otherwise the customers suspected that the valve had leaked and part of the product was gone.

[11] One author of this paper, Andersen, was a participant in the CIAP Assessment while completing graduate school at the University of California, Berkeley. The part of the study Andersen participated in concluded that the predicted shortening of the frost-free growing season and increases in UV light would have a significant impact on agricultural yields, particularly for northern latitude grain production in Canada and the Union of Soviet Socialist Republics.

1985 (May): Scientists from the British Antarctic Survey finally sounded the alarm that ozone levels above Antarctica had been significantly depleted every Antarctic spring since at least 1981 (Farman et al., 1985). Although there was no proof of causation, their paper and presentations went beyond the evidence and attributed the Antarctic ozone depletion to CFCs. Joseph C. Farman was quick to organize news conferences and interviews and he confidently put the blame on CFCs (Pearce, 2008). Ozone depletion over Antarctica quickly became known as the 'ozone hole' and was frequently illustrated with images created by NASA, which depicted levels of reduced column ozone as circular regions cantered near and around the South Pole (Andersen and Sarma, 2002).

1986: Seventy-nine European and American environmental NGOs urge the total phase out of CFCs within 10 years; environmentalists and school children confront McDonald's use of CFCs in foam food packaging; and Greenpeace activists campaign against CFCs at Hoechst's Germany and Dupont's Luxembourg plants.

1986–Continuing: First a few and soon many companies dependent on ODSs embraced the science, and the highest levels of management made ODS phaseout a priority. Environmental leadership companies and other organizations viewed the market transformation to ozone-safe technology as a moral imperative and a business opportunity and invested heavily in next-generation technology (Andersen et al., 2007). Military organizations viewed ozone depletion as a national security risk and quietly and then loudly became part of the solution, with leadership pledges, wholesale abandonment of military specifications requiring ODSs, and research and commercialization of next-generation technology, which was made available worldwide (Andersen and Morehouse, 1997; Andersen et al., 1997; Parson, 2003).

1987: A US EPA "Tiger Team"[12] of respected and influential experts from France, Germany, Japan, the United Kingdom, and the United States identified fluorocarbon alternatives for ODSs. The team estimated that the cost of producing these new chemicals was only 3–5 times the cost of CFCs, which were priced at between $1.30 and $1.75/kg (Nelson, 1988). [13] Furthermore, they estimated that the cost of refrigerant and solvent containment, "recovery and recycle," and recovery was lower than the cost of the new alternatives and could be implemented faster.

1987: The Natural Resources Defense Council (NRDC) uses US EPA chemical emissions data to "blame and shame" America's largest CFC emitters: AT&T, General Electric Company, General Motors, IBM, US Air Force, and United Technologies (Andersen and Sarma, 2002).

1987 (September 16): 24 nations and the European Commission signed the Montreal Protocol, *starting* with meagre controls on just chlorofluorocarbons (CFCs) and halons. The Montreal Protocol had immediate traction because almost all countries responsible for production and significant use were signatories and because the trade barriers would persuade or compel action, whether member or not (Brack, 1996). Furthermore, it turned out that a significant portion of ODS use in developing countries was in factories owned by multinational corporations that were:

- headquartered in countries that were parties to the Montreal Protocol;
- manufacturing products for export to developed countries.

Mexico was the first country to sign the Protocol and first to ratify.

1988: UN Environment Program (UNEP) Executive Director Mostafa Tolba organized four Montreal Protocol Assessment Panels to guide the pace and focus of adding substances to the treaty and accelerating the control measures in response to scientific advice and technical and economic feasibility. The Panels were:

- the Scientific Assessment Panel (SAP);
- the Environmental Effects Assessment Panel (EEAP);
- the Technology Assessment Panel (TAP);
- the Economics Assessment Panel (EAP).[14]

Tolba implemented path-breaking independence from political interference, with panels only accepting qualified experts and with findings published without political censorship. Significantly, Dr. Tolba endorsed the participation of industry and military experts on the TAP, with focus on experts from organizations that had pledged and were seeking phaseout (Andersen and Sarma, 2002; Canan and Reichman, 1993, 2002).[15] This independence and integrity endures today.

1989: "Endangered Earth" gets Time Magazine's 'Person of the Year Award.'

1990: With leadership by British Prime Minister Margaret Thatcher, Indian Minister of Environment

[12] A Tiger Team is defined as group of like-minded experts brought together to solve problems that otherwise would have catastrophic human consequences. Tiger Teams are multidisciplinary, confident, agile and nearly always successful.

[13] The strategy of tiger teams was the brainchild of EPA's Stephen O. Andersen who had been hired to make the case that it was technically and economically feasible to replace ODSs. At that time and now, EPA typically hires articulate consultants with academic credentials to prove such feasibility, and then fights it out with "experts" from companies and their associations opposed to regulation. Andersen reasoned that he could recruit and empower respected and influential experts from responsible companies that were already searching for solutions. These experts could out-gun and outmaneuver the opposition and commercialize alternatives, with government clearing away barriers and putting in place appropriate standards and incentives.

[14] After the first assessment, the Technology Assessment Panel (TAP) and the Economics Assessment Panel (EAP) were merged to become the Technology and Economics Assessment Panel (TEAP).

[15] In October 1988, Andersen and Buxton organized a workshop in The Hague specifically to demonstrate to Tolba and other environmental authorities the environmental advantage of including progressive companies on the technology assessment. Thus, Andersen and Buxton, who were appointed co-chairs of the technology assessment, were allowed to recruit members rather than rely on nominations. The first assessment excluded experts from ODS producing companies, but later allowed their participation.

Table 1
Strengthening the Montreal Protocol by controlling more substances.

Year	Action[a]	Controlled substance
1985	Vienna Convention	Framework only
1987	Montreal Protocol	CFCs (Annex A, Group I) Halons
1990 (2nd MOP)	London Amendment	CFCs (Annex B, Group I) Methyl chloroform, Carbon tetrachloride (CTC)
1992 (4th MOP)	Copenhagen Amendment	Hydrochlorofluorocarbons (HCFCs) Hydrobromofluorocarbons Methyl bromide
1997 (9th MOP)	Montreal Amendment	Methyl bromide trade measures
1999 (11th MOP)	Beijing Amendment	Bromochloromethane production controls on HCFCs
2016 (28th MOP)	Kigali Amendment and Energy Efficiency Decision	HFCs (nearly ozone-safe GHGs[b])

[a] Adjustments at the 1990 2nd, 1992 4th, 1995 7th, 1997 9th, 1999 11th and 2007 19th MOP.
[b] HFCs are not really ozone-safe, albeit with small ODPs, because they modify stratospheric temperatures, and thereby ozone.

Monika Ghandi, and North American and Nordic negotiators, the Montreal Protocol created the Multilateral Fund (MLF) to pay the agreed incremental costs of transition for developing countries using less than 0.3 kilograms ODS/capita (as classified under Article 5 of the Protocol and thereafter known as Article 5 Parties) (Andersen and Sarma, 2002; Parson, 2003). Paul McCartney and Capital Records launch a world 'Rescue the Future' tour promoting the Friends of the Earth's stratospheric ozone protection campaign.

1994: A Greenpeace protest at Dow Chemical's Norrkoping, Sweden, foam plant gets wide media attention when the Dow CEO holds up a piece of foam and says: "This is the problem, [. . .] I mean this is the product."

1990–2016: The Montreal Protocol was rapidly *strengthened* by five Amendments to control additional ozone-depleting and HFC greenhouse gas (GHG) substances and by six Adjustments to accelerate the phaseout of thirteen controlled substances (Table 1).

1995: Nobel Prize for Chemistry awarded to Paul Crutzen, Mario Molina, and F. Sherwood Rowland. "Without a protective ozone layer, animals and plants could not exist, at least not upon land. It is therefore of the greatest importance to understand and protect the atmosphere's ozone content" (Royal Swedish Academy of Sciences, 1995).

2007: *Entrepreneurial scientists* branded as the Velders Team (named for lead author Guus J.M. Velders from the Netherlands) published a paper in the Proceedings of the National Academy of Sciences (PNAS) that was the motivation for the 2007 acceleration of the HCFC phaseout. The HCFC phaseout acceleration was justified by climate benefits with ozone co-benefits (Velders et al., 2007).

2009: With the leadership of Marco Gonzalez and the Secretariat, the Montreal Protocol became the first treaty to be universally ratified by all 196 UN States, a historical accomplishment that few other treaties on any topic have so far achieved.

2009: The Velders Team published a paper in PNAS that was the motivation for the 2016 Kigali HFC Amendment, justified solely by climate benefits, because HFCs are ozone-safe (Velders et al., 2009). Many other scientists have since confirmed and elaborated the Velders findings (Molina et al., 2009; Velders et al., 2012; Xu et al., 2012; Zaelke et al., 2012).

2016: Parties to the Montreal Protocol sign the Kigali Amendment to phase down HFCs and decide to examine costs and look at opportunities to increase the energy efficiency of replacement technology.

2017: 99% of controlled ODSs are phased out, with just 15% of applications that once used ODSs switching to fluorinated chemicals (HFCs), and now hydrofluoroolefins (HFOs) replacing some high-GWP HFCs. About 85% of ODS uses have been replaced by "not-in-kind" (NIK) technology (Andersen et al., 2007; Leahy, 2017; Seidel et al., 2016), containment, and doing without frivolous or non-essential products once made with ODSs. [16] The atmospheric abundances of ODSs have peaked and are now decreasing. The ozone-depleting concentration of chlorine and bromine will continue to decline and will return to pre-1980 levels around mid-century.[17] The ozone layer is on the path to recovering by the end of this century to the condition prior to emergence of the Antarctic ozone hole, provided that countries abide by the Montreal Protocol ODS controls. Increasing atmospheric concentrations of GHGs [primarily carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), HFCs, perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6)], will accelerate stratospheric ozone recovery above natural levels if these GHGs are not rapidly controlled (Zaelke et al., 2018).

The policy take-home messages are:

- pursue and embrace the science;
- start and strengthen;

[16] ODS emissions will continue from leaking foam and equipment for many decades. The impact of the most prominent ODSs (CFC-11 with atmospheric lifetime of ~55 years and CFC-12 with atmospheric lifetime of ~140 years) will continue for many decades after emissions have ceased.

[17] Equivalent effective stratospheric chlorine (EESC) is the metric estimating the total effective amount of halogens (chlorine and bromine) in the stratosphere. It accounts for quantity of ODSs emitted into the troposphere, the various transport times into the stratosphere, and the ozone depletion potential (ODP) of each substance.

- one step at a time;
- learn by doing;
- relentlessly pursue incremental progress;
- be flexible in compliance and enforcement;
- sustain scientific, policy and corporate environmental leadership.

2. Individual, company, and military leadership in commercializing and implementing alternatives to ozone-depleting substances (ODSs)

2.1. Inventing, marketing, then over-marketing ODSs

Consider that:

- until about 1970, no one suspected that manufactured chemicals could destroy the stratospheric ozone layer;
- until 1974, no one knew that CFCs were ozone-depleting substances;[18]
- until 1975, no one knew that CFCs were GHGs.[19]

Now policy makers are just beginning to appreciate the science of how climate change impacts stratospheric ozone and vice versa (Haigh and Pyle, 1979; Luther et al., 1977). Thus, ozone depletion and climate forcing, until very recently, were unintended consequences of the intentional quest for non-flammable and non-toxic chemicals in support of prosperity (Andersen and Gonzalez, 2013; Andersen et al., 2014).

Until about 1900, stratospheric ozone was held in balance by natural processes that created ozone as rapidly as it was depleted. However, the stratospheric ozone layer came under increasing threat as manufactured chemicals were invented, commercialized, marketed, and emitted in ever-increasing quantities.

The first relatively minor human threats to stratospheric ozone balance were manufactured ODSs commercialized around 1900: carbon tetrachloride used as a solvent and fire extinguishing agent, and methyl bromide used as a fire extinguishing agent, anesthetic, and pesticide.

The greater threat to ozone balance occurred after 1928, when Thomas Midgley, Albert Henne, and Robert McNary, working for General Motors (GM) and its refrigerator manufacturing division, Frigidaire, identified and patented chlorofluorocarbons (CFCs) as refrigerants. Belgian scientist Frédéric Swarts had first synthesized CFCs in the 1890s. CFCs are non-flammable, non-explosive, non-corrosive, very low in toxicity, and odorless. Their vapor pressures and heats of vaporization made them suitable for refrigeration applications. Within a year, GM patented the family of CFCs and, with their partner DuPont, perfected the manufacturing process. In 1928, CFCs seemed to be "wonder gases," with every known reason to promote wide and extensive use (Andersen et al., 2014).

In the four decades after the invention of CFCs, DuPont and other fluorocarbon manufactures promoted uses beyond refrigeration and air conditioning, including: aerosol propellants, solvents, flexible and rigid foam blowing agents, pesticides, fire inerting and extinguishing agents, and as feedstock and process agents in the manufacture of other chemicals and plastics. By the time Molina and Rowland published their 1974 warning, the ozone layer was in grave danger. The Antarctic ozone hole was evident in 1982 but was not reported until 1985. Therefore, at the same time that Molina and Rowland reported their chemical hypothesis, the urgency of the threat of ozone depletion compelled them to call for a ban on cosmetic and convenience aerosol products (mainly spray deodorant and hairspray), which, at that time, accounted for about half of global ODS emissions when weighted by ozone depletion potential (ODP).

Fortunately for all humans, US, Canadian, Netherlands and Scandinavian citizens responded to the Molina and Rowland ozone depletion warning by boycotting CFC aerosol hairsprays and deodorants. The SC Johnson Company immediately shifted its product line to hydrocarbon propellants and aggressively advertised the environmental advantage. In the United States, Gillette and Williams quickly offered ozone-safe alternatives, with aggressive advertising support for hydrocarbon and NIK creams, pumps, sprays, rollers and sticks. However, despite this consumer and business effort in North America and Scandinavia, Europe and most other countries continued CFC aerosol use almost unabated, such that more than one-third of ODP-weighted global ODS use in 1987 was for cosmetic and convenience aerosol products. Fluorocarbon manufacturers assured their customers that the stratospheric ozone was not jeopardized by these uses.

Unfortunately, most citizens and environmental authorities did not appreciate that there were many other run-away uses of ODSs. Continued aggressive marketing quickly overcame the decline in aerosol product sales, and atmospheric concentrations continued almost unabated. Meanwhile, UNEP Executive Director Dr. Mostafa Tolba was quietly setting the stage for controls to come under a treaty. When the Antarctic ozone hole was discovered in 1985, UNEP was ready to act fast and with global reach.

In 1985, news of the Antarctic ozone hole immediately energized attacks by environmental activists on foam food packaging, which was already considered a litter problem and a hazard to terrestrial and aquatic organisms, which would ingest the fine non-biodegradable particles formed when hard foam is degraded by mechanical action such as waves. These "Styro-Wars" were a threat to McDonalds and other fast-food chains using foam clamshell packaging. In response, these companies notified their suppliers to find a different packaging material (Andersen et al., 2007; Cook, 1996; Sherman, 1989). Although not all foam food packaging contained CFCs, the products became a target for legislation and boycotts because they were perceived as a frivolous CFC use.

The US EPA brought affected companies together with environmental NGOs (ENGOs) to find a fast and fair

[18] It was not until 1992 and 1999, respectively, that methyl bromide and bromochloromethane were identified as significant ODSs. The Montreal Protocol has not yet controlled ozone-depleting nitrous oxide (N_2O) or *n*-propyl bromide (nPB).

[19] Ramanathan, 1975; Ramanathan et al., 1985.

solution and to avoid the political fallout and backlash if foam food packaging factories closed and jobs were lost. Companies and ENGOs signed an agreement with EPA in which companies agreed to halt fully halogenated CFC use within one year, to transition to the hydrocarbon-produced foam as quickly as safely possible (mindful of the need to comply with manufacturing and shipping safety codes), and to share CFC-free technology worldwide (Sherman, 1989).

EPA succeeded in securing fast approval from the Food and Drug Administration (FDA) for the use of HCFC-22 (ODP = 0.2; GWP = 1750) as a blowing agent transition alternative to CFC-12 (ODP = 1.0; GWP = 10,200) and agreed to monitor and report progress (FDA, 1988a, 1988b). ENGOs agreed to halt the campaign against foam food packaging and to explain to the press the advantage of a CFC phaseout. The result was that dozens of food packaging, restaurant, and associated companies supported ozone layer protection with pride and satisfaction, which made later phaseout of ODS in the food cold chain faster and less contentious than it might otherwise have been. EPA was learning that voluntary programs could be faster, fairer, and less expensive than the traditional approaches of confrontation and "command and control." Friends of the Earth UK made similar voluntary agreements with foam producers to phase out ODSs (Andersen et al., 2007; Cook, 1996).

2.2. The signing of the Montreal Protocol signaled business opportunities in development and marketing of alternatives and substitutes

In January 1988, American Stephen O. Andersen and Canadian Victor Buxton of the Conservation Foundation organized the first annual *International Conference on Alternatives to CFCs and Halons* in Washington DC, which drew more than a thousand participants, including industry stakeholders who wanted to do their part in protecting the ozone layer and also sought to supply the new markets. AT&T punctuated the opportunity by announcing development of aqueous electronics cleaning technology as effective as CFC-113. Subsequent annual conferences migrated to sponsorship by industry and EPA, and drew as many as 2000 or more participants. The conference, renamed the Earth Technology Forum, became known as the occasion where new global, regional, and national regulations and next-generation technology would be announced.

On the sidelines of the 1988 conference, the US EPA, with the Mobile Air Conditioning Society (MACS), Underwriters Laboratories, dozens of automobile manufacturers, service equipment suppliers, and a half dozen ENGOs led by Friends of the Earth, began a year-long project to develop recovery and recycle technology for CFC-12 used in motor vehicle air conditioning. By 1988, the recovery/recycle equipment was perfected, tested for performance by Underwriters Laboratory (UL), and agreed by automobile manufacturers for repair under new car warranties. The market was jump-started by bulk equipment purchases by European, Japanese, and North American auto companies, which mandated use by all their dealerships. Within a year, more than US$2 billion in recovery/recycle equipment had been sold (Atkinson, 2008).

Automotive manufacturers and service associations continued their leadership, including cooperative projects to:

- reduce refrigerant leaks;
- verify the materials and lubricant compatibility for next-generation HFC-134a refrigerant.

Most spectacularly, automobile manufacturers made a joint announcement that they would implement HFC-134a as soon as available, even though HFC-134a had not completed regulatory approval and was not yet in commercial production. That announcement gave fluorocarbon manufacturers the confidence to move ahead with investment long before the Montreal Protocol would have required it (Atkinson, 2008; Andersen and Sarma, 2002).

Beginning in 1988, multinational companies—including AT&T, Nortel, and Seiko Epson—began to pledge to phase out CFC solvents in electronics and precision product manufacturing. Simultaneously, ministries of defense—particularly the US Department of Defense (DoD) and its services (Air Force, Army, Navy, Marines, and Coast Guard)—inventoried their dependence on ODSs and worked with their own centers-of-excellence and contractors to find solutions. (Andersen, 1988; Andersen et al., 1997; Hoffman, 1990; Miller, 1990). Dozens of private corporations and military organizations were instrumental in transforming markets, by supplying the necessary new technology, by promptly implementing the new technology, and by sharing technology and technical know-how worldwide (Andersen et al., 2007).

Meanwhile, the US EPA and the US DoD formed a partnership to reduce and eliminate ODSs in weapons systems as soon as technically and economically feasible. DoD recruited military authorities from Australia, Canada, Finland, Germany, Netherlands, Sweden, and the UK. After securing endorsement from the North Atlantic Treaty Organization (NATO) for phaseout under the Montreal Protocol, the US DoD and US EPA extended their cooperation to the Union of Soviet Socialist Republics (USSR) (Andersen and Sarma, 2002). These military partnerships were among the first to characterize ozone and climate risk as national security concerns, with international conferences urging fast action: Williamsburg, Virginia (1991), Brussels (1994, 1998 and 2001), Washington DC (1997), and Paris (2008).

One measure of the power of corporate and military leadership is the collection of technical handbooks published by OzonAction, the US EPA, and other partners, ranging from electronics soldering, aircraft maintenance, and rocket manufacture to forensic science (developing latent finger prints), testing oil in water, and ODS-free thermal insulating foam. A measure of co-benefits is that many of the products replacing those made with or containing ODSs are more energy efficient, more reliable, and have higher technical performance (Andersen and Morehouse, 1997; Andersen et al., 2007). A measure of enduring influence is that most of the companies that were champions of ozone layer protection are now champions of climate protection (Andersen and Zaelke, 2003).

After 1989, when the Economic and Technology Assessment Panels were organized, most of the Technical Options Committees operated as a focal point for voluntary and coordinated action (Cook, 1996). For example, Halon TOC co-chair E. Thomas Morehouse was responsible for the US Air Force halon phaseout, and Halon TOC co-chair Gary Taylor was also chair of the National Fire Protection Association (NFPA) committee setting standards for halon. Together, Taylor and Morehouse orchestrated the research and demonstrations necessary to halt testing and training with halon, which accounted for 90% of emissions. Solvents TOC co-chair Stephen O. Andersen also co-chaired the DoD committee approving ozone-safe alternatives in electronic and aerospace manufacturing. Electronics experts from the Solvents TOC documented that most electronics equipment could be safely protected with water sprinklers rather than halon, and that data security and continuity of business operations were the real risks solved by off-site data storage and computers. These actions taken together persuaded the Parties to phase out halon production in 1994, two years faster than any other ODS. TEAP co-chair Suely Carvalho became the trusted source for developing countries (classified as Article 5 Parties (A5 Parties) under the Protocol) regarding which technologies were best and was soon recruited by the United Nations Development Program (UNDP) to spearhead investment under the MLF.

The US EPA was particularly ambitious at organizing voluntary partnerships after success with the foam food packaging phaseout, motor vehicle refrigerant recycling, the automobile manufacturers' pledge to implement ozone-safe HFC-134a, and the halon community's abandonment of testing and training. EPA, with the support of the DoD, organized the Halon Alternatives Research Corporation (HARC) to seek new alternatives to halon in uses without proven options. With AT&T and Nortel Corporation, the US EPA organized the Industry Cooperative for Ozone Layer Protection (ICOLP) to speed the development of new technology to replace CFC-113 as a solvent in electronics and aerospace manufacturing and service.

Chemical companies, with the support of the Chemical Manufacturers Association (CMA) (today reorganized as the American Chemical Council – ACC), founded and financed the Alternative Fluorocarbon Environmental Acceptability Study (AFEAS) to determine the atmospheric fate and ecological impact of alternatives, as well as the Program on Alternative Fluorocarbon Testing (PAFT) to determine the toxicity of the new substances. By pooling their resources, global companies avoided duplication of effort, selected the most respected and influential scientists to conduct the work, and more rapidly persuaded global environmental authorities, who would also enjoy the benefit of cooperation and collaboration (Andersen et al., 2007; Andersen and Sarma, 2002).

It is also important to recall the leadership of Article 5 Parties in identifying national companies that had often avoided dependence on ODSs simply because ODSs were expensive or unavailable because fluorocarbon companies did not bother to market in remote locations or because engineers came from different intellectual traditions. For example, Mexico had avoided halon fire suppression systems in factories using hydrocarbons by building facilities that were cross-ventilated by the wind in locations where heating and cooling were unnecessary. Mexican companies had also learned how to blow foam products at higher altitudes, where CFC foaming agents were less necessary.

The invention of no-clean soldering by ICOLP companies was partly inspired by Brazilian engineers at Ford Sao Paulo, who had developed from local plants a soldering flux that was less corrosive after heating in the molten solder wave than flux made from pine species and used elsewhere (Andersen and Sarma, 2002).

In Thailand, ICOLP members discovered that 80 or 90% of ODS solvent use was for export products manufactured by multinational companies (including their own companies). The rapid response was to organize a pledge by multinational companies to stop ODS use in overseas operations within one year of halting in their home country. In Vietnam, ICOLP members discovered that European and Japanese companies were dumping obsolete CFC equipment already phased out elsewhere. The rapid response was to organize the "Vietnam Pledge" by multinational companies to not increase the dependence of Vietnam on ODSs and to implement alternatives as soon as possible.

ICOLP members doing business in the United States were faced with a well-intentioned requirement under the Clean Air Act to label products made with or containing ODSs. The problem was that there are thousands of components of unknown origin in many electronic products and it would be impossible to be sure that all parts were made without ODS. A law with comparable intent had been passed in California that required labelling products with materials or ingredients suspected of causing cancer, which resulted in almost every product being labelled as potentially hazardous, and thus camouflaging those that were truly hazardous.

Electronics companies pleaded with EPA to not mindlessly enforce universal labelling, which would waste money that would be better spent on ODS phaseout and would also weaken the distinction between companies doing their part for ozone protection and those who do not. The solution was that EPA agreed to quietly not implement the labelling rule for electronics in exchange for a campaign to make the companies' common and shared supply chains ODS-free. Electronics companies wrote to their subsidiaries and suppliers notifying them that they would no longer purchase anything not certified as ODS-free, and that they would finance an immediate transition to ozone-safe manufacture and pay more for parts, if necessary.

Under the leadership of one or more ICOLP companies in each country (developed or developing) suppliers were certified ODS-free and added to master lists for use by all companies. Thus, the ODS solvent phaseout was accelerated worldwide, responsible companies were rewarded for environmental protection, and US companies came to appreciate and praise EPA for seeing beyond the legal requirement to the Earth protection requirement (environmental performance not prescription.)

All the while, regulators worldwide were pressing hard against ODSs using command-and-control, ODS taxes (USA and Singapore), citizen campaigns, government procurement, and promotion of alternatives. The EU that had once blocked agreement on an ozone treaty managed to phase out CFCs and halons about a year faster than required by the control schedule and faster than the US, which was also ahead of schedule. The EU also moved faster on HCFCs, while a faulty US allocation system actually promoted maximum HCFC use (Andersen et al., 2007).

3. The Montreal Protocol becomes a climate treaty

In 2005, experts from the Vienna Convention/Montreal Protocol and Framework Convention on Climate Change/Kyoto Protocol cooperated on the first integrated assessment to look at interrelationships and synergies (IPCC/TEAP, 2005). Among the findings was the realization that HFCs that had been commercialized to replace ODSs could be used in previous ODS applications where environmentally superior alternatives and substitute were available. The assessment also found that the phaseout of ODS had protected climate far more than was appreciated by policy makers and most scientists. In 2006, unable to persuade the IPCC authorities to spotlight the finding that the Montreal Protocol protects climate, TEAP co-chair Andersen approached the Montreal Protocol SAP co-chairs to include the findings, but learned that it was too late for the 2006 SAP Scientific Assessment of Ozone Depletion Report because no one had systematically estimated and published the estimates of climate benefit in a peer-reviewed journal, as required by the SAP terms of reference. To solve this problem, a "science dream team" was organized, with Guus J.M. Velders as lead author and including Stephen O. Andersen, David W. Fahey, John Daniel, and Mack McFarland. Ozone Secretariat executive director Marco Gonzalez and IGSD President Durwood Zaelke, with colleague Scott Stone, served as informal communication and outreach advisors (Andersen et al., 2009).[20]

The first Velders team paper (Velders et al., 2007) *The Importance of the Montreal Protocol in Protecting Climate*, was published in the prestigious *Proceedings of the National Academy of Sciences (PNAS)*. The scientific findings were featured at the mid-year 2007 meeting of the Montreal Protocol Open-Ended Working Group (OEWG) and were one of several contribution factors for an Adjustment to the Montreal Protocol, which was agreed at the 2007 Meeting of the Parties (MOP) and accelerated the HCFC phaseout. Realization of the benefits of climate protection catalyzed support for the accelerated HCFC phaseout, since the phaseout previously in place would have protected stratospheric ozone without the acceleration.

The Velders study estimated that the climate benefit of ODS phaseout actions under the Montreal Protocol in 2010 was about 11 gigatons carbon dioxide (CO_2)-equivalent per year, which is 5–6 times the reduction target of the first commitment period (2008–2012) of the Kyoto Protocol, as illustrated in Fig. 1. The Montreal Protocol net reduction in ODS radiative forcing in 2010 was equivalent to about 7–12 years of growth in radiative forcing of CO_2 from human activities. In addition, the study estimated that it is technically feasible to further protect the ozone layer while reducing global GHG emissions by up to 5% for ten years or more by adopting the following:

- collection and destruction of surplus or contaminated ODS;
- acceleration of the HCFC phaseout in developed countries;
- adoption of technologies that are both ozone and climate safe wherever feasible;
- accelerated ODS phaseout in developing countries.

Line (a) represents historic and predicted future global CO_2 emissions. Area (b) represents the CO_2-eq of ODS emissions that would have occurred if Molina and Rowland had not warned the world about CFCs (could have been greater than CO_2!). Area (c) represents the CO_2-eq of ODS emissions without the Montreal Protocol. Area (d), representing annual GWP-weighted emissions, is the total estimated climate protection provided by the Montreal Protocol, estimated at ~11 Gt CO_2-eq (Velders et al., 2007). The black line is the actual CO_2-eq ODS emissions as reduced by the Montreal Protocol.

The findings of the Velders science team energized diplomats to use the Montreal Protocol to protect the ozone layer by accelerating the phaseout of HCFCs, mindful that an earlier phaseout would also further protect the climate. As a consequence, in 2007, the parties adjusted the Protocol to accelerate the HCFC phaseout in both developed and developing countries. The findings were integrated into subsequent SAP reports and ozone science anthologies (Andersen et al., 2009; Zerefos et al., 2009).

In 2009, Velders et al. published a second paper that estimated the climate benefits of a phasedown under the Montreal Protocol of the production and consumption of ozone-safe HFC greenhouse gases. Velders co-chaired a United Nations Environment Program (UNEP) assessment in 2012 that endorsed and strengthened these findings and stimulated dozens of supporting studies (Velders et al., 2012). These papers presented the scientific foundation for the 2016 Kigali Amendment to the Montreal Protocol to control HFCs. Parties reinforced this new climate focus by agreeing a decision to develop cost guidelines for maintaining or enhancing energy efficiency during the transition from HCFC and HFC refrigerants and thermal foam blowing agents.

4. The Montreal Protocol: diplomatic and environmental success story

> "Perhaps the single most successful international agreement to date has been the Montreal Protocol."

[20] On the occasion of the 30th Anniversary of the Montreal Protocol, the United Nations awarded the 2017 Scientific Leadership Award to the Velders science team (Stephen O. Andersen, David W. Fahey, John Daniel, Mack McFarland, and Guus J.M. Velders) and the Velders communication team (Marco Gonzalez and Durwood Zaelke).

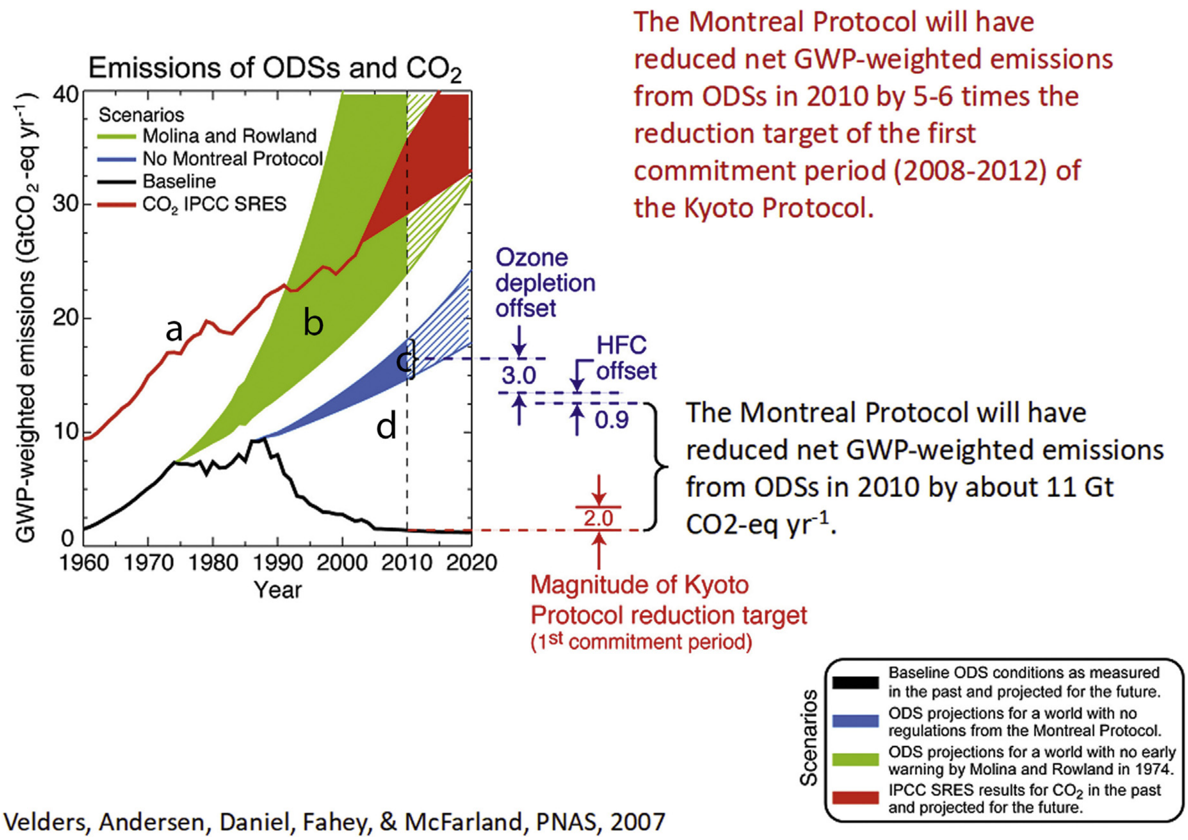

Fig. 1. The Montreal Protocol protects climate.

Kofi Annan, former Secretary-General of the United Nations[21]

The Montreal Protocol was designed from the beginning as a flexible and adaptable "start-and-strengthen" instrument. Drawing on the reports of the Assessment Panels, Parties to the treaty have been able to implement increasingly stringent control measures in response to emerging scientific evidence and technological developments. The Protocol is designed to evolve in response to new atmospheric challenges facing humankind now and in the future.

Another essential element of the Protocol was its recognition of the different needs and circumstances of countries at different stages of development, without forgetting that the stratospheric ozone layer would be lost unless all countries took action. Thus, the 1987 Montreal Protocol was a clear application of the principle of common but differentiated responsibility to protect and manage the global commons, which was agreed at the UN Conference on Environment and Development (UNCED) in 1992. This principle is reflected both in differentiated control schedules and in the existence of the Multilateral Fund, with its record of providing technical support and finance for the incremental costs of phaseout.

Since its inception in 1991, the financial mechanism of the Montreal Protocol, the Multilateral Fund (MLF), has financed activities worth more than US $3. billion for industrial conversion, technical assistance, training and capacity-building. One of its unique achievements has been to support the network of National Ozone Units (NOUs) with training and experience sharing among countries in the different regions. No other environmental treaty does this. Ozone officers are properly trained to manage activities and ODS data reporting responsibilities. They play a central role in monitoring compliance and setting local policies. The ozone officers are supported by implementing agencies of the MLF throughout the developing world.

As the Protocol has evolved, it has developed an effective data collection and reporting system. And this, in turn, has allowed the assessment of compliance and provision of assistance to countries experiencing difficulties in meeting their obligations. The Protocol's compliance system, overseen by the hardworking members of the Implementation Committee, has a mature, flexible and sophisticated structure that continues to function successfully. It is regarded with respect internationally and is considered to be a model to be emulated in other international agreements.

[21] United Nations, 2006. Report to the General Assembly's Millennium Summit. New York.

5. Opportunities to improve the success of the Montreal Protocol

In any environmental campaign, it is important to recognize success, but also to identify opportunities for improvement in order to make regulatory amends and to inform future actions. Other treaties may have had a significant number of difficulties, with the difference that they had little of the success of the Montreal Protocol.

This is the authors' list of opportunities for improvement, in order of environmental importance:

- Finance phaseout and phasedown when A5 Parties want to go beyond compliance. The Parties to the Montreal Protocol considered compliance with the control measures of Montreal Protocol as the criteria for replenishment of the MLF, and non-Article 5 Parties inserted the concept of "uniform replenishment." When replenishment is just enough for compliance, it is only possible to phase out faster when the costs are very low or when the companies making the change are inspired by environmental responsibility and pay part of the cost. A5 Parties that could phase out faster than compliance were discouraged to ask for funding and were denied funding when they asked. A consequence of funding only for compliance is that A5 Parties are often unable to set regulations to avoid ODS growth in the period prior to the freeze and during the period between the freeze and the first reduction step, when they finally become eligible for funding. The growth of consumption prior to the freeze and first reduction step forced A5 Parties to fund themselves, in some cases for a large amount of ODS reduction, without being financed. The definition of A5 Parties, based on consumption per capita, short-changed sectors that are critical for successful global phaseout, such as the servicing sector, and prevented small island states and low consumption A5 Parties from receiving enough financial help to sustain activities and keep trained personnel;
- Embrace the co-benefits of climate protection and clean air in setting the pace of control measures. The myopic view of most donors was that energy efficiency of the replacement technology was not compelled by the Protocol and therefore not to be funded. In some cases, energy savings achieved in manufacturing that resulted in lower operating costs were considered as funds to be returned to the MLF, discounted from the grant;
- Demand mandatory collection and destruction of unwanted ODSs associated with the phaseout of ODS and potential emissions after lifetime. In the case of halons, Parties acted far too slowly in the 1994 halon phaseout, and, as a result, surpluses were so vast that the commercial aviation industry saw no need to transition to alternatives. With the assistance of the International Civil Aviation Organization (ICAO), the industry dragged its feet in resistance to transition. As result of halon oversupply, poor halon bank management, and recalcitrant aviation companies, the TEAP Halon Technical Options Committee (HTOC) currently predicts that the aviation industry will apply for essential use exemptions once halon supplies are exhausted or considered too expensive due to scarcity;
- Promote sustainable alternatives to ODSs and HFC NIK solutions that would completely avoid fluorocarbons and other manufactured chemical substances that are GHGs or have atmospheric by-products like trifluoroacetic acid (TFA). Although NIK solutions replaced 85% of ODSs, more could have been accomplished if greater priority had been given to sustainability and uniformly available additional funding for environmentally superior alternatives. The absence of sustainability priority also allowed the Foam Technical Options Committee (FTOC) to consider itself focused only on ODS foam replaced by non-ODS form rather than a broader focus on replacing ODS foam with alternatives that are not foam, such as mineral wool and fiberglass;
- Better manage TEAP and its TOCs to avoid technical bias. There were occasions, such as the introduction of methyl formate foam, where the FTOC dismissed available market information and over-promoted fluorocarbon alternatives. Similarly, the RTOC was sometimes biased against hydrocarbon natural refrigerants and failed to appreciate that engineering solutions can allow the safe use of flammable substances. The RTOC was also biased in favor of CO_2 natural refrigerants for motor vehicle air conditioning (MACs) despite slow progress, sporadic prototyping, and poor technical, environmental and financial performance;
- Renew and refresh TEAP and its TOCs. As the organizations sponsoring experts from non-A5 Parties completed their own ODS phaseouts, they lost interest in continued participation. In particular instances, Parties refused the requests of TEAP Co-Chairs to sponsor necessary members with the specific expertise required by new technology changes and products. Sponsored non-A5 and A5 experts were allowed to remain as members, even after their skills were no longer needed;
- Investigate and rationalize fluorocarbon production. The phaseout of ODSs and phasedown of HFCs with allowed use for feedstock and process agent applications will destabilize the balance of fluorocarbon production in ways not completely understood. The goals of a comprehensive assessment of fluorocarbon production could include:
  - Avoiding overproduction or underproduction of substances as replacements for HCFCs and HFCs and as feedstocks for HFOs,
  - Minimizing the cost of MLF financing by shifting HCFC and HFC production capacity to feedstock and process agent applications rather than paying to shut down capacity, while at the same time building capacity for the same substance,
  - Alerting fluorocarbon manufacturers to emerging technology that limits the refrigerant charge and therefore reduces the demand for alternatives.

6. Conclusion

This paper explains how the invisible threat of stratospheric ozone depletion became so vivid that every country in the world has taken strong action, with 99% of almost one hundred ODSs phased out so far, and with the Montreal Protocol poised to do more to protect the climate.

The policy take-home messages are:

- pursue and embrace the science;
- start and strengthen;
- one step at a time;
- learn by doing;
- relentlessly pursue incremental progress;
- be flexible in compliance and enforcement;
- sustain scientific, policy and corporate environmental leadership.

Protection of the ozone layer is grounded in science and continuously influenced by scientific findings. Successful integration of science into policy usually requires aggressive action by the scientists themselves, NGOs, and/or policy makers. Science influenced stratospheric ozone protection historically and now explains how the Montreal Protocol can be strengthened to phase down the production and consumption of HFCs, which were once necessary as substitutes for ODSs, but are now obsolete and unsustainable. It is clear that the networks of experts created and maintained by the Assessment Panels remain central to the discovery, integration, synthesis, and communication of new science. The take-home message might be that we should redouble our efforts to support the best possible scientists, working with necessary resources, in cooperation worldwide and unencumbered, in communicating warnings and direction to citizens and policy makers.

Appendix A. Core readings on the Montreal Protocol

The Harvard University Environmental Science and Public Policy Archives (ESPPA) has a large collection of photographs, personal notes and previously confidential information, such as records of government negotiating positions and corporate strategy that were donated by Stephen O. Andersen, K. Madhava Sarma, Edward A. Parson and others. Additional donations are welcome. http://hcl.harvard.edu/libraries/lamont/collections/environment/.

The ozone science wars and building support for international action

Lydia Dotto and Harold Schiff (1978). *The Ozone War* is the most comprehensive early account of conflict among scientists, citizens, industry, and political activists.

John R. Gribbin (1988). *The Hole in the Sky: Man's Threat to the Ozone Layer* documents the triumph of science and diplomacy in securing the Montreal Protocol.

Seth Cagin and Philip Dray (1993). *Between Earth and Sky: How CFCs Changed Our World and Endangered the Ozone Layer* is the story of CFCs and the ozone layer in a historical context.

Ozone diplomacy

Mostafa Tolba (1998). *Global Environmental Diplomacy: Negotiating Environmental Agreements for the World, 1973–1992* shows that protecting the ozone layer was accomplished with a deliberate strategy. Mostafa Tolba is rightly credited with orchestrating scientists, diplomats, government experts, and environmental and industry NGOs to agree on the Montreal Protocol and its most important amendments and adjustments.

Richard Benedick (1998 edition). *Ozone Diplomacy: New Directions in Safeguarding the Planet* is a first-hand narrative from the perspective of the senior US negotiator of the 1987 Montreal Protocol, featuring interpretations of the bargaining motivation and stratagems of other countries.

Stephen O. Andersen and K. M. Sarma (2002). *Protecting the Ozone Layer: The United Nations History*. is an authoritative and exhaustively documented history of the science and diplomacy that led to the Montreal Protocol. It contains a detailed account of the contribution of business, industry, and government to develop environmentally sound alternative technologies to restore the ozone layer. Provides a careful record of the role of the media and non-governmental organizations in evolving the global response to the destruction of stratospheric ozone. It is the official UN history of the Montreal Protocol.

Stephen O. Andersen, K. Madhava Sarma and Kristen N. Taddonio (2007) *Technology Transfer for the Ozone Layer: Lessons for Climate Change* is a meticulous investigation of how technology cooperation, MLF finance and its global implementing agencies, and industry and military leadership dramatically accelerated ODS phaseout.

Duncan Brack (1996). *International Trade and the Montreal Protocol* covers the role of trade as a governing principle for international agreements and the perspective of various national economic positions regarding trade sanctions as an impetus for participation and compliance.

Edward A. Parson (2003). *Protecting the Ozone Layer: Science and Strategy* explains how the Montreal Protocol was organized from the first international action in the 1970s to the mature treaty. It includes discussion of politics and negotiations, scientific understanding and controversy, technological progress, and industry strategy. The book argues that authoritative scientific assessments were crucial in constraining policy debates and shaping negotiated agreements.

Social and technical networks of the Montreal Protocol community

Penelope Canan and Nancy Reichman (2002). *Ozone Connections: Expert Networks in Global Environmental Governance*. A sociological analysis of the extent and effectiveness of a small number of experts, organized in communities of practice, who were instrumental in protecting the ozone layer. Looking systematically at the connection between technology, global environmental policy, and the social connections of experts, the authors focus on the TEAP. By combining formal network analysis, biographical interviews and participant observation, they demonstrate that treaty implementation relies on social relations, trust, and the collaborative leadership of institutional entrepreneurs.

Naomi Oreskes and Erik M. Conway (2010). *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming*. This book is a carefully constructed and referenced analysis showing the connections of scientific critics, including those who denied the threat of stratospheric ozone depletion and climate change.

Atmospheric science translated for policy makers

David W. Fahey and Michaela I. Hegglin (2014). *Twenty Questions and Answers About the Ozone Layer: 2014 Update* is a remarkably clear introduction to atmospheric science of stratospheric ozone depletion and associated climate change. https://www.esrl.noaa.gov/csd/assessments/ozone/2014/twentyquestions/intro.html

UNEP (2016). *Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer* includes a wealth of detail and expertly organized explanations of the evolution and operations.

Scholars and interested readers will discover that the remarkable publications telling the story of science, environment, diplomacy and technology of the Montreal Protocol does not stop here. Google and enjoy wherever it takes you.

Appendix B. Translation of acronyms and abbreviations

A5 Parties	Parties covered under Article V (Article 5) of the Montreal Protocol (typically developing countries)
ACS	American Chemical Society
CFC	Chlorofluorocarbon
CIAP	Climatic Impact Assessment Program
CMA	Chemical Manufacturers Association – now renamed as the American Chemical Council
DoD	Department of Defense (U.S.)
EPA	Environmental Protection Agency (U.S.)
GHG	greenhouse gas
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
ICEL	International Cooperative for Environmental Leadership (was ICOLP)
ICOLP	International Cooperative for Ozone Layer Protection (now ICEL)
IGSD	Institute for Governance & Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
MLF	Multilateral Fund for the Implementation of the Montreal Protocol
MOP	Meeting of the Parties
NASA	National Aeronautics and Space Administration (U.S.)
NOAA	National Oceanographic and Space Administration

NO	nitric oxide
N_2O	nitrous oxide
NGO	non-governmental organization
ODP	ozone depletion potential
ODS	ozone depleting substance
SAP	Scientific Assessment Panel (of the UNEP Montreal Protocol)
SST	supersonic transport
TEAP	Technology and Economic Assessment Panel (of the UNEP Montreal Protocol)
UNEP	United Nations Environment Program
UV	ultraviolet

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