Substantia
An International Journal of the History of Chemistry

Firenze University Press
www.fupress.com/substantia

OPEN ACCESS

Citation: M.A. Murphy (2020) Early Industrial Roots of Green Chemistry - II. International "Pollution Prevention" Efforts During the 1970's and 1980's. *Substantia* 4(2): 15-57. doi: 10.13128/Substantia-894

Received: Apr 03, 2020

Revised: May 15, 2020

Just Accepted Online: May 30, 2020

Published: Sep 12, 2020

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

Feature Article

Early Industrial Roots of Green Chemistry - II. International "Pollution Prevention" Efforts During the 1970's and 1980's

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Abstract. Many literature articles and/or conventional histories of "Green Chemistry" describe its start as being a result of actions at the US Environmental Protection Agency ("EPA") and/or in Academia during the 1990's. But many examples of environmentally friendly Real-World chemical processes were invented, developed and commercialized in the oil refining, commodity chemical, and consumer product industries starting about the time of World War II. Those efforts dramatically accelerated and evolved into explicitly environmentally oriented "Pollution Prevention" efforts during the 1970's and 1980's. A UN conference in November 1976 brought together over 150 attendees from industry, academia, and governmental and non-governmental organizations from 30 countries to address environmental issues related to preventing pollution caused by the chemically-related industries. Seventy-nine papers published in 1978 from the conference proceedings (titled "Non-Waste Technology and Production") addressed a wide variety of technical, economic, environmental, and policy issues and approaches, and documented many examples of already commercialized environmentally friendly chemically based processes. On a parallel track, in 1975 the 3M Corporation initiated a major corporate-wide program called "Pollution Prevention Pays ("3P") that commercialized thousands of environmentally oriented Real-World processes and/or inventions, in many countries, and simultaneously saved 3M large sums of money. Similar "Pollution Prevention" approaches were emulated and elaborated by many chemically based corporations in many countries during the 1980s. The "Green Chemistry" terminology adopted by the EPA and Academia in the 1990's evolved from the "Pollution Prevention" approaches, programs, and commercialized inventions that had occurred long before the 1990s.

Keywords: Green Chemistry, Green Engineering, history, non-waste technology, pollution prevention, Economic Commission for Europe (ECE), 3M Corporation, 3M3P, Environmental Protection Agency, American Chemical Society.

> *If I have seen further it is by standing on the shoulders of Giants.*
> Isaac Newton in 1675[1]

1. THE ORIGINS OF GREEN CHEMISTRY?

According to the U.S. EPA's website in 2012,[2] "Green chemistry consists of chemicals and chemical processes designed to reduce or eliminate negative environmental impacts. The **use and production** of these chemicals may involve reduced waste products, non-toxic components, and improved efficiency. Green chemistry is a highly effective approach to **pollution prevention** because it **applies innovative scientific solutions to real-world environmental situations**" (bolding added).

There is much justifiable emphasis in this EPA definition on "use and production," "pollution prevention," and on the application of "innovative scientific solutions to real world environmental situations." It seems obvious from this definition, and from common sense, that Green Chemistry (and Green Chemists and Green Engineers) should address themselves (though perhaps not exclusively) to "Real-World" situations and considerations.

Over the last twenty years, conventional histories of "Green Chemistry" (see for example Linthorst (2010, ref 54)) and/or many Academic and/or educationally oriented papers[3] have often repeated a "narrative"[4] about the origins of Green Chemistry, describing it as arising in the early 1990s from concepts and actions by the US Government and Environmental Protection Agency (EPA), and/or from research and publications from the Academic world. Green Chemistry (and Engineering) has subsequently blossomed into an avalanche of research, with multitudes of specialized academic journals and scientific conferences devoted to the new field, all over the world (see for example Anastas and Beach, (2009, ref 12), Figure 1).

Nevertheless, Professor Martyn Poliakoff (one of the earliest Academic champions of Green Chemistry) recently noted that "Although most people agree that the EPA gave birth to green chemistry, there is much less certainty about its conception", (Poliakoff 2013, ref 63). As will be seen below, the words "Pollution Prevention" described a set of Real-World concepts and commercialized inventions that long preceded and was the evolutionary precursor of the "Green Chemistry" terminology that was coined at the U.S. EPA and then became recognized as an "Academic field" in the 1990s and afterwards.

There can be no doubt that the "Green Chemistry" terminology, narratives, and "movement," that became popular in Academia in the 1990s, and at least some of the inventions afterwards, were aided and/or accelerated by the activities of the US Government, the EPA, the ACS, and Academia. But this author (who conceived in 1984 one of the earliest and well-known industrial examples of Green Chemistry the BHC Ibuprofen Process) recently argued that the complex evolutionary origins of "Green Chemistry" began long before the 1990s and provided several examples from the commodity chemicals industry that traced their origins to shortly after World War II, see Murphy (2018, ref 59).

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[1] Newton's statement in his letter to Robert Hooke in 1675 apparently echoes earlier similar sentiments going back (at least) to Bernard of Chartres in the 12th Century. See https://en.wikipedia.org/wiki/Standing_on_the_shoulders_of_giants. The Visual Abstract shows a portrait of Newton painted in 1689 by Godfrey Kneller (and copied from a Wikilpedia article about Newton), and a photograph of the 2011 Presidential Green Chemistry Challenge Award trophies, taken from an August 4, 2011 Chemical & Enginering News article by Stephen K. Ritter, and used herein with permission of the American Chemical Society.

[2] The quotation was first accessed by the author on the EPA website, http://www.epa.gov/greenchemistry/pubs/about gc.html in 2012, but is no longer available there. A very similar and earlier passage was recited by the EPA's 2002 Green Chemistry Program Fact Sheet stored at the National Service Center for Environmental Publications at https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1004H5E.TXT

[3] To see a few of many literature examples of this "narrative" about the origins of "Green Chemistry", consider Anastas (1994, ref 2); Anastas and Williamson (1996, ref 6); Anastas and Williamson (1998, ref 7); Anastas and Warner (1998, ref 8); Cann and Connely (2000, ref 19); Anastas, Bartlett, Kirchhoff, and Williamson (2000, ref 9); Hjeresen, Anastas, Ware and Kirchhoff (2001, ref 38); the "Green Chemistry Program Fact Sheet, Chemistry Designed for the Environment" (2002, ref 34); Poliakoff, Fitzpatrick, Farren, and Anastas (2002, ref 63); Warner (2004, ref 85); Woodhouse and Breyman (2005, ref 87); Anastas and Beach (2007, ref 11); Anastas and Beach (2009, ref 12); Gurney and Stafford (2009, ref 36); Laber-Warren, E.L., *Scientific American* (2010, ref 51); Anastas and Eghbali (2010, ref 13); Anastas, P.T. (2011, ref 4); Sanderson (2011, ref 73); Anastas, P.T. (2012, ref 5);Wolfe, J., *Forbes* (2012, ref 88); Lynch (2015, ref 56); Lynch, W.T., (2015, ref 57); "History of Green Chemistry, Origins of Green Chemistry" (2017, ref 42); Howard Grenville *et al.*, (2017, ref 41); Török and Dransfield (2018, ref 81); and the Thomas History of Green Chemistry and Processes (2019, ref 80).

[4] See below a discussion of Nassim Nicholas Taleb's criticism of "The Narrative Fallacy" and its relevance to "Green Chemistry," in Section 10.

This article will describe and provide many more examples of individual, corporate, governmental, and/or collaborative international actions that grew into many examples of the Real-World industrial commercial practice of "Non-Waste Technology" and "Pollution Prevention" decades earlier than the 1990s, beginning after World War II and especially during the 1970's and 1980s. Those early but currently largely unrecognized examples of "Non-Waste Technology" and "Pollution Prevention" will be the focus of this article.

2. CONVENTIONAL HISTORIES OF GREEN CHEMISTRY

A widely cited history of "Green Chemistry" (Linthorst 2010, ref 54) divides the history of Green Chemistry into three periods based on a graph (see Linhorst's Figure 1) of the number of academic publications over time using several specific alternative terminologies; i.e. "clean chemistry", "green chemistry", "benign chemistry," "sustainable chemistry," and "environmental chemistry." Linthorst's first period, wherein the mention of any one those terms was infrequent in the Academic literature, was described as having "no formal starting point" and ending in 1993. A purported "second period" from 1993-1998, "when there is a marginal increase in the use of the specific term Green Chemistry" in the academic literature, was then asserted to have been followed by a third period of expansion from 1998 till 2008, "because a huge linear growth has taken place," especially in the use of the specific term "Green Chemistry".

Examining Linthorst's discussion more closely, Linthorst's very short discussion of his "first period" briefly mentions Rachal Carson's 1962 book "Silent Spring", then mentions the creation of the US Environmental Protection Agency in 1970 (during the Nixon Administration), when the "US EPA adopted a **command and control policy** in the execution of environmental regulations" (bolding added).

Linthorst's account then skips forward to the mid 1980's, asserting that "a shift in paradigm occurred in the OECD (Organization for Economic Co-operation and Development) countries. During the 1985 meeting of the Environment Ministers of the OECD countries, the focus was on three themes: Economic Development and the Environment, **Pollution Prevention** and Control and Environmental Information and National Reviews." Shortly thereafter Linthorst mentions that "Internationally, the idea of command and control policy (often referred to as end-of-pipeline control) shifted towards an approach of **pollution prevention**."

Linthorst's account then shifts back toward the U.S. government, stating:

> "A shift in paradigm of the US EPA policy also started in the 1980s. **Pollution prevention** instead of end-of-pipeline control had to become the option of first choice, as was confirmed by the US EPA officers David Stephan and John Atcheson in their "The EPA's approach to **pollution prevention"** (Stephan and Atcheson 1989)… US EPA and the chemical industry, cooperating in developing new processes more and more, mainly based this paradigm shift on a shared financial interest and modification of old processes, based on the **pollution prevention** principle (Stephan and Atcheson 1989). As a consequence, in 1988 the Office of **Pollution Prevention** and Toxics was established within the US EPA, even before the concept was politically formalized in 1990…. In 1990, US Congress passed the "**Pollution Prevention** Act of 1990" under the Administration of President George H.W. Bush (**Pollution Prevention** Act 1990). This occurred in a bad economic period that also featured serious environmental problems…. This emphasized the environmental and economic urge to adopt the policy of **pollution prevention**." (bolding added)

The Linthorst account then describes the US 1990 Act, outlining "that there was a shared interest of government (e.g. US EPA) and chemical industry to cooperate and meet environmental and economic goals"… and "included the establishment of an annual award program to recognize a company or companies which operate outstanding or innovative source reduction programs." "One of these was "Alternative Synthetic Design for **Pollution Prevention**" developed within the Office of Pollution Prevention and Toxics" (Anastas 1994, ref 2).

In the remainder of Linthorst's account, the adoption and use of the particular term "Green Chemistry" appeared to be the major factor in the explosive growth and popularity of an Academic/governmental Green Chemistry "network," and a resulting avalanche of "Green Chemistry" Academic publications.

A 2011 Chemical & Engineering News article titled "Twenty Years of Green Chemistry," (see Anastas 2011, ref 4) displayed a graph similar to the Linthorst graph, of the frequency of "Scientific Papers" using the term "Green Chemistry" in their titles, over time, and asserted that the beginnings of "Twenty Years of Green Chemistry" occurred about 1991. Many, many academic publications have subsequently repeated that narrative (see for example the references in footnote 3), which will be called the "1990s Green Chemistry Narrative" in this paper.

Conspicuously absent (in this author's opinion) from Lindhorst and/or Anastas accounts (and from many subsequent Academic "Green Chemistry" publications, some of which are cited herein) was any recognition of or significant discussion of the many, many much earlier environmentally friendly commercialized inventions and other Real-World efforts at "Pollution Prevention" in the oil refining, commodity chemical, and consumer products industries, decades earlier. As we shall see below, the "1990s EPA Narrative" about the origins of Green Chemistry, was and is highly incomplete and oversimplified, and even deceptive.

Similarly, the American Chemical Society's brief current website account of the history of Green Chemistry[5] briefly mentions, with respect to the 1960s, the Environmental Movement, Rachael Carson, and the 1969 US National Environmental Policy Act (NEPA). With respect to the 1970s, the ACS account briefly mentions the establishment of the US Environmental Protection Agency (EPA) in 1970, and "a series of regulatory laws…such as the Safe Drinking Water Act". It also briefly noted "the discovery and publicity surrounding the Love Canal… scandalized the chemical industry."

Regarding the 1980s, ACS's History stated (at least since 2012 and until very recently),

> "Until the 1980s, the chemical industry and the EPA were focused mainly on pollution clean-up and obvious toxins, **but a major paradigm shift began to occur among chemists**. **Scientists, who came of age during the decades of growing environmental awareness, began to research avenues of preventing pollution in the first place. Leaders in the industry and in government began international conversations addressing the problems and looking for preventative solutions**." (bolding added)

Recently, the ACS website slightly revised its History by adding the following two paragraphs.

> "The Organization for Economic Co-operation and Development (OECD), an international body of over 30 industrialized countries, held meetings through the 1980s addressing environmental concerns. They made a series of international recommendations which focused on a co-operative change in existing chemical processes and **pollution prevention**.
> The Office of **Pollution Prevention** and Toxics was established within the EPA in 1988 to facilitate these environmental goals."

As we shall see below, even these recent corrections to the "1990s EPA Narrative" remain highly incomplete, and even deceptive.

This author originally conceived, in 1984, one of the most widely recognized early industrial examples of "Green Chemistry", the BHC Ibuprofen process. The technical details of the BHC ibuprofen process were first published in a European patent publication in 1988 and issued as a US Patent in 1991 (Elango, Murphy, Smith, Davenport, Mott, Zey and Moss 1991, ref 28). The BHC Ibuprofen process was commercialized at Bishop Texas in 1992. The BHC Ibuprofen Process invention won Chemical Engineering Magazine's 1993 "Kirkpatrick Award" and one of the very first Presidential Green Chemistry Awards in 1997.

But multiple 3d party Academic and/or popular publications told and/or repeated inaccurate narratives about that BHC Ibuprofen Process invention. In 2018 this author published an Open Access article (see Murphy 2018, ref 59) that described the Real-World history of that BHC Ibuprofen Process invention, from an inventor's perspective. That paper documented some of the decades-long evolution of industrial methods for making acetic acid and its derivatives (and other related commercial syngas-based chemistries such as olefin hydroformylation) that were the main technical inspirations for and/or precursors of the BHC ibuprofen invention. That paper also described many economic / human / cultural factors and/or motivations (including the "Quality Movement" of the 1980s and its focus on waste avoidance) that drove those early industrial "Green" inventions. Those acetic acid and/or BHC Ibuprofen Process invention stories will not be retold in this article.

But a similar complex combination of technical, economic, human / cultural roots, factors, and motivations also contributed to the many other early examples of industrial "Pollution Prevention" that were in actual commercial practice long before the 1990s. The remainder of this article will document and focus on the individual motivations, actions, and/or voluntary collaborative activities of a large international collection of industrial and academic chemists, engineers, economists, managers, corporations, and international governments, starting after World War II, and accelerating during the 1950's, 1960s, 1970s and 1980s. Those actions and collaborations resulted in the invention, development, and commercialization of many examples of the "Non-Waste Technologies" and "Pollution Prevention" long before the adoption of the "Green Chemistry" terminology that became popular during and after the 1990s.

3. ENVIRONMENTALLY FAVORABLE EVOLUTIONARY PROCESSES IN THE EARLY OIL REFINING INDUSTRY

The evolutionary pathway that led toward "Green Chemistry" appears to have had its origins in the oil

[5] See https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/history-of-green-chemistry.html .

refining industry boom that began at about the time of World War II. This author is not genuinely expert, either technically or historically, regarding the details of the technical developments in and/or the evolution of the oil and/or oil refining industry. But a simple inspection of readily available literature sources[6] revealed that multiple environmentally positive major process modifications and/or improvements which produced positive Real-World environmental benefits began to evolve in the oil refining industry from about the time of World War II. Some examples from that history that illustrate the evolution of increasingly environmentally friendly oil refining processes will be briefly reproduced/ outlined in this section.

The first oil well was drilled by Colonel Edwin Drake in Titusville Pennsylvania in 1859. Prior to World War I, oil refining was typically carried out by very simple atmospheric pressure distillations of crude oil, with the primary goal of producing kerosene for heating and lighting. A large proportion of the light and heavy residues from those simple distillations were often dumped, burned, and/or or evaporated into the atmosphere.

In 1912 Amoco introduced a thermal cracking process at a refinery near Chicago that converted some of the heavy residues to lighter gasoline-like fractions. Then more modern fractional distillations came into practice in the 1920s (after World War I), and "increased the efficiency of separating crude oil into its constituents by 25%." After World War I, the use of automobiles and airplanes increased very rapidly, creating a growing demand for gasolines. The gasolines produced by distillation had low octane numbers however, limiting the compression ratios of the engines and therefore their power and fuel efficiency. In 1921, chemists at General Motors discovered that adding small amounts of alkyl lead compounds to gasoline significantly increased the octane numbers, but the resulting environmental problems were ignored and weren't actually addressed until the 1970's (lead also fouled the expensive noble metal catalysts in the new catalytic converters for automobile exhaust gases).

In 1936 Eugene Hoody introduced a fixed bed catalytic cracking unit that doubled the volume of gasoline produced from the lower value heavy residues[7]. The heavy residues were mixed at very high temperatures with solid alumina-containing clays that caused the heavy molecules to crack into lighter and more valuable organic molecules. Esso introduced a much-improved fluidized bed catalytic cracker into its Baton Rouge refinery in 1942. Later (in the 1970s and later) the natural clay catalysts originally used were replaced with synthetic zeolite catalysts that were more selective for producing products in the desired gasoline ranges.

Use of such catalytic cracking processes in oil refineries greatly increased the availability and decreased the price of ethylene and propylene. Jira remarked (Jira 2009, ref 45) that the increasing availability and lower price of ethylene was a major motivation for his 1956 co-invention of the Wacker process for the aqueous air oxidation of ethylene to acetaldehyde, which may have been the first major industrial process that was both highly atom economical and genuinely environmentally friendly (see Jira 2009, German Patentcraft 1 049 845 filed January 04, 1957 and published February 05, 1959. Also see Murphy (2018, ref 59) for a short discussion of the chemistry and environmental friendliness of the Wacker Process).

New catalytic "alkylation" processes entered service in U.S. refineries about 1940. Alkylation is a class of reactions in which volatile alkenes (such as propylene or butenes) are condensed with branched alkanes (often isobutane) in the presence of strong acids (initially and typically HF or sulfuric acid) to produce higher branched alkanes (typically iso-heptane and iso-octane) with high octane numbers.[8] The products of alkylation units and processes are also typically low in alkenes and/or aromatics that don't burn as cleanly as the desired branched alkanes. The HF catalyst was more easily and efficiently recycled than the sulfuric acid catalyst, but because of HF's volatility, corrosive properties, and toxicity it represents a significant safety risk at the plant site.[9] As the decades passed, many refineries began to replace HF with H_2SO_4 for safety reasons, as exemplified by US Patent No. 5,284,990 to Peterson and Scott.

In 1949, the first catalytic reforming process was started up at the Old Dutch Refining Company of Muskegon Michigan. Catalytic reformers convert napthas (from the initial distillations and which contain large amounts of normal alkanes and napthenes) into iso-alkanes, and aromatics, which dramatically increased octane numbers.[10] The by-product hydrogen liberated from the reforming processes is used elsewhere in the

[6] The early (pre-1970) history of oil refining recounted herein is based on Leffler's 2008 book (ref 48) titled "Oil Refining" and/or from Wikipedia articles on "Oil Refinery" (see https://en.wikipedia.org/wiki/Oil_refinery) and "Gasoline" (see https://en.wikipedia.org/wiki/Gasoline).

[7] See Leffler (2008), chapter 8.

[8] See Leffler (2008), chapter 9, and https://en.wikipedia.org/wiki/Alkylation_unit.

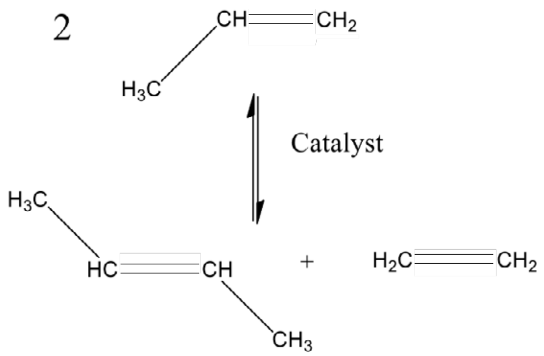
[9] A 380 page Hydrogen Flouride Safety Study, and Final Report to Congress under Section 1112(n)(6) of the Clean Air Act was generated in 1993, after a refinery accident occurred in 1987. A copy of that report is available at http://www.documentcloud.org/documents/70516-epa-hydrogen-fluoride-study.html .

[10] See Leffler (2008) Chapter 10.

refineries, especially in hydrocrackers. The reforming catalysts typically contain platinum on heterogeneous supports (and sometimes other metals and promotors such as chlorine). The reforming catalysts were originally used in fixed-bed designs, but later fluidized bed catalyst designs improved performance and decreased the downtime needed to regenerate fouled catalysts.

Catalytic hydrocracking[11] was introduced during the 1950s and continued to further develop later. Hydrogen and heavy distillation fractions such as diesels, kerosene's, heavy gas oils, etc. are heated to high temperatures and pressures in the presence of catalysts (typically comprising cobalt, molybdenum, nickel, sulfur, and supports such as aluminas) to produce lighter napthenes, paraffins, and other gasoline-range components. Hydrocracking also breaks up the rings of heavy aromatics to produce branched alkanes (such as isobutane) of higher value. Hydrocracking also removes sulfur and nitrogen hetero atoms from the heteroaromatics in the feeds.

Olefin metathesis is sometimes used in commercial refineries for upgrading low molecular weight olefins produced by cracking processes to higher molecular weight and octane number components for gasoline blending.[12] The olefin metathesis reaction was serendipitously discovered in 1956 by H.S. Eleuterio of the Du Pont petrochemicals department (see Eleuterio 1991, ref 29). Eleuterio was investigating the then novel Ziegler-Nata polymerization of olefins such as ethylene and propylene (see Ziegler 1955 ref 89). Eleuterio detected the unexpected formation of ethylene and 1- and 2-butenes from propylene over molybdena containing catalysts (as illustrated below) and investigated the unexpected reaction further.



Metathesis of Propylene

Eleuterio recognized some of the potential scope and value of the olefin metathesis reaction at the time, and suspected the likely involvement of "carbene-type intermediates", but "Although the chemistry was recognized as novel, with much up-side theoretical and synthetic potential, a decision was made to terminate the work by writing a summary research report along with appropriate patent notes." One of Eleuterio's proposals for a patent, to claim a process for upgrading propylene to butene, "was rejected by the section manager with the comment that "Du Pont was not in the oil business". Another Eleuterio patent proposal directed to polymeric compositions prepared by metathesis of cyclic olefins was filed in 1957, and granted as a German patent 1 072 811 in 1960, and U.S. patent No. 3,074,918 in 1963.

Patenting or publication of Eleuterio's discoveries relevant to the polypropylene metathesis reaction "was set aside because some of the results were considered relevant to pending polymer and copolymer patent applications." A major round of patent litigations relating to the polyolefin compositions and methods resulted between Du Pont, Standard Oil of Indiana, Phillips Petroleum, Hercules, and Montecatini. The patent litigations did not get settled for decades, and "further complicated an already complex information generation and transfer process, inhibiting the ripening of time for many ideas…"

Yves Chauvin started his career in the French petrochemical industry in the mid-1950s and apparently encountered olefin metathesis reactions there. In 1960 Chauvin moved to the public Institut Français du Pétrole, and in 1971 Chauvin publicly proposed a mechanism for olefin metathesis involving metal carbene complexes[13] that is now widely accepted. Subsequent developments led to many new olefin metathesis applications in both industry and synthetic organic chemistry (see for example Delaude (2005, ref 24)), and eventually led to a "Green" Nobel Prize (along with Robert H. Grubbs and Richard R. Schrock for later developments) in 2005.[14,15]

When lead additives were banned from gasolines during the 1970s, a need for new secondary refining processes that could efficiently produce increased volumes of high-octane non-leaded gasolines became acute. A tremendous amount of R&D effort. over dec-

[11] See Leffler (2008) Chapter 11.

[12] See for example https://en.wikipedia.org/wiki/Olefin_metathesis.

[13] Jean-Louis Hérisson, P.; Chauvin, Y. (1971). "Catalyse de transformation des oléfines par les complexes du tungstène. II. Télomérisation des oléfines cycliques en présence d'oléfines acycliques". *Die Makromolekulare Chemie* (in French). **141** (1): 161–176. doi:10.1002/macp.1971.021410112.

[14] Grandin, K.; ed. (2005). "Yves Chauvin Biography". *Les Prix Nobel*. The Nobel Foundation. Available at https://www.nobelprize.org/prizes/chemistry/2005/chauvin/facts/

[15] See https://www.treehugger.com/sustainable-product-design/nobel-prize-in-green-chemistry.html .

ades, was poured into developing new synthetic zeolite catalysts for a wide variety of refinery applications.[16] The improvements in the catalysts typically increased the efficiency of conversion of the raw materials into salable products, and decreased the amount of waste to be disposed of, both of which improved the economic results. Decreased waste production and waste disposal costs became increasingly important in view of the anti-pollution statutes that were passed in many countries in the 1960s and 1970s. Appreciation for the altruistic environmental benefits of lower waste production, as well as addressing the concerns of the governments and the customers also grew over time. As Leffler noted in 2008, "Most of the technological change in the last 20 years has been driven by environmental concerns, causing refiners to tweak existing processes, especially with the introduction of new and improved catalysts."

An unexpected invention that arose from the zeolite catalyst work in the 1960s and 1970s and the oil shortages of the 1970s was the now well-known Mobil Methanol to Gasoline processes. Several patents issued for various embodiments of such processes.[17] As already summarized in many places (including Murphy 2018) methanol can be prepared very efficiently and atom economically on industrial scale from methane, or less efficiently from coal. In the Mobil process, in a first catalytic stage methanol is dehydrated to form a mixture of water, methanol, and dimethyl ether, then the stream is passed over a zeolite catalyst to form olefins, which further condense to form paraffins, napthenes, and methylated aromatics. The size selective zeolite catalyst limits the product range to about C_{11}. The process was piloted in 1979 and commercialized in New Zealand in 1985 at a scale of 14,500 barrels per day. A second-generation process was piloted in China in 2009 at a scale of 2,500 barrels per day, and agreements for additional larger scale units are in place.[18]

By the time Robert Sheldon (a European chemical industry veteran who moved to academics in 1991) published his seminal 1992 *Chemistry & Industry* paper (Sheldon, 1992, ref 74) that first publicly defined the "E-Factor", Sheldon estimated that the oil refining industry (where the use of catalysis was common) was producing only about 0.1 kg of waste per kilogram of useful products, as compared to estimates of 5-50 kg/kg in the fine chemical industry segment, and 25->100 kg/kg in the pharmaceutical industry segments (where use of traditional synthetic organic chemistry techniques were dominant). Clearly the evolutionary progress in the oil refining industry, over decades, had come a very long way toward environmentally friendly processes by 1992. Much of that progress was achieved by improving catalysts, and Sheldon argued that catalysis had initially developed as an industrial discipline largely separate from traditional synthetic organic chemistry, only to have the separate fields start to merge as the field of organometallic chemistry developed in the 1960s and 1970s.

The oil and gas industry was also actively addressing process safety issues long before "Green Chemistry" became fashionable in Academia in the 1990s. On October 16-18, 1991, the National Petroleum Refiners Association held a meeting Denver that included a question and answer session with a panel of experts. The session was reported in the Oil & Gas Journal (1992, ref 62) in an article entitled "Refiners Discuss HF Alkylation Process and Issues". One audience question was "What progress is being made on developing a solid catalyst for the alkylation of light olefins and isobutane?" A panel expert named McClung answered "I cannot be terribly encouraging on this subject. What progress is being made is published in patents, which I review just about monthly….I know that it is the "Holy Grail" of the petroleum industry to find this kind of process, and there is a lot of work being done. I think Mobil is your most reliable source for progress". Another expert, Michael Humbach from UOP stated "We concur with what has been said. We have a fairly intense R&D effort going on right now in this area. What we are finding is that indeed it is going to take a breakthrough, not only in catalyst technology, but also in process technology."

The oil refining industry's "Grail Quest" has required 20-25 additional years, but the needed breakthroughs have finally come. In September 2016, Honeywell UOP announced[19] that after 5 years of small-scale testing, it initiated conversion of the alkylation unit of its Salt Lake City refinery to use of an ISOALKYL™ technology which uses an ionic liquid as an alkylation catalyst. Honeywell UOP licensed that ionic liquid technology from Chevron, and the technology appears to be related to U.S. Patent No. 7,495,144 by inventor Salch Elomari. A parallel breakthrough in refinery alkylation chemistry appears to have come from Albemarle

[16] See for example Rabo, J.A. (ed.), "Zeolite Chemistry and Catalysis", 1976, ACS Monograph 171, American Chemical Society (ref 67), which contains thirteen papers predominantly from industrial authors, seven of which address synthesis, characterization, and properties of then new zeolites, and six papers relating to the catalytic properties of new zeolites.

[17] See for example U.S. Patent No. 3,931,349 issued January 6, 1976 to Kuo and assigned to Mobil Oil Corporation, and several other related U.S. Patents recited therein and assigned to Mobil.

[18] See https://www.exxonmobilchemical.com/en/catalysts-and-technology-licensing/synthetic-fuels

[19] See https://www.hydrocarbonprocessing.com/news/2016/09/honeywell-uop-introduces-ionic-liquids-alkylation-technology

of the Netherlands. In June 2007, Albemarle Corporation announced the development of a breakthrough zeolite-based solid acid catalyst for refinery alkylation processes.[20] That process appears to be related to related to U.S. patent application initially filed in January 2007 and eventually issued in 2012 as U.S. Patent No. 8,163,969, to four Netherlands inventors; Van Brockhoven, Harte, Klaver, and Nieman. The invention won one of the 2016 Presidential Green Chemistry Awards[21] In November 2017 Albemarle and its corporate partner CB&I were awarded *Chemical Engineering* magazine's biannual "Kirkpatrick Chemical Engineering Achievement Award" for the zeolite-based alkylation process.[22]

Overall, the oil refining industry clearly has, since World War II and continuing to present time, consistently made and is continuing to make significant strides, both economically and environmentally.

Since World War II, some of the commodity chemicals companies also made comparable strides to invent, develop, and commercialize many examples of clean and highly atom efficient processes for making non-toxic commodity chemical products for Real World customers, often via the use of catalytic processes. Examples include the air oxidation of ethylene to ethylene oxide, Wacker and methanol carbonylation processes for producing acetic acid (and then onward to polyvinyl acetate and polyvinyl alcohol, major commodity polymers that are biodegradable). Rhodium catalyzed olefin hydroformylation has also developed into highly efficient and atom economical processes for making commodity aldehydes, alcohols, carboxylic acids and esters. Some of those developments preceded and partially inspired the BHC Ibuprofen Process invention that won Chemical Engineering Magazine's Kirkpatrick Award in 1993, and one of the very first Presidential Green Chemistry Awards in 1997. Some of the history of those early "Green" developments in the commodity chemical industry was recounted in this author's prior paper, see Murphy (2018, ref 59).

4. NON-WASTE TECHNOLOGY AND PRODUCTION

This section will describe and summarize excerpts from a 1978, 681page book,[23] that documents some of the earliest international efforts to improve the environmental performance of the chemically related industries. The book, titled "Non-Waste Technology and Production" (1978, ref 61), was published by the United Nations and/or its Economic Commission for Europe. The book contains papers based on a November 1976 UN/ECE Seminar. The book has an "Introduction," a list of "Conclusions and Recommendations," then a compilation of seventy-six individual papers and two inaugural addresses. A listing of the individual titles, authors, nationalities, and affiliations of the individual papers and inaugural addresses presented at the 1976 conference is listed in Appendix I of this paper.

According to the 1978 book, the UN's Economic Commission for Europe, after "many years of activity by the ECE in various environmental fields" had established a body of Senior Advisers in 1971. In 1973 the Senior Advisers "decided to include, among other subjects, the principles and creation of non-waste production systems in their work programme."

In Geneva in 1974 the Senior Advisers defined Non-Waste Technology as "the practical application of knowledge, methods and means so as, within the needs of man, to provide the most rational use of natural resources and energy and to protect the environment. Non-Waste Technology, it was stressed, should be seen as a long-term strategy, as a philosophy of the evaluation of the environmental complex."

The Senior Advisors decided to hold a Seminar, which "was held in Paris from 29 November to 4 December 1976. More than 150 representatives of thirty countries and nine international inter-governmental and non-governmental organizations took part."

The "Conclusions and Recommendations" section of the resulting "Non-Waste Technology and Production" book stated the following:

> "The question today is whether technology can solve the environmental problems which technology has helped to cause. There is widespread belief that this question can be answered positively…
> Awareness of negative side effects of modern technology has, in recent years brought about new economic and legislative measures which are fostering new industrial attitudes and approaches. Attention has been mainly focused on problems connected with treatment of wastes at the end of the production line, once the product (and its consequent wastes) has been produced. But more and more frequently it is being asked whether it would not be economically and socially less costly to minimize all along

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[20] See for example https://www.biospace.com/article/releases/albemarle-corporation-and-partners-develop-breakthrough-catalyst-for-refinery-olefin-alkylation-process-/

[21] See https://www.epa.gov/greenchemistry/presidential-green-chemistry-challenge-2016-greener-synthetic-pathways-award

[22] See https://www.chemengonline.com/cbi-and-albemarle-win-the-44th-kirkpatrick-chemical-engineering-achievement-award/

[23] The selected quotations in this section of this article are reprinted from "Non-Waste Technology and Production" Copyright (1978, ref 61), with permission from Elsevier, current owner of the copyrights originally held by the original publisher Permagon Press on behalf of the United Nations.

the line the creation of wastes that need to be treated – from the extraction of raw materials to the end of life final consumer goods. The essence of non-waste technology is in the answer to this question…
An examination of the papers submitted on this topic has made it clear that there are many different points of view as to how to promote non-waste technology and to what degree it should be promoted. Even though the range of ideas was very wide, the need for a technology that reduces or avoids waste was universally recognized. Thus, even though the various countries demonstrated their unique problems, they all supported the promotion of non-waste technology and agreed on the possibility of discussion of the common themes."

In a section relating to "Concepts and Principals of Non-waste Technology," M.G. Royston, an economist at the Centre d'Etudes Industrielles of Geneva Switzerland (whom we shall see later became a leader in the economic analysis / legal aspects of Non-Waste Technologies), contributed a paper entitled "Eco-Productivity: A Positive Approach to Non-Waste Technology". Some comments from Mr. Royston's paper (ref 71) are reproduced below:

"Pollution is waste. Waste today leads to shortages tomorrow, "Waste not want not" is a motto as true now as it was for all those generations before the brief flowering and decaying of the affluent/effluent society. The very sustainability of dignified life on this planet Earth must depend on re-establishment of a non-waste society, a non-waste economy, a non-waste technology, and above all a non-waste value system."
"In a finite world, the one resource which is unlimited is the human spirit and the love, sense of purpose, and quest for knowledge that flows from it. Indeed, the one resource in this world which grows is this resultant knowledge and from which human understanding, human wisdom and, hopefully, human institutions and technology spring. Thus, one key to the new 'product-not-waste society' is the liberation of the human spirit, the encouragement of new scientific research and the application of the new insights to develop the new systems which meet human needs without creating waste."

Royston commented multiple times in his paper about the many prior European efforts by both governments and corporations to deal with waste and environmental issues, writing:

"In the public sphere, in Europe again, it has been common practice for many years to burn garbage in specially designed plants in order to generate electricity, Such plants exist in Geneva, Zurich, Munich, Stuttgart, Paris and many other cities and can provide around 15 per cent of a city's need in power.
Also in this area, a number of power plants in Europe have for many years used their waste heat to supply hot water and space heating for houses and apartment blocks. The lack of development of these processes in the U.S. is almost entirely due to much lower energy costs in the U.S. compared with Europe. Since the oil crisis however,[24] American engineers and city authorities have made up for this lack of interest."

Royston then commented on possible waste-savings and anti-waste approaches that could be undertaken in the Energy, Organic Chemicals, Inorganic Chemicals, Non-metallic Minerals, and Metallic Minerals industries, and efforts that could be taken to economically and even profitably undertaken to reduce pollution of the Air, Land, and Water.

In the book's section about relating to Topic IIb, "The Industrial Experience," the following comments were made:

"Numerous discussion papers received for this topic provide information on many industrial applications of this technology. It was noted that different methods could be used to eliminate or significantly reduce wastes:
(a) by improving existing technologies: recycling, increasing yields, development of recovery processes, and waste transformation;
(b) by creating new techniques or by radically modifying existing techniques, in order to obtain production processes which produce less wastes and noxious pollutants.
It is clear that the research work necessary to promote non-waste technology has not attained a desirable level. Countries must develop multi-disciplined research in order to improve non-waste technology for all branches of industry. The economic aspects of the rational utilization of raw materials and energy must be tackled simultaneously."

In a subsequent comment, it was observed that:

"The introduction of non-waste technology in industry cannot be accomplished without the active participation of everyone concerned. It is therefore necessary that educational institutions (particularly for technical staff) take practical measures to ensure that their courses take into account the impact on the environment of the technologies which are being taught and that the ideas relative to non-waste technology are propagated. Moreover, it is necessary that, in the course of their education, young people are familiarized with environmental problems, such

[24] This footnote is not part of Royston's original paper. Some younger readers may not recall that after the Arab-Israeli War of 1973, OPEC embargoed oil shipments to the US and some European countries, causing years of severe oil and gas shortages, skyrocketing oil prices, and economic damage and inflation in those embargoed countries.

> as the use of natural resources, protection of the countryside, etc."

In the book section about Topic IIc, "Case Studies" the following comments were made regarding the iron and steel industry:

> "It was recognized that the iron and steel industry is one of the most polluting sectors with respect to water and air pollution. In addition, it is an important source of solid waste. Nevertheless, efforts already undertaken in all countries have permitted large reductions in the emission of these pollutants."

The following comments were made regarding the pulp and paper industry:

> "The traditional technologies to transform wood and vegetable fibres into pulp and paper generate various kinds of waste: … For ten years, great progress has been made to reduce this waste by:
> - trying to utilize the whole tree;
> - using closed circuits in pulp and paper production;
> - utilization of oxygen instead of chlorine as a bleaching agent;
> - systems of recovery of wood fibres in paper production.
>
> These objectives can only be attained through considerable research and development efforts and by continued association of the paper industry with the mechanical and chemical industries."

The following comments were made regarding the packaging industry:

> "The non-waste technology of a package type must be examined in all its aspects before definitive conclusions may be drawn. These aspects include the stages of design, production, distribution, transport, consumption, recycling and waste management and environmental impact."

The following comments were made regarding Topic III, "Cost-Benefit Aspects of Non-Waste Technology: "All nations have limited budgets for environmental expenditure. Benefit/cost analysis, along with other evaluation methods, can be used to help select those non-waste technologies that should be given high priority, and thereby assist in making the environment as clean as possible."

Somewhat later there was a comment that: "There is an additional matter that must be understood. There are sometimes several ways of reducing pollution. The benefits of each method may exceed their respective costs. But the appropriate method is to select the approach which can achieve the objective in the lowest-cost manner, in order to honor the true spirit of non-waste technology." Yet another subsequent comment was that "Over a period of time, it is likely that waste treatment will become increasingly costly and that non-waste technology will become less costly. This reality must start to be included in present decisions."

In the "Recommendations" section the following comment was made: "It is recommended that the Senior Advisers on Environmental Problems envisage wide consideration of the problems of non-waste technology in the chemical and petro-chemical industries and possibilities for the creation of energo-technological complexes with no harmful discharges into the environment."

But the "Non-Waste Technology and Production" Seminar/book didn't just produce abstract ideas and/or strategies for the future. It also documented multiple Real-World examples of "Non-Waste Technology and Production" that had already been implemented in Real-World commercial production! Some relevant examples and comments from the sections on "National Experience and Policy" and "Industrial Experience" will briefly reproduced below.

In the "National Experience and Policy" section of the book, A.J. McIntyre (rapporteur) summarized multiple papers from national representatives of many of the attending nations (whose details will not be reproduced here). McIntyre made the following comments:

> Austria – "The list of Non-Waste Developments in Austria is extensive and impressive."
> Belgium – "The government's interest in financing research and development and the response of industry has been very productive indeed." "The motivation for these programmes is a mix of raw material saving, energy saving, and pollution abatement."
> Canada – "…Canada has some evident interest in Non-Waste Technology. The balancing that goes on between social, economic, and political processes is seen to have resulted in some relevant policy and in certain tangible developments." "The tangible results are most clearly seen in the Can-Wel project and in the Reeve-Rapson process."
> Federal Republic of Germany – "The level of state activity in the Federal Republic of Germany is both advanced and extensive."
> France – "This paper focuses on the term "clean technologies" which refers to those technologies that reduce or evade waste or pollution."
> The Netherlands – "This country seems to have considerable interest in Non-Waste Technology and is actively involved in developing approaches that are expected to promote and encourage industry to innovate in socially acceptable ways."
> The United States – "Increasing concern about availability of raw materials is increasing the pace of development of non-waste technology in the US."

> The United Kingdom – "Here we are warned that the real aspirations of society are expressed in economic terms and that if this is not recognized we run the risk of being, or appearing to be, idealistic… We must be realistic in order to be effective."

A next major section of the book related to specific papers and examples of "The Industrial Experience." A few of the major papers will be briefly reviewed below.

Seppo Härkki, of Outokumpu Oy, Finland, described an energy saving and pollution preventing method of smelting copper ore that had been in commercial operation since 1949. Conventional processes had used large amounts of electricity to provide the heat required for smelting copper ore. The Outokumpu process air oxidized the ore, and heat from the oxidation of iron and sulfur in the ore provided most of the heat required for smelting the copper. Furthermore, the sulfur oxides that would have been air pollutants were converted to salable sulfuric acid.

Professor László Marko of the Veszprém University of Chemical Engineering, Hungary was a well-known academic chemist in the field of organometallic chemistry at the time. Professor Markó wrote about the importance of catalysts in increasing the selectivity of chemical reactions and thereby increasing yields and reducing waste in the organic chemical industry. Markó addressed the resulting important problem of how to recycle or reactivate the metal-containing catalysts, and methods for recovering potentially toxic metals from the heterogeneous catalysts including the recovery of nickel from spent Raney nickel.

The later part of Markó's paper discussed the importance of the then new field relating to the use of homogeneous metal complexes containing optically active ligands as catalysts for organic reactions, to produce optically active products that are highly relevant to biological/pharmaceutical applications. Although not explicitly mentioned, this discussion was clearly related to the then new discoveries of asymmetric hydrogenations of olefins by William S. Knowles of Monsanto, who pioneered that field. Knowles work at Monsanto resulted in a commercial synthesis of L-Dopa and eventually resulted in a Nobel Prize in 2002.

Dr Joseph Ling, Vice President for Environmental Engineering and Pollution Control at 3M Corporation gave an important talk about 3M's already established and extensive experience (since 1974 or before) in Non-Waste Technologies, entitled "Developing Conservation-Oriented Technology for Industrial Pollution Control." Some quotations from Ling's 1978 paper are reproduced below:

> "Successful application of a resource conservation-oriented pollution-control technology program throughout a single transnational company has been especially encouraging. It also indicates that on a large scale involving many countries, the rate of industrial conversion to this technology may depend largely on the amount of practical support given by governments."
>
> "Legislative requirements or the short-term deadlines of recent environmental legislation, particularly in the United States, have forced industry to use removal technology, which is not always the most environmentally efficient method."
>
> "Within industry, the primary objective in management of pollution-control activities is achievement of the highest degree of pollution reduction with the lowest use of human, material and financial resources. Non-waste technology programs appear to be the best means of meeting this objective in many cases."

While describing some specifics of 3M's experiences with its internal program, Ling commented that:

> "One extensive non-waste technology program recently was implemented by the 3M Company, a large diversified transnational manufacturing company based in the United States. The firm, with nearly 80,000 employees in more than 40 countries, stresses new and improved products. Manufacture of these products often produces pollution-control problems that require special solutions.
>
> Initial results of the 3M program are particularly encouraging because they demonstrate the superiority of this new pollution-control approach over removal technology.
>
> The program was aimed at applying conservation-oriented technology to the company's facilities around the world. It began with the strong support of top management, which was considered essential for successful implementation throughout the firm."
>
> "Appropriate prevention methods include:
>
> 1. Product reformulation.
> 2. Process modification.
> 3. Equipment redesign.
> 4. Recovery of waste materials for reuse.
>
> In 9 months the program was introduced in fifteen countries. In the United States, non-waste technology projects eliminated 70,000 tons of air pollutants and more than 500 million gallons of wastewater per year. In addition, the program saved an estimated $10 million in actual or deferred costs associated with pollution control, including energy and raw materials as well as retained product sales."

Dr. Ling also briefly described three example projects from the 3M program:

> "The company developed a new cotton herbicide chemical. The original process emitted a toxic substance and one that caused a strong odor. It also introduced 12

pounds of pollutants per pound of product. Using non-waste technology, the laboratory then developed a new process that eliminated the toxic substance and the odor. It also reduced other pollutants to only 2 pounds of waste per pound of product. In addition, manufacturing costs were significantly reduced.

Another case involved control and recovery of hydrocarbon solvents, which can contribute to photochemical smog when released into the atmosphere. The firm developed and built a unique inert gas drying process. It features a large oven that operates as a closed system. This prevents hydrocarbon emissions and allows recovery of most of the valuable solvents.

In a third case, a mercury free catalyst was developed for a resin product to prevent a mercury problem. This made the product more environmentally acceptable and prevented a substantial loss in sales."

Lastly, Dr. Ling introduced a concept that "In a sense, many pollutants can be considered misplaced resources… But it took knowledge (technology) to turn these former pollutants into resources." Dr. Ling then restated the concept into an "equation" form that was often quoted (and put into practice) later:

"Pollutants (waste materials) + Knowledge (technology) = Potential Resources"

In retrospect, it is obvious from the "Non-Waste Technology and Production" seminar/book, that during the 1970s (and even well before) many people and organizations in many countries were actively conceiving, reducing to practice, and commercializing "green" chemical processes and downstream chemically-based products that were intended to be both environmentally **and** economically efficient. A variety of scientists and engineers (industrial and/or academic), economists, and national and international governmental authorities were already voluntarily collaborating to achieve such goals long before the 1990s.

5. 3M'S "POLLUTION PREVENTION PAYS" ("3P") PROGRAM

3M's corporate "Pollution Prevention Pays" Program ("3P"), already mentioned above in connection with the 1976 "Non-waste Technology and Production" Seminar and 1978 book, formally began in 1975. A pioneer in those 3M efforts was Dr. Joseph T. Ling who was the 3M Vice President for Environmental Engineering and Pollution Control. Dr. Ling was elected to the National Academy of Engineering in 1976, and many of the facts recited in this section were sourced from a Memorial Tribute to Dr. Ling published by the National Academies after Dr. Ling's death in 2006 (see Joseph T. Ling (2008, ref 50). An on-line version is available at https://www.nap.edu/read/12473/chapter/31.

Dr. Ling was born in China in 1919, educated as an engineer, and left China in 1948 to obtain a Ph.D. in sanitary engineering from the University of Minnesota. Ling worked briefly at General Mills, then returned briefly to China before returning to the US in 1960 to become 3M's first professionally trained environmental engineer. Dr. Ling moved 3M away from pollution control (treatment) approaches and toward pollution prevention and/or natural resource conservation approaches that could simultaneously improve efficiency, production yields, and economics. Ling wrote a new environmental policy for 3M that was adopted by its Board of Directors in 1975.

"Joe realized that government and public awareness was essential to regulatory and legislative acceptance of this new approach, so he 'went public' with the idea in 1976," at the ECE Non-waste Technology and Production Seminar described above. "He stressed the need for cooperation among industry, government, academia, and the general public, because 'the environmental issue is emotional … the decision is political … but the solution must be technical.'"

This author conducted a 2018 telephone interview with one recently retired 3M employee, Keith Miller, an engineer who had just ended a 37-year career at 3M as a "sustainability strategic advisor". The telephone interview was a follow-on to a 2015 "exit interview" published at Greenbiz (see https://www.greenbiz.com/article/exit-interview-keith-miller-3m). Miller recalled that after graduation as a chemical engineer from the University of Minnesota he began his first job at 3M in 1974. Miller said his first major project assignment was to a convert a process for making an adhesive tape product from a solvent-based adhesive application process to a hot-melt process. Miller recalled that he collaborated with 3M chemists to identify suitable hot-melt formulations and develop practical methods for economically and reliably applying the adhesive to produce a good quality adhesive tape product that was acceptable/desirable to the customers. Miller recalled that he was involved in environmental projects using similar multi-disciplinary teams and approaches throughout his career.

When asked, Miller also recalled being trained, in the 1980s, in Deming style "Total Quality Management ("TQM") methods.[25] Miller recalled finding the "Quali-

[25] See Murphy (2018) for more description of Deming's "Quality" approaches, philosophy, and techniques and their relevance to the conception and invention of the BHC Ibuprofen process in the mid-1980s.

ty" training useful and "compatible" with 3M's operating methods and approaches, which were being applied to thousands of different products. When asked, Miller did not recall much patenting activity, believing that most of the company's intellectual property, for its many products, was primarily protected by trade secret IP strategies, rather than patents.[26] Most of all, Miller seemed very appreciative of the strong support the 3P program and approaches had received from 3M Management, over decades.

That support was highly economically and environmentally productive. The National Academy Memorial Tribute to Dr. Ling (in 2008) remarked that "After 30 years, the 3P Program is still a key strategy in 3M's Environmental Management Plan. From 1975 to 2005, with some 8,500 pollution prevention activities and programs in 23 countries, the company was able to keep from producing an estimated 2.2 billion pounds of pollutants while saving nearly $1 billion."

Subsequent to the 1976 ECE Seminar, several countries including England, France, and Germany, adopted the Pollution Prevention strategy as national policy. "In 1977, the Environmental Protection Agency (EPA) and U.S. Department of Commerce conducted a series of industry/government seminars on pollution prevention." Dr Ling and other 3M speakers spoke at many of those seminars and 3M published multiple subsequent papers describing its 3P program. Examples of the papers include Susag (1982, ref 76), Zoss and Koenigsberger (1984, ref 92), Koenigsberger (1986, ref 47), Susag (1987, ref 77), Zosel (1990, ref 90), and Zosel (1994, ref 91). Those papers were united by their description of the general approaches 3M employed over many years, directed to many types of its chemically based consumer products, by working with many people at most levels throughout their international organizations, using many kinds of processes, in many countries. The papers consistently emphasized the importance of the high level of support for those activities received from 3M management. The National Academy noted that "by 1988, 34 states had established pollution prevention programs."

6. THE IMPORTANCE OF ECONOMICS IN POLLUTION PREVENTION

By the time of the UN/ECE "Non-Waste Technology and Production" Seminar in 1976, many individuals and organizations had recognized the high economic costs and industrial resistance that had been produced by the "command and control" / "end of the tailpipe" approaches mandated by many environmental statutes of the early 1970s, especially in the United States. The importance of the economic issues was crystalized and summarized by Professor Michael G. Royston of the Center of Education in International Management in Geneva. Professor Royston's paper at the 1976 conference has already been described, but his analysis further crystalized in his 197-page book, "Pollution Prevention Pays" (Royston 1979, ref 71).

Royston's book adopted its title (with permission) from 3M and/or Dr. Joe Ling, and Ling wrote the foreword to Royston's book. Ling's foreword commented that "Most environmental laws, regulations, and technologies have been devoted to cleaning up pollution, with little or no attention paid to prevention…. Government, industry, and the public are beginning to become aware of the shortcomings of conventional pollution controls, not to mention their cost." Ling then added that "The conservation approach…. Means eliminating the causes of pollution before spending money and resources to clean up afterwards. It also means learning to create valuable resources from pollution…" Ling further commented that "The concept is embodied in *Pollution Prevention Pays*, which speaks to the proposition that it is environmentally, technically, and economically superior to eliminate the sources of pollution before clean-up problems are created."

Royston's book stated (on page 9) that its purpose was to demonstrate:

> "That environmental protection is economically justified both from the point of view of the community and at the national and regional level;
> That the resources required for development or even the maintenance of the *status quo* can be damaged by pollution;
> That the damage is likely to cost the community more than it would have to spend to prevent the damage from occurring at all;
> And finally the positive contribution environmental protection policies make to the development of enterprises – both public and private."

Royston was critical of both socialist and capitalist traditional economic approaches, asserting that both had actually produced increasing concentration of decision-making power in fewer and fewer hands, and an underlying economic justification that "was typically Cartesian in its scope, completely linear in its approach…" Royston further commented that "in both these centralized systems the vital link between man and his envi-

[26] This author has done some cursory searching for patents (in the US or abroad) that issued to 3M during the 1970s and 1980s, and found surprisingly few patents, and no patents of clear relevance to Green Chemistry.

ronment is broken… For the central planner or the Wall Street banker alike, the environment is a free resource to be fed into the economic development system… Both of them are remote from the environmental results of their decisions and from the people who suffer from those results."

Royston asserted that "The modern manager has a responsibility not only to the company which he manages, but also to the society in which his country functions." Royston continued (on page 43) that "Gone are the simplistic notions of maximizing production or maximizing profit. In their place is the reality of multiple objectives, often defined in terms of "profit (or productive surplus), growth (quantitative or qualitative), survival, and human and social responsibilities"

In his Chapter 7 entitled "Non-Waste Technology" (pages 87-113), Royston described many examples from many countries where chemically-related industrial companies, had already (as of 1979) begun using "Pollution Prevention" or "Non-Waste Technology" strategies to simultaneously reduce or eliminate pollution while simultaneously saving money, energy, reduce waste and/or make positive profits. Examples included 3M at multiple locations, Union Carbide at a ferro-alloy plant in West Virginia, Dow Chemical at Midland Michigan, Dow Corning at Hemlock Michigan, a U.S. Goldkist poultry plant, Kamchai Iamsuri rice millers in Thailand, several Scottish whiskey distilleries, an Ahlstrom pulp and paper plant in Varkaus Finland, a Great Lakes Paper plant, a Westvaco paper plant, a French dying process, a Georgia Pacific plant in Bellingham Washington that produced 190 proof ethanol, a Shell Canada refinery process for utilizing refinery sludge, a Mobil Oil refinery in England wherein waste heat from the refinery was used to grow hothouse tomatoes, and many, many more. An "Index of Non-Waste Technology" at the end of Royston's book documented 215 such already existing "Non-Waste Technology" projects in many countries.

Part III of Royston's book, "Why Technocrats Fail" addressed the reasons for the failures of the "command and control" legal/regulatory approaches to pollution control. Legally inspired "command and control" approaches were common, especially in the US, in the 1970s. He stated (Chapter 8, page 117) "What we have seen so far is that pollution control as a whole and particularly its costs form an extremely complex issue, involving as it does values, social aspirations, and the total system in which individuals and institutions are embedded….Given the complex nature of the problem of pollution control, one would not expect solutions to it to be unitary." Later in the same paragraph, Royston states "Such a solution requires a system view of products, wastes, and natural resources so that even a pollutant is seen to be a potential raw material. As was shown in Chapter 2 this systems view includes links and feedback loops from the outputs of the development process to the inputs…. Given this complex problem, one might ask whether government legislation reflects anywhere the intricacy of this highly sensitive system with its particularly effective negative feed-back loops? Unfortunately, the answer is, except in one or two notable instances that it does not."

Royston then went on to analyze in some depth the failures of "command and control" legally-based approaches based on the political/legal imposition of abstract "legal standards" that ignore the great importance and effects of the Real-World complexity and evolution, and the failure to take local circumstances into account.[27] Royston stated (page 121) that

> "The difference between the centralized legalistic tradition based on standards and a more decentralized pragmatic approach based on case-by-case examination typifies the extremes which are to be found. In between there is a whole series of systems based on regional administrations, which enable individual states, provinces, or regions to set their own standards within the overall frame law.
> Given what has been said so far in this book, it might be supposed that national governments faced with the complex problem of pollution control would respond by trying to match pollution standards to local environmental conditions, by integrating pollution within the environmental system and by matching technology to economic factors. But that is not the case."

In Chapter 9, Royston argued that "the benefits of pollution control are considerable," and provided many examples. In Part IV, Chapter 10, Royston argued for an "Integrated Approach." "The most effective, harmonious, and economical approach to pollution prevention is one which works through the whole environmental system, using an integrated systems approach," that addressed "technological, economic, physical, cultural, social, and political aspects". First, Royston asserted that "From the technological point of view the solution to the environmental problem lies in the application of non-Waste technology to pollution problems. Non-Waste technology is a subsystem which integrates inputs and outputs, resources, product and waste." Royston then turned the economic aspects of a systems approach, saying "The prerequisites of a successful strategy are…the inter-

[27] This author has long planned and hopes to soon begin writing a series of legally oriented articles and/or books about "Dr. Murphy's Corollary: Law is Mostly a Bunch of Linear Approximations of a Non-Linear World"

nalization of all environmental damage caused by any party in the economics of a particular operation, and … the provision of economic incentives to encourage the clean-up of the environment and to create the economic benefits which result from a clean-up operation." In his Chapter 11, Royston detailed "Action programmes for the community, for government, and for industry," whose details will be bypassed in this paper.

7. THE WIDENING COMMERCIALIZATION OF POLLUTION PREVENTION STRATEGIES DURING THE 1980S

Subsequent to publication the UN/ECE book in 1978, and the publication of *Pollution Prevention Pays* in 1979, several of 3M's representatives, Professor Royston, and others engaged in a sustained campaign of writing and speaking about Pollution Prevention strategies.

In 1980 Royston published an article in the Harvard Business Review (Royston 1980, ref 72). The article cited many examples from Europe and the US wherein corporations were already commercializing "Pollution Prevention" strategies, and as a result simultaneously attaining profits and growth. Royston (and 3M representatives) spoke at more international and regional technical conferences on Pollution Prevention strategies. A book of papers from a 1982 regional conference in Winston-Salem North Carolina (Huisingh and Bailey, 1982, ref 44) contained contributions from many corporations that were already implementing Pollution Prevention strategies in their Real-World businesses. A listing of authors and titles from those papers is attached in Appendix II.

Articles about Pollution Prevention strategies also began to appear in the mainstream consumer press. On January 4, 1981, William Greider, an assistant managing editor at the Washington Post, published an article titled "The Rise of Corporate Environmentalism" (Greider 1981, ref 35). The article described Royston's book, and commented about other "environmentalists who do not usually get much fanfare. I am thinking, for instance, of Boeing, Exxon, Dow Chemical, Minnesota Mining, Caterpillar Tractor, Shell, British Petroleum, Krupp, and Phillips, to name a few." The article described existing projects at Hercules Powder, Goldkist Poultry, Haynes Dye and Finishing, and noted that corporations were discovering that "complying with Federal Standards on pollution produced a startling result for them. It increased their profits."

A 1984 New York Times article entitled "The Recycling of Chemical Waste" (Marcus 1984, ref 58) described successful projects to recycle chemical wastes at several companies, including Allied Corporation, Du Pont, Monsanto, 3M, and Dow Chemical. But the article noted the tremendous variety of the problems being addressed and remarked that "decades will be needed to approach this goal." The article quoted an Arthur D. Little consultant as saying, "We end up with many examples – successes in smaller and smaller packages – that are not transferable to other wastes." Bob Bonchek, a director of environmental affairs at Du Pont, remarked that "Each technique requires great imagination and persistence, and none is a panacea."

By the 1980s, at least some major segments of the chemical industries were considering waste/pollution issues as a routine part of their business, research, and/or culture. This author' recent article titled "Early Industrial Roots of Green Chemistry…" recounted the genuine[28] and previously untold story of how the BHC Ibuprofen process began and was developed and commercialized (starting in 1984) (see Murphy 2018). This author recalled that "One thing I was told very soon after my arrival at Celanese, in no uncertain terms, by several veterans, was that any project or process that I proposed to work on that generated significant quantities of waste products, especially inorganic salts, would have a very large strike against it. That strong internal prejudice against processes that produced significant amounts of wastes was already very much a part of Celanese culture the day I arrived there in January 1983."

Independent industrial efforts were going on internationally. For example, the "Responsible Care®" initiatives in the Canadian chemical industry were formalized in 1985, though the roots went significantly earlier (see Belanger et. al., 2009, ref 15, and a Wikipedia article on "Responsible Care"). Responsible Care® "is now a global, voluntary initiative developed autonomously by the chemical industry for the chemical industry. It runs in 67 countries whose combined chemical industries account for nearly 90% of global chemical production. 96 of the 100 largest chemical producers in the world have adopted Responsible Care." Similar current initiatives are being carried out by the American Chemistry Council (2018, ref 1).

As noted in the National Academy's tribute to Joe Ling, "by 1988, 34 states had established pollution prevention programs, and EPA had published a national

[28] A continuing series of highly incomplete (to the point of being almost false) narratives have long propagated in the academic literature about the origins of and motivations behind the BHC Ibuprofen Process invention, which won one of Chemical Engineering Magazine's Kirkpatrick Awards in 1993 and one of the first Presidential Green Chemistry Awards, in 1997. (See Murphy 2018).

policy and established the Office of Pollution Prevention. In 1989, the American Institute for Pollution Prevention was founded, sponsored by EPA, with Joe [Ling] as its chairman. In 1990, Congress passed the Pollution Prevention Act, requiring that pollution prevention be considered the first phase of any environmental enhancement program."

And there had been even earlier efforts in the U.S. Federal government. In September of 1986 the U.S. Congress's Office of Technology Assessment published a long document entitled *Serious Reduction of Hazardous Waste: For Pollution Prevention and Industrial Efficiency* (U.S. Office of Technology Assessment 1986, ref 83). Participants in the preparation of the report included many representatives of major corporations, smaller corporations, major environmental groups, Academia, OTA and EPA staff, and multiple state-based agencies involved in pollution control efforts. The Foreword to the report noted the prior Superfund clean-up efforts, but then stated "Now Congress is turning its attentions to preventing hazardous waste problems by cutting down on the generation of hazardous waste at its source through innovative engineering and management… But while everyone agrees in a philosophical sense that waste reduction is good, there is confusion about definitions and methods." The report then went on to try to address such definitional and methodological issues and noted that "over 99 percent of Federal and State environmental spending is devoted to controlling pollution after waste is generated. Less than 1 percent is spent to reduce the generation of waste" and estimated that it costs 10 to 100 times more money to clean up toxic waste contamination than it would have cost to prevent the original releases into the environment.

Related activities had also progressed in Europe. ACS's history of Green Chemistry[29] was recently amended to note that "The Organization for Economic Co-operation and Development (OECD), an international body of over 30 industrialized countries, held meetings through the 1980s addressing environmental concerns. They made a series of international recommendations which focused on a co-operative change in existing chemical processes and pollution prevention." In 1983 the United Nations founded a "World Commission for Environment and Development" to prepare a report about long-term sustainable and environmentally friendly economic development, and in 1987 issued the "Brundtland Report", see Brundtland (1987, ref 18).

Similarly, Linthorst (2010) noted that "During the 1985 meeting of the Environment Ministers of the OECD countries, the focus was on three themes: Economic Development and the Environment, Pollution Prevention and Control, and Environmental Information and National Reviews. Between this meeting and 1990 several (OECD Council Acts) Decisions, Decisions-Recommendations and Recommendations were formulated," and referenced a comprehensive history of the OECD and environmental issues by Long (2000, ref 55).

The EPA's Office of Pollution Prevention and Toxics (OPPT) was established in 1988 to pursue "pollution prevention" approaches. In 1989, Stephan and Atcheson of the EPA (Stephan, Atcheson, 1989, ref 75) wrote about "The EPA's Approach to Pollution Prevention." They stated "The recent focus on pollution prevention as the 'first choice' for environmental protection by the Environmental Protection Agency is *very* real, and it involves a true, operative, non-adversarial approach by the agency, perhaps a first for the EPA in its 18-year history… It has become apparent to the Congress that even strongly enforced end-of-the-tailpipe and top-of-the-stack discharge and vigorously regulated hazardous waste disposal alone will not solve all the environmental problems in the United States." Another early leader at the EPA was Dr. Joseph Breen, who was a chemist and manager at the EPA for 20 years and played a major role in creating the "Design for the Environment," and "Green Chemistry" programs at EPA. After retirement from the EPA in 1997, Breen helped found and was the first director of the Green Chemistry Institute that was founded in 1997, as an independent non-profit organization. Breen passed in 1999, but the Green Chemistry Institute continued and later joined the American Chemical Society in 2001.

The industrial efforts were also getting more attention in the popular press. In March 1988 the *Journal of Commerce* ran an article by Craig Dunlop (Dunlop 1988, ref 25) that reported that in 1986 Dow implemented a formal program called "Waste Reduction Always Pays," and reported waste reduction successes at its Dalton Georgia and Freeport Texas plants. At the Dalton latex plant, workers installed scrubbers for gas emissions that recovered latex starting materials and cut "emissions by 90% while generating sufficient raw material to pay for the recovery process." At Freeport, a byproduct from the production of anti-freeze and airplane de-icer was being used as a feedstock to produce dry-cleaning fluid in Louisiana, California, and West Germany. A Dow spokesman named Delcambre was quoted as saying that "the industry's mind-set is changing and waste reduction is becoming a top priority with virtually every U.S. chemical company." A 1990 article in the Baltimore Evening Sun (Ferrier 1990, ref 30) reported that Dows WRAP program had reduced air emissions by 44% and

[29] See https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/history-of-green-chemistry.html

hazardous wastes by 25% and been awarded a 1989 Gold Medal Award for International Corporate Environmental Achievement by the World Environmental Center. The article also reported that that Dow had spent $47 million on 47 projects in two years, and that the average payback period for a "WRAP investment is only eight months."

Similar early "green chemical" advances were also occurring at many smaller companies, though those efforts and results tended to get less or no publicity. One example was the development of copper-based wood preservatives used to pressure treat wood by Chemical Specialties Inc. (CSI – now Viance). The CSI "ACQ" (ammoniacal copper quarternary) wood preservatives replaced much of the prior uses of chromated copper arsenate wood preservatives and won a Presidential Green Chemistry Challenge Award (in the Designing Greener Chemicals Category) in 2002. The story goes much earlier however and illustrates the inherently interdisciplinary nature of Green Chemical research, especially at small companies. The ACQ story was told to this author in a 2018 personal interview with Dr. Kevin Archer, originally with CSI, which later became Viance.

CSI had an established business making and selling chromated copper arsenate wood preservatives, but regulatory pressures to remove the chromium and arsenic from wood preservatives began in the 1970s, especially in Europe. The discovery work on the ACQ wood preservatives was done by David Finlay and Neil Richardson of Domtar Inc. of Canada (both now deceased, see U.S. Patent No. 4,929,454 first filed Feb 05, 1981, PCT Patent Publication WO 82/03817, and Richardson (1991, ref 70)). The patents and some early phase demonstration compositions were licensed to CSI for commercial development in North America. Alan Richardson had begun his career as a professor of plant pathology at the University of Canterbury in New Zealand, and Dr. Kevin Archer had received a Ph.D. under Richardson there, for studies of wood decay. Both men had personal interests in making more environmentally friendly wood preservatives. Preston moved briefly to Michigan Tech in the US, then to CSI. In June of 1988 Archer followed Richardson to CSI and both became involved in the several years of product development/testing required to develop the Domtar lab compositions into viable and customer-acceptable commercial products.

After conducting a series of three-year field tests, in 1992 CSI introduced its first commercial product, which used ammonia as the amine part of the wood treating compositions, along with copper oxide and quarternary ammonium chloride salts. The new copper compositions cost four times as much as the prior chromated copper arsenate compositions and gave the treated wood a smell and blue color that customers disliked. Sales were initially slow due to the high cost and color / smell issues, but regulatory pressures continued to build. In 1995 CSI brought out a new version of the ACQ preservatives that replaced ammonia with ethanolamine and had a better smell and more desirable green color. But problems were also being encountered related to chloride corrosion of metal pieces in the wood (caused by the quarternary ammonium chloride salts). Those problems were overcome by modifying the compositions to employ quarternary ammonium carbonates. Significant commercial success finally resulted about 2002. Preston and Archer (both biologists by training) prepared the applications for the Presidential Green Chemistry Awards, but the 2002 Presidential Green Chemistry award said nothing about the history of the development of the invention, or it's inventors or developers.

8. THE EARLY 1990S − INTEREST BROADENS

In the late 1980s and early 1990s, interest in the ongoing "Pollution Prevention" approaches began to grow rapidly in the U.S. government and in Academia. The Pollution Prevention Act of 1990 was signed by President George Herbert Walker Bush in October 1990. The history of the legal / statutory / regulatory development of the provisions of the Pollution Prevention Act, and similar amendments to the Clean Air Act, the Clean Water Act, the Emergency Planning and Community Right to Know Act, the Resource Conservation and Recovery Act (RCRA) and Toxic Substances Control Act (TSCA) were reviewed by Walzer and Maynard in March 1993 (Walzer 1993, ref 84).

In 1991, Professor Barry M. Trost of Stanford University published an article in *SCIENCE* entitled "The Atom Economy – A Search for Synthetic Efficiency) (Trost 1991, ref 82). Trost was later awarded a Presidential Green Chemistry Award in 1997, for "The Development of the Concept of Atom Economy." But the ACS/EPA's published commentary to Prof. Trost's Presidential Green Chemistry Award also noted "When Prof. Trost's first paper on atom economy appeared in the literature, the idea generally was not accepted by either academia or industry. **Many in industry, however, were practicing this concept without enunciating it**." (bolding added)

In 1991, EPA's Office of Pollution Prevention and Toxics launched a model research grants program called "Alternative Synthetic Pathways for Pollution Prevention". It has also been reported in the literature (see Sanderson

2011, ref 73) that in 1991 Dr. Paul Anastas (who had been out of graduate school and employed at EPA for just two years) coined the term "Green Chemistry".

Also in 1991, two veterans of Academia and/or the U.S. Congress's Office of Technology Assessment, and non-governmental "Pollution Prevention" projects, published a book entitled "Prosperity Without Pollution – The Prevention Strategy for Industry and Consumers" (Hirschhorn and Oldenburg 1991, ref 39). They argued that Government should not be counted on, and was often part of environmental problems, because it often focused most of the country's political and financial resources on new programs and mandatory "end-of-the-tailpipe" approaches, rather than endorse spending money on maintenance and preventative solutions. They argued that industry should take individual responsibility and focus on preventing, rather than cleaning up waste.

In October 1991 the EPA's OPPT issued a major report (Pollution Prevention 1991, ref 65. 197 pages plus Appendices) that reported in considerable detail the status of Pollution Prevention efforts at a wide variety of entities of the U.S. Federal Government, the states, universities, and localities. On-going programs were detailed for a wide variety of corporate entities.

In 1992, Breen and Dellarco of EPA edited volume 508 of the ACS Symposium Series entitled "Pollution Prevention in Industrial Processes; The Role of Process Analytical Chemistry". The book documented and highlighted the already on-going industrial efforts to use Analytical Chemistry in the Prevention of Pollution that were the precursors of one of the later "Principals of Green Chemistry," i.e. "Real Time Analysis for Pollution Control" (see discussion below). But the first paper of the book (also authored by Breen and Dellarco) had a more general theme and was entitled "Pollution Prevention – The New Environmental Ethic" (Breen and Dellarco 1992, ref 16). The abstract stated:

> "Prosperity without pollution has become the fundamental environmental theme of the 1990s. Or at least, the consideration of how we will achieve this economic and environmental imperative. The new paradigm - pollution prevention - will serve as the keystone of federal, state and local environmental policy. Support for the new approach - the new ethic - is broad based and includes environmentalists, industrialists, lawmakers, academicians, government regulators and policy-makers, and the general public. The challenge is to switch from two decades of environmental policy based on pollution controls and government mandated regulations, to a future environmental policy based on pollution prevention, source reduction, recycling, and waste minimization. It will require a new social compact amongst environmental, industrial, and regulatory interests. The roles and contributions of the chemical engineer, synthetic organic and inorganic chemist, and the process analytical chemist will be integral to the full articulation and implementation of the new vision."

The 1992 Breen article then went on to describe the considerable progress toward Pollution Prevention that had already been achieved by various trade associations, individual companies, state and local programs, and Federal agencies. In reviewing company-based pollution prevention programs, Breen and Dellarco remarked in 1992 that:

> "Some companies have programs which they are willing to share with the public and other companies whose efforts are considered internal and proprietary. The more accessible programs are usually with large multi-facility companies. They are engaged in a wide range of operations, from specialty chemicals to high technology electronics. Some programs are well established with formal names and acronyms. Others are newer and more informal. The earliest dates back to 1975, with some following in the early and mid-1980s and others initiated in the 1990s."

A few paragraphs later Breen and Dellarco remarked:

> "a major change in industrial perspective on the way business is to be done has taken place. Most programs and activities are voluntary. The programs initiated by industry on pollution prevention are important because they raise expectations for future progress. If the successes are real and include financial gains, there is a legitimate expectation other firms will follow the leaders into this new era of environmental protection."

Regarding status in Academia, Breen and Dellarco remarked that "Pollution prevention interests and coursework are newcomers to the campuses of the United States. Historically, few faculty members had developed the relevant background to make it an important element in the environmental, chemical engineering or business curricula," but commented that the level of interest was increasing. The article noted however that the American Institute of Chemical Engineers (AICHE) "aggressively encourages industry sponsorship of university research." The article characterized the efforts of the American Chemical Society at that time as "modest," and commented that "Clearly contributions are needed from the synthetic organic and inorganic chemists to build more environmentally friendly molecules - molecules designed for the environment, while still fulfilling their intended function and use."

Also, in 1992, Freeman, Harten, Springer, Randall, Curran, and Stone of the Pollution Prevention Research Branch of EPA in Cincinnati Ohio published a 49-page paper in the *Journal of the Air and Waste Management Association* (Freeman et. al., 1992, ref 33) entitled "Industrial Waste Prevention: A Critical Review." The paper was initially begun as a critical review of the papers, articles, reports and books relating to "Pollution Prevention" from the prior four years. But the authors stopped collecting new papers "at 472 such sources, recognizing that our first conclusion was that there has been an awful lot written on the subject the last few years."

The first issue addressed in the Freeman paper was terminology, noting that while "Pollution Prevention" was popular in the U.S. and in use at the EPA, its Table 1 also listed 35 other alternative terminologies that were being used in various places. The paper then addressed many benefits of Pollution Prevention techniques (which were being abbreviated as "P2"), including economic and cost advantages. The paper then went on to describe very many P2 activities that were already ongoing in 1992, including activities at several major U.S. Federal Agencies, legislative activities, EPA, the Office of Technology Assessment, the Department of Defense, the Department of Energy, and the Post Office.

Freeman et. al. also described many activities that were then ongoing at state and local agencies, noting that "before 1985 there was only one state law which dealt with any aspect of Pollution Prevention. Six years later there are almost 50 laws dealing with some aspect of Pollution Prevention," and that "as of April 1, 1991, over half of the states have passed pollution prevention laws." They also documented a good deal of such activity going on internationally, and much already on-going activity in "Industrial P2 Programs." As of 1991 EPA had documented "the P2 programs for 24 major companies whose program, goals, and accomplishments are company-wide," specifically mentioning already functioning programs at Chevron, Dow, General Dynamics, IBM, and Monsanto. The article then documented ongoing efforts by the Chemical Manufacturers Association and its Responsible Care program.

In a 1992 article entitled "Pollution Prevention methods in the Surface Coating Industry" (Randall (1992, ref 68), Paul M. Randall of EPA's Risk Reduction Engineering Laboratory in Cincinnati reviewed then on-going efforts aimed at Pollution Prevention in the paints and coatings industry. Randall remarked that "In response to the environmental and economic crisis, the surface coating industry is re-examining the production, application, and disposal of paints to reduce VOCs to meet environmental regulations and for coating manufacturers to optimize processes to reduce costs and increase profits." Randall then went on to discuss many aspects of those efforts.

Obviously, by 1992, many organizations and people from many disciplines and many countries (especially industrial chemists and engineers) were already working on and had already made very significant Real-World progress in "Pollution Prevention."

Interest in the environmental / chemical waste issues also began to increase in the Academic chemistry fields. In December 1992, Professor Roger Sheldon, a long-time veteran of the European chemical industry who had moved to Academics in 1991, published his seminal paper "Organic Synthesis – Past, Present, and Future" in the industry trade journal *Chemistry & Industry*. Sheldon's article reviewed the history and evolution of organic chemistry and its problems with waste generation. Sheldon also reviewed the largely separate industrial progress and evolution on the waste issues toward better "E-factors," via the use of catalysis. Professor Sheldon identified (Sheldon, 1992, ref 74, page 904) an industry segmentation of the ecological performance of the existing industrial processes:

> "The seriousness of the problem is readily appreciated by considering the amount of waste produced per kilogramme of product – the '**E factor**' in various segments of the chemical industry (see Table 1)."

In 1991, few in Academia had recognized that environmental performance in the oil refining and commodity chemicals industry segments (where catalysis had been in common use) was so dramatically better than in the fine chemical and pharmaceutical industries (where the use of traditional synthetic organic chemistry was dominant and use of catalysis was uncommon). Sheldon exemplified the progress on the waste generation in the commodity chemical industry with a discussion of the modern and highly atom economical industrial commercial synthesis of ethylene oxide by catalytic air oxidation of ethylene, the industrial synthesis of acetic acid by methanol carbonylation (that had been invented at Monsanto in 1966[30]) and "light at the end of the tunnel"

Table 1. The **E Factor.**

Industry Segment	Product Tonnage	Kg byproduct / Kg product
Oil Refining	10^6-10^8	ca. 0.1
Bulk Chemicals	10^4-10^6	<1 - 5
Fine Chemicals	10^2-10^4	5 - >50
Pharmaceuticals	10-10^3	25 - >100

(from Sheldon, 1992).

[30] See Paulik, F.E., Hershman, A, Know, W.R. , and Roth, J.F., U.S. Patent 3,769,329 issued October 30, 1973, assigned to Monsanto. Murphy

BHC Ibuprofen Process[31] which was commercialized at Bishop Texas in 1992, and had a very low E-Factor for a fine chemical / pharmaceutical process.

In January 1993 the Clinton Administration was inaugurated in the U.S. and the EPA, NSF, and Counsel for Chemical Research cooperated to initiate a special research grant program titled "Environmentally Benign Chemical Synthesis and Processing Program" (see Anastas 1994, ref 2, page 18).

In November 1994 ACS published Volume 577 of its Symposium Series (see Anastas 1994) entitled "Benign By Design – Alternative Synthetic Design for Pollution Prevention." The book consisted of papers from a Symposium sponsored by the ACS Division of Environmental Chemistry at the 206th ACS National Meeting in Chicago in August 1993. Chapter 1 of the book, authored by P.T. Anastas of EPA's OPPT, began with a brief description of the prior "Pollution Prevention" efforts, and mentioned in passing Dow's WRAP program and 3M's "3P" program, but it didn't describe them any further or provide useful citations to those programs. The only other industrial inventions or programs included in the book were two papers from Monsanto and one from DuPont.

The Anastas (1994) article did describe the passage of the U.S. Pollution Prevention Act of 1990 and noted that the statute mandated that EPA "pursue pollution prevention in all its environmental protection initiatives." Somewhat later Anastas characterized "early approaches to pollution prevention" as "housekeeping solutions" and/or "low-hanging fruit." Anastas then went on to describe some ideas about how synthetic organic chemists should go about designing environmentally friendly new molecules and/or new chemical processes. It made no mention of or reference to Sheldon's 1992 *Chemistry & Industry* article, or the history and/or technologies it described. The Anastas (1994) article did not use the term "Green Chemistry".

An early public use of the term "Green Chemistry" occurred at the 208th ACS National Meeting in August 1994. Papers from a symposium (organized by Joseph Breen and Allan Ford and sponsored by the ACS Division of Environmental Chemistry) were published in Volume 626 of the ACS Symposium Series, in 1996 (ref 6). The book was titled "Green Chemistry – Designing for the Environment," and contained seventeen article / chapters authored by a variety of scientists from U.S. and foreign governments, industry, and Academia from several countries. Its Preface said it described "the current research efforts and recent results of leaders in the field of green chemical syntheses and processes."

Chapter 1 of that 1996 book, titled "Green Chemistry: An Overview," authored by Anastas and Williamson, began in its Abstract with the statements that "Green Chemistry is an approach to the synthesis, processing, and use of chemicals that reduces risks to humans and the environment. Many innovative chemistries have developed over the past several years that are effective, efficient, and more environmentally benign." The first sentences of the article's text stated that "Over the past few years, the chemistry community has been mobilized to develop new chemistries that are less hazardous to human health and the environment. This new approach has received extensive attention (1-16) and goes by many names including Green Chemistry, Environmentally Benign Chemistry, Clean Chemistry, Atom Economy and Benign By Design Chemistry." A bit later the article noted "Simply stated, Green Chemistry is the use of chemistry techniques and methodologies that reduce or eliminate the use or generation of feedstocks, products, by-products, solvents, reagents, etc., that are hazardous to human health or the environment." That definition was certainly broad and certainly encompassed many of the 20 prior years of "Pollution Prevention" efforts by others.

The article then briefly described some of the prior "Pollution Prevention" efforts and the U.S. Pollution Prevention Act of 1990. Then the article commented that "There is no doubt that over the past 20 years, the chemistry community, and in particular, the chemical industry, has made extensive efforts to reduce the risk associated with the manufacture and use of various chemicals." But then the article commented that "Many different ways to accomplish pollution prevention have been demonstrated and include engineering solutions, inventory control and 'housekeeping' changes. Approaches such as these are necessary and have been successful in preventing pollution, but they also are not Green Chemistry." The authors seemed to be implying that "engineering solutions" weren't "Green Chemistry," a very questionable proposition given that the many prior "engineering solutions" had been developed and implemented in industry as solutions to "chemical" problems. The statement also seemed to ignore the large number of genuinely "chemical" Pollution Prevention inventions and/or solutions that had been invented, developed, and commercialized by industrial chemists over the prior 20 years, typically using multi-disciplinary approaches that integrated the chemistry and engineering together to produce the desired prevention of pollution.

(2018) details several more commercial examples from the commodity chemicals industry that had nearly perfect E-Factors.

[31] See Elango, V., Murphy, M.A., Smith, B.L., Davenport K.G., Mott, G.N., Zey, E.G., Moss, G.L.: "Method for Producing Ibuprofen," US Patent 4,981,995, granted January 1, 1991, and Murphy (2018).

The article then went on to discuss a handful of techniques, goals, and concepts of "Green Chemistry", along with multiple examples of each of those techniques, goals, and concepts that that had already been explored by a variety of international academic, governmental, and/or industrial researchers. Those techniques, goals, and concepts (which appear to have been precursors of the "Principals of Green Chemistry" formally announced later in 1998) included "Alternative Feedstocks and Starting Materials," "Alternative Synthetic Transformations and Alternative Reagents," "Alternative Reaction Conditions," "Alternative Products and Target Molecules," "Atom Economy," and "catalysis." Examples from each of these categories were cited from a variety of prior Academic and Industrial researchers and/or reports in Academic journals and even from several patents. This author remains unclear as to how the allegedly new "Green Chemistry" was or is different than the many prior research and/or "Pollution Prevention" efforts that had gone before, other than using a new terminology.

In 1995-1996 the EPA/ACS "Presidential Green Chemistry Challenge Awards" were created and generated a great deal of publicity, in Academia and elsewhere. As EPA / NSF grant money flowed into Academia, Academic interest in "Green Chemistry" started to increase dramatically. For example, in an August 1996 Chemical and Engineering News article (Breslow 1996, ref 17), ACS President Ronald Breslow described "The Greening of Chemistry," and recounted that "Several events make it clear that the chemical community, including our major chemical companies, has decided that we can and must be environmentally benign." Breslow described a visit to Eastman Chemical's plant in Kingsport Tennessee where chemicals were already being manufactured cleanly from coal.[32] Breslow mentioned the efforts of the Responsible Care program of the Chemical Manufacturer's Association. Breslow also described participating in a ceremony for the first Presidential Green Chemistry Challenge Awards, and a first Gordon Conference on "Environmentally Benign Organic Synthesis." Breslow concluded that "Although some thoughtful chemists have been concerned with these matters for a while, 1996 saw important firsts: the first Green Chemistry Challenge Awards and the first Gordon Conference devoted to this topic. There is no turning back."

In 1997 Joseph Breen retired from the EPA and co-founded (with Anastas) the non-profit Green Chemistry Institute that later (in 2000) merged into the American Chemical Society. Tragically, Joseph Breen died in 1999 of pancreatic cancer.

In 1998, Anastas and Warner's now famous book, "Green Chemistry: Theory and Practice" (ref 8) was published, with 10 Chapters. This author will now comment on some of those chapters, which began with some bits of history, then proceeded to abstractly describe at some length a variety of theories about "Green Chemistry," and then finally arrived at "Practice" and/or Examples in Chapter 9.

Introductory Chapter 1 briefly addressed some bits of the early history of the chemical industry and its historical problems with waste generation, dumping, and pollution, as well as the rise of the environmental movement and its negative reactions to the pollution. Chapter 1 then briefly mentions the "command and control" regulatory approach of many of the environmental statutes of the 1970s. Chapter 1 briefly mentioned the U.S. Pollution Prevention Act of 1990, but says almost nothing about similar activities in the rest of the World, or the many "Non-Waste Technology" and "Pollution Prevention" efforts that had preceded the U.S. 1990 Act. It did however remark on page 8 that "Green chemistry [6,7,8] which is discussed throughout this book, is a particular type of pollution prevention."

On page 9 the article remarked that "Historically, synthetic chemists, those who design new chemicals and their manufacturing processes, have not been particularly environmentally conscious." While that statement may have reasonably described the history of Academic synthetic organic chemistry, as seen above it was not a complete description of the work of the many industrial chemists in the oil refining, commodity chemical, and consumer products and some other chemically based industries in the twenty years preceding the book.

Chapter 2 of the Anastas / Warner 1998 book began by redefining "Green Chemistry" as compared to the prior Anastas publications. The first sentence of Chapter 2 did remark that "Green Chemistry environmentally benign chemical synthesis, alternative synthetic pathways for pollution prevention, benign by design; these phrases all essentially describe the same concept." This author agrees with that statement, and that "Green Chemistry" clearly was and still is "a particular type of pollution prevention." As described above, many examples of chemically oriented "Pollution Prevention" products and processes had been invented, developed, and commercialized in industry for more than twenty years before 1998.

This author disagrees with the second sentence of Chapter 2; "Green chemistry is the utilization of a set

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[32] See Murphy (2018) and the original references cited therein for a brief discussion of the details of the chemistry of Eastman Chemical's then new commercial (in 1983) and perfectly atom-economical process for producing acetic anhydride via catalytic carbonylation.

of principles…" The prior Anastas 1996 definition had stated that "Green Chemistry is the use of chemistry techniques and methodologies that reduce or eliminate the use or generation of [things] that are hazardous to human health or the environment." Many such "techniques and methodologies" had been in regular and repeated use for twenty prior years, but their many (mostly) industrial users didn't consider those already well-known techniques to be new and abstract "principals."[33]

Chapter 3 of the 1998 Anastas / Warner book, titled "Tools of Green Chemistry" abstractly expounded on six such "Principals", i.e., "Alternative feedstocks / starting materials," "Alternative reagents," "Alternative solvents," "Alternative product / target molecules," "Process Analytical Chemistry," and "Alternative catalysts." As seen above and below, chemists had been inventing, developing, and commercially using these "Alternative tools" for decades, but only one of them, the frequent prior uses of catalysis in industry, was explicitly acknowledged in the book.

Chapter 4, described at abstract length the twelve now famous "Principals of Green Chemistry," but did not discuss examples or cite the work of the many prior industrial inventors.

The following chapters 5-8 were written in similar abstract, theoretical, "professorial" styles. Only in Chapter 9 did the book reach or discuss anything resembling "Practice." A few specific examples of the prior work of others were described, but only publications from Academic journals, or from the EPA / OPPT were cited. There were no citations at all to patents or chemical trade journals.

9. THE "1990S GREEN CHEMISTRY" NARRATIVE DEVELOPS

During the Clinton Administration, the events at the EPA described above became the source of what this article terms "The 1990's Green Chemistry Narrative," namely that "Green Chemistry was conceived and developed at the EPA in the 1990s". That "1990s Green Chemistry Narrative" has since been repeated many, many times in the Academic literature and taught as fact to at least hundreds of thousands of students. This section will examine the origins, development, and validity of that narrative.

That "1990's Green Chemistry Narrative" was clearly stated in Anastas and Beach's 2009 paper entitled "Changing the Course of Chemistry" (see Anastas and Beach 2009, ref 12). The book was published just as Anastas was moving from Yale back to the EPA. The Anastas / Beach paper from the book was titled "Changing the Course of Chemistry" and was mainly focused on changing the way chemistry is taught at Universities. However, on page three a single paragraph / section of the 2009 article was entitled "Introduction of Green Chemistry as a Field." That paragraph is reproduced below.

> "**The idea of green chemistry was initially developed as a response to the Pollution Prevention Act of 1990**, which declared that U.S. national policy should eliminate pollution by improved design (including cost-effective changes in products, processes, use of raw materials, and recycling) instead of treatment and disposal. Although the U.S. Environmental Protection Agency (EPA) is known as a regulatory agency, it moved away from the "command and control" or "end of pipe" approach in implementing what would **eventually** be called its "green chemistry" program. By 1991, the EPA Office of Pollution Prevention and Toxics had launched a research grant program encouraging redesign of existing chemical products and processes to reduce impacts on human health and the environment. The EPA in partnership with the U.S. National Science Foundation (NSF) then proceeded to fund basic research in green chemistry in the early 1990s. The introduction of the annual Presidential Green Chemistry Challenge Awards in 1996 drew attention to both academic and industrial green chemistry success stories. **The Awards program and the technologies it highlights are now a cornerstone of the green chemistry educational curriculum**. The mid-to-late 1990s saw an increase in the number of international meetings devoted to green chemistry, such as the Gordon Research Conferences on Green Chemistry, and green chemistry networks developed in the United States, the United Kingdom, Spain, and Italy. **The 12 Principles of Green Chemistry were published in 1998, providing the new field with a clear set of guidelines for further development** (1). In 1999, the Royal Society of Chemistry launched its journal Green Chemistry. In the last 10 years, national networks have proliferated, special issues devoted to green chemistry have appeared in major journals, and green chemistry concepts have continued to gain traction. A clear sign of this was provided by the citation for the 2005 Nobel Prize for Chemistry awarded to Chauvin, Grubbs, and Schrock, which commended their work as "a great step forward for green chemistry" (5)." (bolding added)

The substance of that paragraph has been repeated and/or cited in the Academic / educational literature, and popular press an enormous number of times in the last ten years. But there is a major problem with this paragraph, and especially its first sentence, i.e. "The idea

[33] This author (and many of his colleagues) were some of those many prior "users" at the time.

of green chemistry was initially developed as a response to the Pollution Prevention Act of 1990…"

It is arguably (though not literally) true that the words "Green Chemistry" were first used in the current context at the EPA.[34] It is also arguably true that the developments, "principals," and new terminology that were adopted by the EPA in the 1990s were at least an important factor in the beginnings of "Green Chemistry," provided one defines "Green Chemistry" as an "Academic Field."

But if "Green Chemistry" is defined as the invention, development, and commercialization of practical Real-World scientific solutions to Real-World chemical / environmental /economic problems, Green Chemistry" was not invented or "developed" at the EPA, or in Academia. As we have seen above, many environmentally conscious compositions, and processes were purposefully conceived, invented, developed, and commercialized by many industrial inventors, in many countries, long before the 1990s. "Green Chemistry" (as a Real-World R&D activity) was actually an evolutionary product of (and/or re-naming) of the broader set of "Pollution Prevention" concepts that had been used, developed and commercialized by many industrial inventors and companies as early as the mid-1970s.[35] Those on-going "Pollution Prevention" concepts were adopted, and intentionally supported and encouraged by the EPA's Office of Pollution Prevention and Toxics in the late 1980s. The new "Green Chemistry" terminology and "Principals" were only popularized well after the Clinton Administration came to office in January 1993.

The Anastas / Warner book, and it's twelve "Principals of Green Chemistry" have since been very widely praised in the governmental, academic, and educational literature for many years, see for example the references cited footnote 3. Praise for the twelve "Design Principals of Green Chemistry" can also be currently found in multitudes of other prominent websites and public press documents, including the current website of the American Chemical Society[36] which references the Anastas / Warner book, and comments that the list of twelve Principals "outlines an early conception of what would make a greener chemical, process, or product." Anastas has been described many times in the popular press as "The Father of Green Chemistry," see for example the website of the American Association for the Advancement of Science (Limpinen 2010, ref 53), *Scientific American* (Kay 2012, ref 46, and Laber-Warren 2010, ref 51) and *Forbes* Magazine (Wolfe 2012, ref 88).

Praise for Anastas and Warner's 1998 book was not universal at the time however, and significant early criticism was leveled from a credible industrial perspective. In June 2000, Trevor Laird, the editor of the ACS Journal *Organic Process Research & Development* reviewed the paperback edition of Anastas & Warner's book (see Laird, 2000, ref 52). Laird criticized the book in the following two paragraphs:

> "The objective appears to be to introduce green chemistry concepts to chemists or chemistry students, to try to influence the way they practice chemistry. The theory and principals expounded in the text are sound enough, and few chemists would disagree with the aim to reduce pollution by appropriate design of chemicals and particularly by the appropriate design of chemicals and particularly by the design of environmentally friendly processes. The "practice" section of the book is woefully inadequate however, reflecting the author's lack of experience of industrial chemistry in the real world. For example, there is no real discussion of the importance for green chemistry of introducing convergence into a synthetic sequence to reduce the overall weight of starting materials, reagents, solvents etc., to produce a kilogram of end product."

This author agrees with Laird that at the time "few chemists would disagree with the aim to reduce pollution by appropriate design of chemicals and particularly by the appropriate design of chemicals and particularly by the design of environmentally friendly processes." As shown above, many industrial chemists and engineers in many companies and in many countries had been consciously and actively inventing, developing and commercializing environmentally friendly and commercially viable processes for decades prior to the 1990s.

Laird then criticized the view of the book that "solvents are always bad," and mentioned the problems that can be generated by use of water as a solvent. Laird then further commented as follows:

> "There is a naivety in the book that indicates that the authors are unaware of how industry has changed in the past few years. This is reflected in the reference list, there are 39 references, and 10 of these refer to papers in a publication from the Office of Pollution Prevention and Toxics. These references are mostly to U.S. based research and do not reflect work done in Europe by, for example, the groups at York or Delft, or to important work being carried out in industry (e.g. Hoechst) which has been pub-

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[34] The words "Green Chemistry" were first literally used in a slightly different context by Clive Cathcart in a 1990 *Chemistry and Industry* article about environmental issues in the Irish chemical industry, see Cathcart 1990, ref 20).

[35] A little noticed sentence in Anastas and Warner 2009, in Section 1.2.5, is that "Green Chemistry, which is discussed throughout this book, is a particular type of pollution prevention."

[36] See https://www.acs.org/content/acs/en/greenchemistry/principles/12-principles-of-green-chemistry.html

lished in the last year… This is an opportunity missed … and cannot be recommended."

The Outokumpu copper smelting process mentioned above and commercialized in Finland in 1949 was an example of early European efforts to invent and commercialize environmentally friendly chemical processes. The catalytic air oxidation of ethylene to ethylene oxide was invented in France in the 1930s and subsequently commercialized all over the world. Another such example was the Wacker process for oxidizing ethylene to acetaldehyde (as a step in a process for making acetic acid and eventually vinyl acetate) that was invented in Germany in 1956 and first published in patent form in 1959. Even if the objective was not expressly environmental at the time (see Jira 2009, ref 45), the Wacker process was perfectly atom economical in theory, extremely efficient in practice, and was carried out in water solvent in the presence of catalysts in 1956! As we have seen, many other such environmentally friendly inventions and processes appeared in the oil refining, commodity chemicals, and consumer products segments of international chemical industries throughout the 1970s and 1980s.

Furthermore, none of the twelve "Principals of Green Chemistry" were actually new as of the early 1990s, and they were already in regular commercial use.

1. **Pollution Prevention** – Prevention of Waste / Pollution was the explicit name and objective of the "Pollution Prevention" concepts and work that began at 3M and in Europe in the mid-1970's and spread widely during the 1980s. Moreover, the first Presidential Green Chemistry Award, in 1996, to Dow Chemical Company for the use of carbon dioxide to replace ozone depleting chlorofluorocarbons as blowing agents in polystyrene foam sheet manufacturing, was based on U.S. Patent No. 5,250,577 to Gary C. Welsh (an engineer!). That patent application was filed August 2, 1989, before the passage of the Pollution Prevention Act of 1990, and almost seven years before the first Presidential Green Chemistry Award.
2. **Atom Economy** - Earlier known good efficiency resulting in low waste production, many examples of excellent "atom economy" had been achieved by use of catalysis in the oil refining industry (as described above) and in the commodity chemicals industries (see Sheldon (1992) and Murphy (2018). Notable examples were the highly atom economical air oxidation of ethylene to ethylene oxide over a heterogeneous silver catalyst by LeFort (See U.S. Patent No. 1,998,878 issued in April 1935 based on an original French patent application filed March 22, 1932) and the Wacker air oxidation of ethylene to acetaldehyde using a homogeneous Pd / Cu / HCl catalyst in water solvent in Germany in 1957 (See Jira 2009, ref 45). The BHC Ibuprofen process that was first published as a patent publication in 1988 was a highly atom economical three-step catalytic process for making a bulk pharmaceutical that replaced an original six-step process with many waste producing steps and poor atom economy with three highly atom economical catalytic steps whose only byproduct was acetic acid.
3. **Less Hazardous Chemical Synthesis** – As described above, as of 1991, replacement of HF as a catalyst for oil refinery alkylation reactions had long been a "Holy Grail" of research in the oil refinery industry. U.S. Patent 5,284,990 to J.R. Peterson and J.B. Scott, assigned to Stratco Inc., filed July 16, 1992, describes an example of such safety-oriented industrial research, i.e. a method for converting a commercial refinery alkylation unit from HF to H_2SO_4 as a catalyst in order to increase process safety.
4. **Designing Safer Chemicals** – It had been routine practice in the pharmaceutical industry for decades prior to the 1990s to design and test pharmaceutical target molecules for low toxicity and increased safety. Safety was also routinely considered in other parts of the industry whenever new products and processes were introduced. 3M, and the paints and coatings, and consumer products industry segments were routinely involved in many such successful efforts.
5. **Safer Solvents** – Many industrial processes and products over decades have utilized the safest of solvents, water. The Wacker Process invented in the 1950s (for air oxidizing ethylene to make acetaldehyde) used water as a solvent, see Jiri 2009 and Eckert (2012, ref 26). Furthermore, there were many successful adaptations of existing processes for applying adhesives in aqueous solution to substrates in in the 1970s and 1980s at companies like 3M. Successful switches toward water as a solvent for paints and coatings occurred at many companies in the 1980s.
6. **Design for Energy Efficiency** – Design for energy efficiency was a very common engineering approach in the chemical industry for decades before the 1990's. The installation of co-generation units to reclaim low grade waste heat from chemical plants / refineries was common during the 1980s. Many processes in the oil and commodity chemicals industry were intentionally solvent-less, to avoid the energy

and equipment costs associated with separating desired products from solvents and/or recycling the solvents (usually by distillation). Many catalytic processes were carried out in the vapor phase over heterogeneous catalysts and avoided the use or recycle of liquid organic solvents altogether. Some homogeneous processes in the commodity chemical industry used the product as "solvent", and thus avoided the energy (and economic) penalties associated with use of solvents. Examples include methanol carbonylation to make acetic acid, and olefin hydroformylation to make aldehydes, both of which processes date back to the 1970s, see Murphy 2018.

7. **Use of Renewable Feedstocks** – Many chemical products were made from renewable resources before World War II (natural rubber and cellulose acetate[37] for example) but were later supplanted after World War II by alternative products that could be produced much more economically (and sometimes with lower waste and energy usage) via petrochemical processes. Nevertheless, the oil and commodity chemicals companies regularly conducted research projects to evaluate whether natural feedstocks could potentially compete. To cite one example known to this author, at the time of the invention of the BHC Ibuprofen process (1984-1986), Celanese had a small biotech research group in their Corpus Christi Texas laboratories evaluating bio-tech processes for making commodity products such as acetic acid and 1,4-butanediol. Those efforts proved futile however (primarily because of the non-competitive costs of isolating those compounds from dilute aqueous solutions). The biotechnologists involved were spun out of Celanese and into a start-up company "Celgene," which has since developed into a major pharmaceutical company.
8. **Reduce Derivatives** – Use of protecting groups and/or derivatives has been very uncommon in the oil refining, commodity chemical, and consumer products industries at any point in time, because doing so is both expensive and un-desirable. Use of protecting groups is a creature of traditional poorly specific organic synthetic methods and/or multi-step pharmaceutical synthesis, and even then, is (as a matter of common sense) used only when necessary.
9. **Catalysis** – Heterogeneous catalysis was invented, developed and extensively used in very many commercial applications in the oil refining and commodity chemical industries after World War II. As more selective homogeneous catalysts were invented (mostly in industry in the 1960s-1980s), their commercial use also became common in the commodity chemical industry. Major examples include the Wacker process for air oxidation of ethylene to acetaldehyde, olefin hydroformylation to produce aldehydes, methanol carbonylation to produce acetic acid, methyl acetate carbonylation to produce acetic anhydride, and the Knowles/Monsanto's asymmetric synthesis of L-Dopa via asymmetric hydrogenation.[38]
10. **Design for Degradation** – Most organic small / soluble molecules are biodegradable to some degree, but many petrochemically derived polymers (such as polyethylene, polypropylene, polystyrene, nylons, polyesters, etc.) are not adequately biodegradable. Nevertheless, other petrochemically based biodegradable polymers had been in widespread commercial use for many decades, such as polyacrylic acids, polyacetals, derivatized celluloses, poly-vinyl acetate, and poly-vinyl alcohol. Moreover, beginning in the 1980s, there were many efforts to develop chemical depolymerizations of some of the non-bio-degradable polymers back to their recyclable monomers, such as polyesters, nylons, and polystyrene.
11. **Pollution Prevention** – (Originally termed "Analytical Methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances"). Real-time monitoring and control of chemical processes had been used in industry for decades prior to the 1990s. The use of such process monitoring for pollution prevention was the principal focus of Breen and Delarco's 1992 ACS Symposium Series volume 508. Papers from Monsanto (Ford et, al. 1992 ref 32), 3M (Eldridge et. al., 1992, ref 27), Du Pont (Fleming et. al. 1992, ref 31), Dow Chemical (Henslee et. al. 1992, ref 37), Amoco (Baughman 1992, ref 14) and Microsensor Systems Inc. (Wohltgen et. al. 1992, ref 86) all described various problems and solutions for on-line analysis and control of Real-World chemical processes in connection

[37] Cellulose acetate was first synthesized in 1865 and was first commercialized about 1910 by Camile and Henri Dreyfus, for producing motion picture films and for coating fabrics used to make aircraft wings and fusilages in those times. See https://en.wikipedia.org/wiki/Cellulose_acetate

[38] See "Profile of William S. Knowles, *Proceedings of the National Academy of Sciences*, November 22, 2005, 102 (47) 16913-16915; https://doi.org/10.1073/pnas.0507546102 . It is worth noting that one of Knowles early projects at Monsanto was a chemical synthesis of vanillin, which was superseded commercially after lignin was identified as a source of vanillin, which was a precursor in the catalytic asymmetric synthesis of L-Dopa. See also U.S. Patent No. 4,005,127 to Knowles, W.S., Sabacky, M.J., and Vineyard, B.D., assigned to Monsanto Company, first filed March 08, 1971 and granted January 25, 1977.

with pollution prevention efforts. Furthermore, several additional papers were published by academic authors from the Center for Process Analytical Chemistry at the University of Washington, which had been established in 1984 as a consortium of over 46 corporate sponsors and four Federal Agency and National Laboratories sponsors, to address multidisciplinary challenges in process analysis and control through fundamental and directed academic research (see http://www.apl.washington.edu/project/project.php?id=cpac). Clearly, process analysis and control research for pollution prevention was well established long before the 1990s.

12. **Safer Chemistry for Accident Prevention** – As already described, by the early 1990s, replacement of HF for alkylation catalysis had already been a "Holy Grail" of refinery research for many years, and a switch from HF to H_2SO_4 had already begun in some commercial refineries.

Furthermore, many industrial scientists and engineers had previously utilized various combinations of those already well known "principals" to make environmentally friendly Real-World processes. The commercialized BHC Ibuprofen process directly exemplified six of the twelve "Principals of Green Chemistry" (i.e. prevention of waste rather than treatment or cleanup, Atom Economy, minimization of solvents, energy efficiency, avoidance of protecting groups, and catalysis). Two more of the "Principals of Green Chemistry" had been utilized by the inventors of ibuprofen as a prescription drug at Boots, (i.e. designing safer chemicals and designing for degradation). Two of the twelve "Principals of Green Chemistry", (i.e. use of renewable feedstocks and Real Time analysis for Pollution Prevention) were of little relevance to that particular problem.

This author's conception of a generic synthetic scheme for "profen" drugs (more specifically including ibuprofen) in 1984 was later developed by an interdisciplinary team and commercialized in 1992. Sheldon (in 1992) speculated (without having communicated with this author or his team-mates) that that the BHC process had been the result of a "catalytic retrosynthetic analysis." He was very close to right, see Murphy 2018. At the time of conception in 1984 this author viewed the BHC process idea(s) (generated via a retrosynthetic analysis using catalytic reactions) as a set of promising potential outcomes that could result from a combination of known techniques selected from a much larger set of known techniques and/or "tools" well known to both industrial and Academic chemists and engineers at the time. At the time of conception that generic set of ideas seemed to have the potential to give good "Quality" (i.e. unexpectedly good potential outcomes), but it was more than a little uncertain and unpredictable at the time of conception. Fortunately the choices narrowed rapidly as a wide variety of facts and information were gathered and then (successful) experimentation and development began and progressed. Empirical FACTS and information provided most of the "guidance", not any "principal" that may have been unconsciously involved earlier. Viewed now retroactively, should "catalytic retrosynthetic analysis" now be declared to be another new Green Chemical "principal"? This "chemist turned lawyer" could easily and honestly argue many sides of such questions now, but certainly didn't consider such questions at the time, or for years afterwards.

This author also agrees with Laird's comments (in 2000) that "The 'practice' section of the book is woefully inadequate however, reflecting the author's lack of experience of industrial chemistry in the real world," and "There is a naivety in the book that indicates that the authors are unaware of how industry has changed in the past few years." There is also a similar naivety in the Anastas / Beach statement in 2009 that the twelve "Principals" provided "the new field with a clear set of guidelines for further development." If the "new field" is defined to be Academic research designed to produce Academic papers, and/or for teaching purposes, then perhaps the "guidance" provided by the "Principals" have had value, a question this author will leave to Academics. In Academic chemistry, the primary customers are other Academic chemists.

But if the "field" of "Green Chemistry" is the Real-World conception, invention, development, and commercialization of new Real-World products and processes to address the Real-World needs of people and ecological problems, then the "Principals" were and still are woefully narrow, theoretical, and inadequate. The "Principals" had little or nothing to say about the Vast and inherently inter-disciplinary nature of Real-World industrial chemical processes, and the economic, business, and customer facets of Real-World chemical research, or the tremendous relevance and importance of Engineering, Biology, competitor technology, economics and business positions, customer preferences, and/or or the legal/regulatory issues. Few of those multi-disciplinary issues were addressed by the twelve "Principals" but **must** be addressed to bring a new and/or improved chemical product or process to the Real-World markets. The attendees of the 1976 ECE seminar understood that!

Furthermore, experienced and competent industrial chemists and engineers are typically employed and paid to be predominantly focused on products and processes that are relevant to that company's business interests, not to pursue abstract "principals". A Real-World industrial chemist ultimately has a wide variety of customers to satisfy, including chemical, engineering, and/or biological peers, business managers, regulators, and ultimately customers who will voluntarily buy and pay for the product, which certainly encourages consideration of many broader perspectives when planning R&D work.

That product / process focus provides far more Real World "guidance" to an Industrial chemist than any of the twelve abstract "Principals"! One of the keys to this author's 1984 conception of the BHC Ibuprofen Process was an unexpected encounter with Prof. John Stille's comment at a conference that identified ibuprofen as a potentially commercially viable **product** molecule. As this author commented regarding the initiation of experimental work for the BHC Ibuprofen Process, "It is important to note that in a Real-World industrial laboratory, as compared to an academic setting, even this exploratory work would very likely not have been supported at all without an identifiable commercial target and/or objective." See Murphy 2018.

This author also seconds another of Laird's complaints about the Anastas and Warner book, that the "naivety" "is reflected in the reference list." Indeed! The Anastas and Warner book all but ignored the large amount of work (some of which is documented above) that had already been carried out internationally, and especially in industry. While the Anastas / Warner book, Chapter 9 ("Examples of Green Chemistry"), refers to multiple academic authors, it doesn't mention the names any industrial inventors, or reference their original publications in trade journals and/or patents. The Anastas / Warner book only rarely mentions even the names of companies from the very few industrial examples it did cite.

From a more current perspective, close examination of the published summaries of the EPA / ACS's Presidential Green Chemistry Awards, from their beginning in 1996 up to the present time, shows that while the names of Academic principal investigators **always** get acknowledged in the Award descriptions, **none** of the names of industrial inventors, or their "publications" are ever disclosed or referenced. It is very hard to understand or justify this rather glaring omission, especially since many at the EPA (Breen and Freeman et. al.) and at ACS (such as Breslow) had been very clearly aware of the many "Pollution Prevention" efforts and inventions that had occurred in worldwide industry in the decades prior to the 1990s.

From an even broader and more current perspective, examination of the over 25 years of international Academic literature related to "Green Chemistry" shows that while the citation of Academic authors in Academic "Green Chemical" journals is frequent, it is rare that the names of industrial inventors, or their publications (such as in patents or trade journals) get a mention, let alone a proper reference. This author could cite many examples, but instead challenges the readers to investigate this point on their own and make up their own minds. How can this widespread failure of Academic or governmental "Green" authors to cite the work, patents, and names of much earlier Real-World industrial "Green" inventors possibly be explained, much less justified??

One last point. Linthorst (2010) and Anastas (2012) presented graphs of the frequency of use of the term "Green Chemistry" over time to justify the contention that "Green Chemistry" began in the 1990s. Those graphs would have looked very differently if the term "Pollution Prevention" had been included among the search terms used. Since EPA's Office of Pollution Prevention and Toxics included the words "Pollution Prevention" in its very name, it is not easy to understand why those words were not included in the search terms used!

10. THE "1990S GREEN CHEMISTRY" NARRATIVE − A "SOVIET-HARVARD ILLUSION"

The contention that "Green Chemistry originated in the 1990s at the EPA" is an example of an oversimplified and/or deceptive "narrative." Wall Street trader turned philosopher Nassim Nicholas Taleb has recently had much to say against reliance on such narratives, in a series of widely acclaimed and best-selling books, the best known of which are "The Black Swan – The Impact of the Highly Improbable" (Taleb 2007, 2010, ref 78) and "Antifragile – Things That Gain From Disorder" (Taleb 2012, ref 79). A major theme of Taleb's books is how we, especially if we consider ourselves "experts", focus too much on the things we do know, and often deceive ourselves and others into ignoring the very many things we don't and can't know, and the extremely important role of those unexpected and unpredictable events in human, economic and even scientific affairs.

In Chapter 6 of "The Black Swan", Taleb discussed one of the ways by which we deceive ourselves, "The Narrative Fallacy." Taleb explains that "We like stories, we like to summarize, and we like to simplify, i.e., to reduce the dimension of matters… The fallacy is associated with our vulnerability to overinterpretation and our predilection for compact stories over raw truths. It severely distorts our mental representation of the world; it is particularly acute when it comes to the rare event."[39]

[39] It is disheartening to realize that such "narratives" seem to be the heart and soul of our politics.

The "1990s Green Chemistry" account of the beginnings of "Green Chemistry" is just such a narrative. The popularization of "Green Chemistry" in the U.S. government and in Academia during the late 1990s and afterwards was certainly inspired by the actions at EPA. But how to account for or justify the obvious and continuing Academic / governmental blindness toward acknowledging the existence and importance of very many long prior Real-World "green" activities in industry and/or in many other countries? Application of a bit of "legal" thinking on such matters seems natural to this chemist / lawyer. Unconscious blindness and/or honest ignorance about industrial work and realities can be understandable and forgivable in complex and unpredictable R&D situations. But knowing and/or willful refusal to either consider or cite industrial work or workers seems very troubling.

Taleb has described a possible explanation; "The Soviet-Harvard Illusion – (lecturing birds on flying and believing that the lecture is the cause of the flying)." See Taleb 2012, Chapter 13. Taleb also severely criticizes "top-down" central planning approaches (exemplified by the former Soviet Union, and which regularly originate in Academia) wherein self-described "experts" rely far too much on highly incomplete knowledge and fallible human logic, and studiously ignore the role and importance of complex, unexpected, and unpredictable events.

Taleb explains that the "Soviet-Harvard Illusion" originates from a "class of causal illusions called *epiphenomena*."[40] Expanding his bird metaphor, Taleb writes that:

> "Think of the following event: A collection of hieratic persons (from Harvard or some such place) lecture birds on how to fly…. The bird flies. Wonderful confirmation! They rush to the Department of Ornithology to write books, articles, and reports stating that the bird has obeyed them, an impeccable causal inference. The Harvard Department of Ornithology is now indispensable for bird flying. It will get government research funds for its contribution…
> It also happens that birds write no such papers and books… so we never get their side of the story. Meanwhile, the priests keep broadcasting theirs to the new generation of humans who are completely unaware of the conditions of the pre-Harvard lecturing days…. Nobody has any incentive to look at the number of birds that fly without such help from the great scientific establishment."
> "So the illusion grows and grows, with government funding, tax dollars, and swelling (and self-feeding) bureaucracies in Washington all devoted to helping birds fly better."

[40] See the Wikipedia article "Epiphenomenon" at https://en.wikipedia.org/wiki/Epiphenomenon

Talab's bird metaphor was a parody of some unfortunately general behaviors in governments and Academia. But Taleb's bird parody very well describes the "1990s Green Chemistry Narrative." Industrial chemical birds had been flying, in many shades of green, all over the world, at least as early as the mid-1970s. They published a few generic descriptions of their ideas, motivations, and philosophy scattered over a variety of multi-disciplinary venues. But they did not publish much about the technical details of their methods and inventions in the peer-reviewed academic journals that academic chemists typically read. As a result, the Real-World accomplishments of those early Industrial green birds were, and often continue to be ignored by many in the U.S. government and Academics.

When EPA and its Office of Pollution Prevention and Toxics was founded in the late 1980s and began to encourage the already on-going industrial "Pollution Prevention" efforts, the progress continued and even accelerated. When the Clinton Administration's EPA changed the "Pollution Prevention" terminology to "Green Chemistry," and government grant money began flowing towards Academia, the "Academic Field" of Green Chemistry and the "1990s Green Chemistry Narrative" were quickly created. In short order the EPA and too many "Green Chemistry" Academics began to publish Academic papers and then lecture both industry and new generations of University students about the "Principals of Green Chemistry" they theorized had caused the "Green Chemistry" progress. The government funding, tax dollars, bureaucracies, and lectures have indeed swollen ever since.[41]

Taleb has an alter-ego for the "Soviet-Harvard Illusion" which he terms "naive rationalism" which is "Thinking that the reasons for things are, by default, accessible to university buildings."[42] Taleb contends that "naive rationalism" overestimates the necessity and importance of academic knowledge in human affairs, which remain highly unpredictable. Taleb also accuses many Academics and government officials of dramatically over-emphasizing the importance of academic theory in both scientific / technical research and in the resulting economic outcomes, by habitually thinking in terms the "Bacon linear model" of R&D:

Academia → Applied Science and Technology → Practice

Taleb asserts there have been relatively few Real-World examples of the "Bacon linear model." The devel-

[41] See Anastas 2012 ref 5, "Fundamental Changes to EPA's Research Enterprise: The Path Forward"
[42] See Taleb 2012 ref 78, glossary.

opment of atomic energy and/or nuclear weapons based on Einstein's relativity theories is however one well known example. There have also certainly been other important inventions that originated in Academia, especially in academic biotechnology (such as the discovery of DNA, the polymerase chain reaction, CRISPR, and immunology) that have gone on to spawn very important downstream applications and Real-World practice.

But Taleb accuses many Academics and government officials of largely ignoring and/or denigrating the uncodifiable, complex, iterative, intuitive, and experience-based type of interdisciplinary knowledge and research that he asserts comes from "random tinkering." But Taleb's "random tinkering" isn't **completely** random. He illustrates "random tinkering" with the example of a Real-World treasure hunter for shipwrecks, who conducts a high-risk but high-reward business. The treasure hunter uses the incomplete knowledge he has to assign grids to be searched by estimated probability of success and the probability of a high payoff. The treasure hunter then searches each high probability grid completely before moving on to another lower probability grid. Such a strategy uses available prior (but incomplete) knowledge, but also considers the importance of uncertainty and unpredictability. Such "random tinkering" strategies avoid searches with low probability of success and payoffs and focuses its effort in areas of high estimated probabilities of success **and** high potential payoffs (or at least clear relevance to existing businesses). Surely readers can recognize that such a "random tinkering" approach can be highly relevant to both Academic and Real-World Industrial R&D, and Green Chemistry as well! As Louis Pasteur once said, "chance favors the prepared mind."

Taleb asserts that a great deal of Real-World R&D and/or change / evolution in commercial / economic practice occurs via very complex, iterative, evolutionary processes similar to those represented by the schematics below:

Random Tinkering (Anti-fragile) → Heuristics (technology) → Practice and Apprenticeship →…
Random Tinkering (Anti-fragile) → Heuristics (technology) → Practice and Apprenticeship →…

Many variations of such complex evolutionary processes typically go on in parallel, individually addressing different local problems, products, or processes or sub-processes, but there is also some communication between the many scientists and engineers carrying out those semi-independent parallel R&D processes. Formal educations and academic / scientific theories certainly play a significant role in these sorts of complex Real-World iterative and evolutionary processes, but many other factors are also involved and often introduce not very predictable outcomes that can nevertheless be very important, technically, environmentally, and economically. What emerges as a holistic outcome from the interactions of many such complex parallel iterative and evolutionary processes and sub-processes is certainly non-linear, somewhat unpredictable, and potentially "chaotic". The entire concept of causation becomes murky in view of the unpredictability of the holistic final outcomes produced by such Vastly complex evolutionary processes.[43]

While the "Academic Field" of Green Chemistry may have originated in the 1990s and/or from the abstract "Principals of Green Chemistry" that were published in 1998, Taleb's "Random Tinkering" model of scientific / technical R&D is much more consistent with the much earlier evolution of Real-World Industrial Green Chemical inventions documented above, and much of the Industrial R&D work that continues to this day. This author contends that Real-World Industrial "Green Chemistry" emerged as a holistic final outcome from an extremely varied and complex set of parallel evolutionary "random tinkering" sub-processes that began about the time of World War II, and that evolutionary process accelerated in the 1970s (See also Murphy 2018, Murphy 2020). That overall evolutionary process was the product of very complex interactions of very many internal and external events, carried out by many human investigators from multiple disciplines and countries, who were individually driven by many different goals, motivations, influences and input factors, including customer / societal needs and desires, economics, the environment, the legal / statutory / regulatory pressures, as well as the constantly evolving state of the underlying sciences of Chemistry, Biology, and Engineering, over decades. Many of the resulting individual inventions were also the direct product of individual human creativity, thought, and logic, as aided by intercommunications between the investigators, as well as the constraints of the laws of Nature, local circumstances, and elements of chance. Soviet-Harvard illusions and lectures could never even hope to reasonably account for or predict such Vastly complex phenomena and evolutionary developments.

There was a fairly recent challenge to EPA's claims for credit for the environmental outcomes produced by

[43] See Chamberlin (2009, ref 21), Holland (2014, ref 40), and Dennett (2017, ref 23). See also Murphy (2018) and Murphy (2020, ref 60) for thoughts about how W.Edwards Deming's "PDCA Circles," which are based on the Scientific Method, can be continuously iterated to incorporate both reductionist and holistic ideas and perspectives, to solve Real-World problems.

"Green Chemistry".[44] Up to 2015, EPA had been including in its internal EPA performance metrics tracking system the credit for the international pollution savings reported by the winners of the Presidential Green Chemistry Challenge Awards. The EPA's Inspector General successfully challenged the EPA claims to credit for those pollution reductions, on the primarily legalistic grounds that the pollution reductions reported by the Award winners were "unverified" and therefore were not "transparent"[45] and therefore should not be included in EPA's internal credits. But in its initial 2015 report[46] the Inspector General had also noted that it is "inappropriate for the EPA to take credit for the results of activities performed by predominantly non-EPA parties." That causation-related objection seems even more valid given that many of the industrial Pollution Prevention evolutionary processes and results began **long** before the EPA activities and programs had even begun.

But as a counterpoint, the 2015 Inspector General's report also noted that the EPA's Presidential Green Chemistry Awards program's budget for fiscal 2015 was "between $80,000 and $90,000," but had "lacked Presidential support" during a number of the prior years, though that support was finally renewed by the White House Office of Science and Technology Policy in July 2015. It is nevertheless disheartening to recognize that the EPA's Inspector General had expended so much time, money, and bureaucracy in the name of "investigating" an obviously beneficial but also very small EPA expenditure of $80,000-$90,000 a year, for public recognition of new Green inventions (and **some** of the inventors) provided by the Presidential Green Chemistry Awards program, regardless of whether or not the EPA actually caused the inventions being recognized. Such seems to be the state of the underlying legal / bureaucratic culture at the EPA…

Yet the "1990s Green Chemistry Narrative" has widely propagated though much of the peer-reviewed scientific literature, university classrooms, and even the popular press over the past 20 years, see the references of footnote 3 for only a few of many examples.

The "1990s Green Chemistry Narrative" has also penetrated the Academic social sciences ("Science and Technology Studies") and the business schools and their Academic literature. See for example Woodhouse and Breyman (2005, ref 87) and Howard-Grenville et. al. (2017, ref 41). The Howard-Grenville paper was authored by three professors of business administration from major universities and two university chemistry education instructors. That *Administrative Science Quarterly* paper was entitled "If Chemist's Don't Do It, Who Is Going To? Occupational Change and the Emergence of Green Chemistry." The abstract begins as follows; "**We investigate the emergence and growth of "green chemistry**" – **an effort by chemists to encourage other chemists** to reduce the health, safety, and environmental impacts of chemical products and processes – **to explore how occupational members**, **absent external triggers for change**, **influence how their peers do their work**." (bolding added) Not one of the authors has done any Green Chemical research.

In the body of the article, the authors asserted that "green chemistry emerged in the 1990s when a small group of chemists began advocating new practices that would enable chemists in academia and industry to reduce the environmental, health, and safety impacts of their work". The article also stated that "green chemistry… emerged as a grassroots effort by chemists to influence their peers to alter their work in accordance with the 12 principals of green chemistry listed in Table 1." These statements were a clear re-statement of the core of the "1990s Green Chemistry Narrative".

The authors had begun by searching "peer-reviewed research publications that reported the science of green chemistry… with 10 keywords selected by chemists on our author team." They identified 6,394 scientific publications that included the term "green chemistry" and/or employed at least one of the "Principals." There is no mention of any search of chemical industry trade journals, or patents, at any point in time. As a result, Howard-Grenville et. al, like so many other Academics before them, remained unaware of the Real-World "Pollution Prevention" industrial efforts that had preceded the 1990's by decades. If the authors had also searched patents, chemical trade journals, or even the consumer press, or included the key words "Pollution Prevention" in their search strategies, virtually all their conclusions would have needed to be dramatically different. They would have encountered the many technical, legal, economic, and cultural "external triggers for change" that did in fact drive the development of "Pollution Prevention," and then later "Green Chemistry," in worldwide industry.

After their initial review of the Academic literature, the authors informally interviewed 36 individual

[44] See the U.S. EPA's Office of the Inspector General's Report, 18-P-0222 dated July 20, 2018 entitled "EPA Completed OIG Recommendations for the Presidential Green Chemistry Challenge Awards Program Lacks Controls over Use of Unverified Results", available at https://www.epa.gov/office-inspector-general/report-epas-presidential-green-chemistry-challenge-awards-program-lacks

[45] See the section below discussing the nature and importance of trade secrets in modern industrial practice.

[46] EPA Inspector General's Report #15-P-0279, September 15, 2015, see https://www.epa.gov/sites/production/files/2015-09/documents/20150915-15-p-0279.pdf

but unidentified Green Chemists "recruited from professional networks of the chemists of our author team, who knew Green Chemistry advocates." They noted that "Our sampling approach was theoretical rather than representative." This author was immediately reminded of Eleuterio's quotation of Sherlock Holmes (see Eleuterio 1991 ref 29), who fictionally cautioned that "it is a capital mistake, my dear Watson, to theorize before one has data. Insensibly one begins to twist facts to suit theories instead of theories to suit the facts."

There were very long "naïvely rationalistic" discussions / interpretations of the interviews and interviewees that essentially presumed the reasons for the "emergence" of Green Chemistry was a strong function of three mental / occupational "frames" that the "Green Chemistry advocates" had presumably used during the "emergence" of Green Chemistry. They discussed a "normalizing frame" wherein "advocates presented green chemistry as consistent with mainstream chemistry, associating it with core norms around discovery, design, and optimization." They discussed a "Moralizing Frame" that "presented green chemistry as an ethical imperative…emphasizing chemist's opportunity to deliver social benefits." Lastly the authors described a "Pragmatizing Frame" "presenting Green Chemistry as a tool that could help chemists gain leverage on problems they encountered in their work." There were discussions of conflicts between the "occupational frames" of the "Green Chemists." None of that discussion contemplated the possibility that "Green Chemistry" had actually existed in the Real-World long before any of the twelve "Principals of Green Chemistry" were published, or any of the "Green Chemistry advocates" interviewed had become either Green Chemists or "advocates".

The authors did note that "green chemistry advocates still lament that many of their peers fail to align with the change effort" of the Moralists, seemingly unaware how long environmental consciousness has been a standard part of industrial culture and practice in some industrial segments for so long. Other than multiple references to the "12 Principals of Green Chemistry" as motivation and/or "guidance" for the way that Green Chemists allegedly "think," and then lecture their peers as to **what to think**, the article doesn't contain a word about what chemists and engineers actually **DO** in their Green Chemical technical work, or how they decide what to **DO**.

There were telling comments on the perspectives of some of the Academic green chemists interviewed. There was a comment from an Academic and alleged "early advocate" of Green Chemistry that the "core content of chemistry curricula is "what [a chemist] learned from their professor and they are passing on to their students". Another explained "This was something that could be taught in a chemistry class." There was very little description of industrial perspectives on or about Green Chemistry, or the extremely complex experience / practice-based types of knowledge that come from industrial R&D and/or industrial inventors, or that industrial scientists and industrial engineers often use. There was however a telling comment from an unidentified industrial chemist who commented "There is an elitism particularly among the academic community. [Chemists say] 'We do basic research…we don't do applied stuff,' [and] Green Chemistry I guess is for those folks who can't come up with better ideas." There was no recognition of or mention of the many "external triggers for change" that drove the early Real-World industrial evolution of Green Chemistry documented above.

In this author's experience in the 30+ years since becoming an inventor of one of the earlier commonly recognized "Green Chemical" inventions, and later a practicing chemical patent attorney, virtually everyone in industry has for decades now recognized that "Greener is better." Almost everyone in in modern industry is motivated at one level or another to at least contemplate "Greener" processes. But not nearly enough people (including many modern "Green Chemists") really know what to DO. Virtue signaling about identity and good intent and/or motivations is a very poor substitute for knowing **how** to figure out what to DO. This author's prior papers passed along some of W. Edward Deming's ideas about **how** to figure out what to DO.

Educating students about **how** to think, or about ecological issues is a good thing. Lecturing professional "peers" about **what to think** is quite another thing. From this author's perspective, the paper of Howard-Granville et. al. (and too many Academic Green Chemistry papers as well) is filled with a veritable bonfire of Soviet – Harvard illusions, delusions, lectures, and vanities, not to mention naïve rationalism. It is terrifying to think that such obvious Orwellian group-think is not only propagating as dogma amongst many chemists, University faculties, and new chemistry students, but is likely even being lectured and propagated as fact and "inspiration" to new MBA's who will soon be making major decisions for the corporations of the world.

11. THE IMPORTANCE OF TRADE SECRETS AND "UNREAD" PATENTS TO GREEN CHEMISTRY

Taleb's books focus on unknown, unexpected and unpredictable events in our lives and society, and our tendency to ignore and/or underestimate their importance. As he notes in his Prologue, "Black Swan logic makes *what you don't know* far more relevant than what you do know." Taleb mentions a friend and writer (Umberto Eco) who maintains a large personal library, containing many "unread books," which he places very high value on, because they represent to him the many things he does not know that can cause many phenomena, expected or unexpected. Taleb asserts that "a library should contain as much of what you do not know as your financial means … allow you to put there."

Self-styled "Green Chemists" in government and Academia would do well to more thoroughly consider what they don't know, especially about what goes on in Real-World Industry. Far too many Academic and Governmental Green Chemists don't know or understand much about Real-World processes, products, and R&D, and their complexity and unexpected facets, in part because they don't appreciate the importance of industrial trade secrets, and they don't often read patents.

Many of the interdisciplinary technical and economic / business details of Real-World industrial processes for making Real-World products are very important to the final desired outcomes but are often withheld from public knowledge because information about them is held in the form of trade secrets. Trade secrets "comprise formulas, practices, processes, designs, instruments, patterns, or compilations of information that have inherent economic value because they are not generally known or readily ascertainable by others, and which the owner takes reasonable measures to keep secret."[47] Unlike patents, trade secret protections can last (at least in theory) as long as the information is kept secret.

3M was an early example of the use of trade secrets in a Green Chemical context. In the 1970s and 1980s 3M repeatedly publicly announced their intent to improve both their environmental and economic performance by means of generically described "Pollution Prevention" strategies. But 3M kept most of the hard-earned technical chemical and engineering details regarding their many consumer products and production processes secret, in order to maintain their advantage over their competitors. In this author's 20+ years of experience as a chemical / pharmaceutical intellectual property attorney, most industrial companies behave similarly, and maintain most of the details of the engineering, production, customer, and economic aspects of their businesses as trade secrets.

[47] See the Wikipedia article "Trade Secret" at the link below for a good introductory discussion of trade secrets and trade secret law, and further references." See https://en.wikipedia.org/wiki/Trade_secret .

Many Academics ignore the Real-World importance of trade secrets, but their Real-World value has recently become clearer in view of massive trade secret theft by malign foreign companies and countries. Trade secret law was traditionally state-based law in the United States, but the Economic Espionage Act of 1996 created potential U.S. Federal criminal penalties for trade secret theft, and the Defend Trade Secrets Act of 2016 created a right for US companies to sue in U.S. Federal Courts for trade secret theft.[48]

Real-World industrial inventors almost always sign confidentiality agreements and sign away their ownership rights to the future inventions they will make on the day they begin employment. Scientific Publications from industrial scientists and engineers are not often permitted by the businesses, and industrial inventors they are only rarely allowed to publish their work, theories, and inventions in Academic peer-reviewed journals. When industrial inventors **are** permitted by their employers to publish technical details about their inventions, they almost always publish it first in the form of a patent application.

In this author's opinion Academic Green Chemists would do very well to start reading patents. Good "lay" introductions to patents and patent law can be found in several articles at Wikipedia. Patents, which can be granted in most countries in the world, give inventors of new and non-obvious inventions a legal right to prevent others from commercially using that patented invention for a limited time (usually 20 years), in return for publicly disclosing some technical details about the new inventions. In most countries of the world, a **patent application must be filed <u>before</u> the technical details of the invention are published anywhere else, or the inventions or its products are offered for sale, or else the potential legal rights are forfeited** (though the U.S. has a short and narrow exception).

Patents were explicitly contemplated in the U.S. Constitution, and are codified in Title 35 of the United State Code. Most of the text of a patent application document is legally rather than technically oriented, one reason most technical Academics don't understand or like to read patents. Most of the text in the patent specifications has the predominant legal purpose of establishing (on paper) words that can be used in or in support of the patent's claims, which are intended to define legally enforceable **boundaries** for legal patent rights, rather than to describe the scientific / technical heart of the inventions. Patent applications are custom legal documents drafted by people having both legal and technical

[48] See https://en.wikipedia.org/wiki/Defend_Trade_Secrets_Act

backgrounds, and are very expensive to draft, prosecute, and enforce against competitors. Because of the considerable expense involved, few companies and/or inventors draft and prosecute patent applications unless they envision a very significant economic or strategic benefit from obtaining the legal patent rights.

But there are also some legally required empirical scientific / technical disclosures in patent applications. The patent specification must describe the claimed inventions in enough detail to allow one of ordinary skill in the relevant technical arts to **make and use** the inventions. Importantly, the **patent examples** are typically empirical / factual descriptions of the procedures followed and empirical results of actual experiments conducted and/or products made. In the U.S. the patent application must also disclose the **best mode for practicing the invention known to the inventor at the time of filing** the application (which is usually early in the R&D process). Once a patent application has been filed in the U.S. (and/or in most foreign countries) the patent application is published as a patent publication 18 months later, then subsequently examined by patent examiners who decide if legal rights and boundaries to the claimed inventions are to be granted.

Chemical patents only rarely disclose scientific theories about how or why the chemistry works, which is one reason Academic chemists often dislike reading patents. Disclosure of scientific theories (which are of course mental states, not verifiable facts) is not legally required in a patent application and disclosing such theories could easily damage the inventors / patent owners and their legal and economic interests. Including "theories" (or "principals") in a patent could provide a patent examiner a "roadmap" for locating other prior publications disclosing similar theories, and then combine those 3d party theories as justification to reject the claims as obvious. Theories could similarly provide a roadmap for a competitor to argue during litigation that the claims to the inventions were invalid for obviousness. Competitors could also use a patentee's theories to inspire and predict new competitor inventions.

As a result, **a competent patent attorney typically avoids including "theories" in a patent application**, preferring to hold their inventor's theories as trade secrets. Very often, the attorneys will strongly argue against disclosing such theories, even in a later published scientific publication, for some of the same reasons. Accordingly, publications by industrial inventors in Academic journals are typically discouraged by the attorneys and/or business managers, for legal / business reasons.

But Academics should read patents because they are a good source of empirical information about new industrial inventions that the inventors and their business managers believe may have both technical and economic value. The Academics can then potentially formulate, test, and publish scientific theories about those new inventions, something the industrial inventors are only rarely allowed to do.

Olefin metathesis appears to have been such a case. Olefin metathesis was discovered serendipitously by Eleuterio at Du Pont in 1956, by what appears to have been a "random tinkering" sort of process. Some of Eleuterio's discoveries were patented, but others were held as trade secrets (see Eleuterio 1991). Chauvin, who was working in the French oil industry encountered the olefin metathesis reaction there and moved to a public institute in 1960. The olefin metathesis chemistry evolved rapidly and produced many practical applications in both the oil and later in the pharmaceutical industries. In 1971 Chauvin publicly proposed a (now generally accepted) mechanism for the olefin metathesis reaction. Chauvin was awarded a Nobel Prize in 2005 (along with Robert H. Grubbs and Richard R. Schrock for later developments).

However, a question (and injustice) remains. If Chauvin's publication of a mechanistic theory about olefin metathesis was deserving of a Nobel Prize, why is it either just or fair that the actual discoverer / inventor's name (Eleuterio) is rarely if ever mentioned alongside those of Chauvin, Grubbs, and Schrock??

Eleuterio was philosophic about such things. He quoted Francis Crick as saying "I enjoyed every minute of it, the downs as well as the ups…the important thing is to be there when the picture is painted." Eleuterio also commented that "Historians continue to wonder whether science drives technology or is it the other way around? In my judgement, a more relevant key question is how do the key variables which are involved in doing science and technology contribute to a synergistic relationship between scientific discovery and technological innovation?"

Despite any injustices, the many Academics that became involved in further developing olefin metathesis (and other catalytic chemistries that were first discovered in Industry) have certainly benefited from the industrial discoveries, most of which are first published in patent publication form. Practicing industrial chemists can also benefit from interactions with Academic chemists.[49] Voluntary interactions and collaborations

[49] Consider Professor John Stille's unknowing contribution to this author's thought process that identified ibuprofen as a potential viable commercial product target, which then led to the conception of the new carbonylation chemistry that was the most important of several keys that led to the invention and development of the BHC Ibuprofen process, see Murphy (2018).

between Industrial and Academic chemists and Engineers, and their multi-disciplinary teammates are highly desirable and deserve to be encouraged, but there is very little justification for Soviet-Harvard style lectures toward other professional researchers.

Lastly, even a few hours training in intellectual property law would tremendously benefit both Academics and Graduate Students in the Academic sciences and engineering, and greatly facilitate positive Academic / Industrial communications and interactions. In this author's experience it is often possible to find IP / patent attorneys (that typically have both legal and technical backgrounds) who are willing to teach Intellectual Property short courses "Pro-Bono."

12. THE REAL-WORLD ORIGINS OF "GREEN CHEMISTRY"

"Green Chemistry" has been very often described in the Academic literature as having begun in the 1990's as a result of concepts and action at the U.S. EPA, and/or in Academia. If "Green Chemistry" is defined as an "Academic Field" designed to produce Academic papers, and lectures for students, then that "1990s Green Chemistry Narrative" description of the origins of Green chemistry has some validity. But if "Green Chemistry" is defined to be "chemicals and chemical processes designed to reduce or eliminate negative environmental impacts," then the Real-World origins of Green Chemistry began decades earlier, mostly in industry.

Beginning about the time of World War II the petrochemical industries began to grow rapidly, in terms of both product volume, value, and the variety of products produced, in response to increasing consumer demands. New processes for producing those new products proliferated. More than a few of those new products and processes were toxic, wasteful, and polluting, and did not consider long-term issues such as biodegradability. There were multiple major oil and chemical / toxic spills and/or intentional dumps of toxic wastes. by some companies and some people. But some of the new products and processes were non-toxic, non-polluting, and/or biodegradable.

But the massive volume of both the products and the wastes in the oil and commodity chemical businesses assured quick recognition of the very practical question of what to do with the wastes. That soon led to the recognition that it was far better to reduce or not make the wastes than to expend money to dispose of them. Many in the oil refining and commodity petrochemical industries soon began to work toward improving the efficiency and lowering the generation and/or release of waste products, even if their motivations were initially and predominantly economic rather than altruistically ecological. But those improvements in efficiency and reductions in waste did benefit the environment.

In the 1960s the negative effects of the wastes and pollution from the increasingly large and diverse chemical industry became increasingly apparent as both the industries and the environmental movement grew. In the early 1970s many countries around the world began to enact environmental statutes intended to curb the pollution, but many of those statutes (particularly in the United States) were based on legally inspired "command and control" approaches. The "command and control" approaches forced companies to begin to address environmental issues, but also legally dictated end-of-the-tailpipe "solutions." The technical limits and negative economic effects of those "end-of-the-tailpipe solutions" rapidly became apparent.

Many researchers in many places and many Real-World industries quickly began to recognize that preventing pollution and waste, rather than cleaning it up after the fact, offered a much superior approach, technically, economically, environmentally, and politically, even though the specific mixture of motivations probably varied tremendously among the individual cases and people, as well as with time. Many Real-World "Pollution Prevention" projects began to crop up at various places around the world. Those inherently interdisciplinary concepts and efforts appear to have first coalesced into an organized "Pollution Prevention Pays" program at the 3M corporation in 1975, led by Dr. Joseph Ling (an engineer). Thousands of Real-World international projects were initiated at 3M over the following years that both reduced pollution and saved/made the 3M company money at the same time. Furthermore, Professor Michael G. Royston from Geneva was an early leader in the analysis of the very complex economic / social / governmental issues that underlay the new "Pollution Prevention" strategy.

The November 1976 UN/ECE "Non-Waste Technology and Production" conference in Paris, and the subsequent 1978 book, seems to have been a turning point that coalesced and broadened interest in the "Pollution Prevention" strategies, which soon began to evolve and spread into many companies and industries around the world, throughout the 1980s. Once industry discovered that it could actually increase profits by preventing rather than cleaning up pollution, the Pollution Prevention concepts quietly went "viral" in industry, even though relatively few Academics were paying attention. The practical technical details of the Real-World inventions, development, and commercialization of specific examples of the general Pollution Prevention concepts varied tremendously, depending on the details of the products, processes, and local technical and economic/business details, as well as the particular people and companies involved.

In the late 1980s the OECD and the U.S. EPA began to actively encourage the already on-going Pollution Prevention industrial approaches. The EPA's Office of Pollution Prevention and Toxics (OPPT) was formed, and was led by many EPA professionals including Stepan, Atcheson, and Breen, a chemist. The OPPT and other government agencies aided in the more general push for passage of the U.S. Pollution Prevention Act of 1990, and new voluntary / cooperative industry / government approaches during the administration of George Herbert Walker Bush. When the Clinton Administration was inaugurated in January 1993, some of EPA's programs were expanded and eventually renamed "Green Chemistry". The new research grants and Presidential Green Chemistry awards accelerated the growth / popularity of "Green Chemistry" in both Industry and Academia.

But "Green Chemistry" (at least as a Real-World phenomenon) was not "created" or "developed" at the US EPA, or in Academia. Real-World "Green Chemistry" emerged from multitudes of complex evolutionary sub-processes and many earlier roots in many places, and from a Vast set of interactions between internal and/or external forces, events, people, and/or motivations.[50]

Green Chemistry had many Fathers and Mothers,[51] and Grandfathers and Grandmothers as well, from many types of technical and business backgrounds. Hopefully the Academic Green Chemistry literature, and university lectures to students, will soon begin to recognize the existence of and significance of those early contributions, both practical / scientific and theoretical / philosophical, from those many early Fathers and Mothers of Green Chemistry.

To echo the perspective of Joe Ling, "the environmental issue is emotional … the decision is political … but the solution must be technical." In this Author's opinion aspiring Green Scientists and Engineers would do well to remain cognizant of the emotional and political issues but focus much of their unique technical skills and attention toward "innovative scientific solutions to real-world environmental situations", as did the many Real-World Fathers and Mothers of Green Chemistry. Hopefully more current and future Green Chemists, Green Engineers, and their team-mates from other disciplines will also recall and appreciate Newton's comment that "If I have seen further, it is by standing on the shoulders of Giants."

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The opinions stated in this article are solely those of the author and were not induced or financially supported in any way by any other person, business, or legal entity.

[50] See Murphy 2018, and Murphy 2020.

[51] The reference list below uses the normal convention of only citing the initials of the cited authors, without regard for sex, race, or nationality. Actual inspection of those references reveals that many females from many countries were authors and contributors to those cited references, and therefore are metaphoric "Mothers" of Green Chemistry.

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APPENDIX I
PAPERS PUBLISHED IN
"NON-WASTE TECHNOLOGY AND PRODUCTION"
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Proceedings of an international seminar organized by the Senior Advisers to ECE Governments on Environmental Problems on the Principals and Creation of Non-Waste Technology and Production, held in Paris on 29 November -4 December 1976

Part I – Concepts and Principals of Non-Waste Technology

Introductory Report, by V. V. Kafarov (rapporteur, USSR Academy of Sciences, Mendeleev Institute of Chemical Technology)
"Main results of the symposium of the CMEA countries on the theoretical, technical and economic aspects of low-waste and non-waste technology, by the Organizational Committee of the CMEA Symposium"
"A broader definition of non-waste technology", by Hussein Saleh, Environment Canada
"New, ways of developing chemical and related procedures free of wastes or low in wastes in Hungary, by Tibor Blickle and Micklov Machace, Research Institute for Technical Chemistry of the Hungarian Academy of Sciences
"Eco-productivity: a positive approach to non-waste technology", by M. G. Royston, Centre d' Etudes Industrielles, Geneva Switzerland
"Concepts and principles of non-waste technology", by J. D. Schmitt-Teqqe, Federal Republic of Germany

Part II – State of Non-Waste Technology- National Experience and Policy

"Introductory report" by A. J. McIntyre (rapporteur, Environment Canada)
"State of non-waste technology in the Netherlands: national experience and policy" by A. W. F. Van Alphen, Ministry of Health and Environmental Production, Netherlands
"Non-waste technology: comments on the Canadian scene" by A. J. McIntyre, Environment Canada
"Austrian national report on non-waste technology" by Rudolf Kauders and Udo Ousko-Oberhoffer, Vienna Austria
"Some aspects of production without waste of mineral raw materials in Poland" by Stephan Gustkowitz, Committee of Science and Technology, Poland
"Non-waste technology: United Kingdom experience and policy" by R. Berry, Department of Industry, London United Kingdom
"French policies in pollution - free technology" by P. Chassande, Minestere de la Qualite de la Vie, France
"Experience and policy with regard to non-waste technology in Hungary" by A. Takats and J. Francia Hungarian National Council for Environmental Protection, Budapest Hungary
"Report from the Swedish Government" by the Ministry of Agriculture, Sweden
"Production sans dechets en Belgique" by I. Van Vaerenberg, Prime Minister's Office, Bruxelles Belgium
"Non-waste technology in Finland" by Jali M. Ruuskanen and Matti Vehkalahti, Finnish National Fund for Research and Development, Helsinki Finland
"State of non-waste technology: United States experience and policy" by David Berg and C. Lembit Kusik, Environmental Protection Agency, Washington D.C., USA
"Experience and policies in the field of non-waste technology in the Federal Republic of Germany" by J. Orlich, Federal Republic of Germany
Experience et politique de la Yougoslavie" by the Government of Yugoslavia

Part III – Industrial Experience

"Introductory report" by D. Moyen (rapporteur, Institut National de la Recherche sur le Securite, Paris France)
"Introductory report" by Laszlo Marko (rapporteur, Professor of Organic Chemistry, University of Chemical Engineering, Veszprem Hungary)
"Introductory report", by M. F. Torocheshnikov (rapporteur, Medeleev Institute of Chemical Technology, Moskow, USSR)
"Protein recovery from liquid potato wastes", by M. Huchette, Establissements Roquette Lestreme France
"Profitable industrial uses for whey" by F. Bertrand, Minstere de l'Agriculture, Antony France
"Dyeing in a solvent medium: STX process" by M. Laurent, France
"How and why we chose integral recycling" by B. Marechal, Tour Rousselle-Nobel, France
"Recovery of the iron contained in pickling solutions and waste ore etching solutions, in the form of magnetite" by D. Lefort, Centre de Recherches de Pont-a-Moussun, France
"Waste exchanges: improved management for a new type of growth" by J. C. Deloy, Editor-in-Chief, "Nuisances et Environment", Paris France
"Metals In the organic chemical industry: problems and aids for non-waste technologies" by Laszlo Marko, Professor of Organic Chemistry, University of Chemical Engineering, Veszprem Hungary
"The use of natural zeolites in the chemical industry" by Denee Kallo, Head of Dept. for Hydrocarbon Catalysis, Central Research Institute for Chemistry, Academy of Sciences, Budapest Hungary
"The utilization of brown coals other than for energy production" , by V. Cziglina, L. Dszida and Z. Meleg, Collieries of Tatabanya, Hungary
"Non-waste technology in Belgium" by A. G. Buekene, Professor, Vrije Universiteit, Warsaw, Poland

"Outokumpu flash smelting method" by Seppo Harrkki, Helsinki Finland

"Methods of conserving raw material and energy and protecting the environment in chemical and electrochemical plating plants" by Bengt Westerholm, Metal Finishing Machines, Lahti Finland

"Experience in designing a complex scheme for refining and reuse of waste waters and creation of a drainage- free scheme of water supply and sewerage in an industrial enterprise" by V.N. Yevstratov and M.I. Kievsky, Ministry of Chemical Industry, Moscow USSR

"A review of non-waste technology problems in some major production branches" by P. Grau, Institute of Chemical Technology, Prague, Czeckoslavakia

"Developing conservation-oriented technology for industrial pollution control" by Joseph T. Ling, 3M Corporation, Minneapolis Minnnesota, USA

"The Nordic organization for waste exchange" K.E. Kulander, L-G. Lindfors and E. Lohrden, Sveriges Industriforbund, Stockholm Sweden

"Program considerations and experiences in optimizing industrial materials flow and utilization for a non-waste technology" by Jerome F. Collins, Division of Industrial Energy Conservation, US Energy Research and Development Adminstration, Washington D.C. USA

"No waste salt, no decontamination: a new step in the salt bath technology" by B. Finnern, DeGussa, Federal Republic of Germany

"The design of non-waste technologies taking the example lignite transformation complex in the German Democratic Republic" by W. Kluge, Institute of Energetics, Leipzig, German Democratic Republic

Case Studies from the Iron and Steel Industry, Pulp and Paper Industry, Packaging and Tyre Industry

"The iron and steel industry: pollution control and recycling" by Y. Hellot, Ministere d l'Industre et de la Recherche, Paris, France

"The outlook for progress and technological methods in a paper industry confronted with environmental problems" by P. Monzie, Centre Technique du Papier, Grenoble Cedex, France

"Non-waste production of bleached kraft pulp" by W. Howard Rapson and Douglas W. Reeve, University of Toronto, Canada

"Reduction de 1a charge de pollution de l'eau provenant d'une usine de pate au sulfate blanchie" by P. Lieben, Environmental Directorate, Paris, France

"Displacement bleaching" by Johan Gullichsen, Archippainen, Gullichasen and Co., Helsinki Finland

"Biological method for purifying kraft pulp mill condensates" by Ilpo Vettenranta, Enso-Gutzeit Osakeyhtio, Paper Division, Imatra Finland

"Packaging alternatives for wine" by W. P. Fornerod, Istitute TNO for Packaging Research, Delft, Netherlands

"The recovery of glass in Switzerland" by YVes Maystre, Environmental Canada, Ottowa Canada

"The status of non-waste technology in the United States steel industry" by Arthur: H. Purcell, Director of Research, T.I.P. Inc., Washington D.C.

"The status of non-waste technology in the United States packaging industry" by W. David Conn, University of California at Los Angeles, USA

"Non-waste technology: the case of tyres in the United States" by Haynes C. Goddard, Environmental Research Center, Environmental Protection Agency, University of Cincinnati, USA

"Two examples of low emission technologies in the pulp and paper industry" by E. Jochem, Fraunhoffer-Gesellschaft, Karlsruhe, Federal Republic of Germany

"Treatment and preparation of dusts and sludges in the steel industry" by M. Haucke and W. Theobald, Eisenhutten Dusseldorf, Federal Republic of Germany

"The application of material-saving and low-waste technologies in the metal container industry with special reference to drawn and wall-ironed beverage cans" by Walter Sprenger, Schalbach-Lubecha Gmbh, Braunschweig, Federal Republic of Germany

"Disposal of ironworks waste" by Rudolf Roth, Mannesmann AG Huttenwerk, Duisburg, Federal Republic of Germany

"The Heye-EPB process, a low-waste technology" by Vollmar- Hallensleben, Prime Ministers Office, Scientific Policy Planning, Bruxelles Belgium

Part IV - Cost/Benefit Aspects of Non-waste Technology

"Introductory report" by Charles J. Cicchetti (rapporteur, University of Wisconsin- Madison, USA)

"Cost-benefit considerations in waste-free production methods" by J. Picard, Agence Financiere de Bassin Moire-Bretagne, Cedex, France

"The introduction of non-waste technological processes in the Hungarian silicate industry" by -Jozsef Talaber, Central Research and Designing Institute for Silicate Industry, Budapest, Hungary

"Economic aspects of non-waste management" by C. Cala and J. Wieckowski, Ministry of Science, Education, and Technology, Warsaw Poland

Part V - Ways and Means of Implementing Non-waste Technology

"Introductory report" by M. Schubert(rapporteur, Techniche Universitate, Dresden, German Democratic Republic)
"The role of design education in non-waste technology" by H. H. van den Kroonenberg, Twente University of Technology, Enschede, Netherlands
"A survey of the location, disposal and prospective uses of the major industrial by-products and waste materials" by W. Gutt, Department of the Environment, Building Research Establishment, Watford UK.
"Statutory and financial provisions for the establishment of manufacturing methods free of waste products" by R. Huissoud, Conseil National du Patronat Francais, Paris, France
"Applications of material flow analysis in resource management" by David W. Nunn, Chr Michelsen Institute, Bergen Norway
"An Overview of solid waste product charges" by Fred Lee Smith, Jr., Environmental Protection Agency, Washington D.C., USA
"Administrative ways and means of implementing non-waste technology" by Martin Neddens, Rat von Sachverstandigen fur Umweltfragen, Wiesbaden, Federal Republic of Germany
"Non-waste technologies: ways and means of implementation" by Robert Reid, Energy and Environmental Analysis Inc., Arlington Virginia, USA

Part VI - Methodological and Strategic Aspects of Non-waste Technology

"Introductory report" by Jean-Franqois Saglio (rapporteur, Directeur de la Prevention des Pollutions et Nuisances, Seine, France)
"General aspects of the development of chemical production systems in regions with a complicated state of environment" by A. Zygankov and V. Senin, State Committee for Science and Technology, Moskow, USSR
"Perspectives for the development of non-waste technological processes in various branches of industry" by B. Laskorin, A. Zygankov, B. Gromov and V. Senin, State Committee for Science and Technology, Moskow, USSR.
"A Method of assessing non-waste technology and production" by Thomas Veach Long II and S. Ellie, Resource Analysis Group, University of Chicago, USA
"Non-waste technology and the materials flow in an economy: facts and perspectives" by M. Fischer, Institut fur Systemtechnik und Innovationsforschung, Federal Republic of Germany

Annex – Inaugural Addresses

Vincent Ansquer, Minister for the Quality of Life, France
James Stanovnik, Executive Secretary, United Nations Economic Commission for Europe

APPENDIX II
TITLES AND AUTHORS OF PAPERS PUBLISHED IN "MAKING POLLUTION PREVENTION PAY, ECOLOGY WITH ECONOMY AS POLICY"
EDITED BY DONALD HUISINGH AND VICKI BAILEY
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Papers Presented at a Symposium held in Winston-Salem North Carolina, USA, May 26-27 1982

Preface – Don Huisingh and Vicki Bailey, North Carolina Board of Science and Technology
Introduction - "Making Pollution Prevention Pay" - Dr. M. G. Royston, International Management Institute, Geneva
"Pollution Prevention Pays: The 3M Corporate Experience" - Russell H. Susag, PhD., P.E. Director of 3M Environmental Operations, St. Paul, Minnesota USA
"In Every Dark Cloud…" - Dan Meyer, Manager, Environmental Control Department, Dow Corning Corporation, Midland, Michigan, USA
"Disposal Cost Reductions From Ciba Geigy Corporation's Cost Improvement Program" - John A. Stone, Ph.D., Manager, Industrial Health Agricultural Division, Ciba-Geigy Corporation, Greensboro, N. C., USA
"Polyvinyl Alchohol Recovery by Ultrafiltration" - H. C. (Nick) Ince, J. P. Stevens & Company, Greenville, South Carolina, USA
"Opportunities for Clean Technology in North Carolina" - Dr. M. G. Royston, International Management Institute, Geneva Switzerland
"Implications and Procedures for Waste Elimination of Hazardous Wastes" - Dr. Michael R. Overcash, Professor, Chemical Engineering Department, Professor, Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, North Carolina, USA
"Chemical Recycling: Making It Work, Making It Pay" - Dr. Paul Palmer, ChemSearch/Zero Waste Systems, Inc., Emeryville, California, USA

"Waste Exchanges: An Informational Tool for Linking Waste Generators With Users" - Elizabeth W. Dorn, Piedmont Waste Exchange, Urban Institute, University of North Carolina– Charlotte, USA, and M. Timothy McAdams, Pacific Environmental Services, Inc., Durham, North Carolina, USA

"Process Design to Minimize Pollution Case Studies" - Donald D. Easson, Division Manager, Process and Environmental Engineering, Daniel International Corporation, Greenville, South Carolina, USA

"A Systems Approach to Waste Management" - James C. Dickerman, Radian Corporation, Durham, North Carolina

"Waste Reduction – Concept to Reality" - A. Brent Brower, P.E., Environmental Design Manager, J. E. Sirrine Company, Research Triangle Park, North Carolina, USA

"Positive Incentives for Pollution Control in North Carolina" - Dr. Carlisle Ford Runge, Public Policy Analysis Program, Department of Political Science, University of North Carolina, Chapel Hill, N.C., USA

"Economic and Environmental Health Through Education and Cooperation Among Industry, Government, and Citizens" - Claud "Buck" O'Shields, Chairman, Governor's Waste Management Board, North Carolina, USA