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The Anthroposphere, Material Flow Analysis, and Chemical Education

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Supporting Information

ABSTRACT: We are about to enter, or already have entered the Anthropocene Epoch. To appreciate how we reached this milestone event and the extent to which human activities have changed the chemistry of Planet Earth, this author encourages chemical educators to introduce the concept of the anthroposphere and to summarize the recent results obtained by material flow analysis (MFA) studies. These studies have generated global maps of metal (e.g., aluminum) flows, demonstrating a significant movement of metal from the lithosphere into the anthroposphere. They also reveal the amount of energy consumption and greenhouse gas (GHG) emissions associated with the transformation of metal ore and recycled scrap into metal products. In the case of aluminum, the data obtained from MFA studies are easily folded into a discussion of primary aluminum production (the conversion of bauxite into liquid aluminum), the acid−base chemistry associated with the Bayer process, the redox chemistry associated with the Hall−Héroult process, and the environmental challenges associated with the byproducts red mud and perfluorocarbons. MFA studies offer a big picture view of some important industrial chemical processes and allow us as chemical educators to address more meaningfully the issue of sustainable practices in light of the magnitude to which humans have changed Earth, leading us into the Anthropocene Epoch.

KEYWORDS: *First-Year Undergraduate/General, High School/Introductory Chemistry, Curriculum, Environmental Chemistry, Public Understanding/Outreach*

INTRODUCTION

In his editorial, "Telling Time: Chemistry Education in the Anthropocene Epoch", Peter G. Mahaffy challenges us, the chemistry education community, to weave into our chemistry lessons the notion that we have now reached a point in our planet's history that human activities are so pervasive that we have "fundamentally changed the chemistry of Planet Earth" and to discuss the evidence supporting this claim.[1] In short, he reports, our geology colleagues are poised to announce that we have entered a new geological epoch, the Anthropocene Epoch.[1]

I wholeheartedly endorse Mahaffy's suggestion, but argue here that it be expanded to include not only mention of the Anthropocene Epoch (a temporal period in geologic time), but also the anthroposphere (a spatial region encompassing much of the planet) that interacts with the four traditional spheres—atmosphere, biosphere, hydrosphere, and lithosphere—and has an ever increasing impact on our lives and the health of the planet.

THE ANTHROPOSPHERE

Baccini and Brunner define the anthroposphere as "mankind's sphere of life, a complex technical system of energy, material, and information flows." This definition comes from the 1991 publication of their book, *Metabolism of the Anthroposphere*. A second edition of this book appeared in 2012.[2]

The Aspen Global Change Institute Web site defines the anthroposphere as anything and everything that is connected with or created by human civilization. They mention "cities, villages, energy and transportation networks, farms, mines, ports, as well as the books, software, blueprints, and communication systems."[3] They also suggest that the anthroposphere extends beyond planet Earth since we have explored parts of our solar system.

ACKNOWLEDGING ACCELERATED CHANGE IN THE ANTHROPOSPHERE

J. R. McNeill[4] in *Something New Under the Sun: An Environmental History of the Twentieth-Century World* details humankind's impact on the planet during the past century and also convincingly argues that the 20th century was unique compared to all previous centuries because its impact was far greater than that of previous centuries. To convey the accelerated pace of change to my general chemistry students (all engineering majors) in the context of sustainable practices, I have relied for the past decade on Table 1, the *Greatest Engineering Achievements of the 20th Century* compiled by the National Academy of Engineering.[5] This list helps students appreciate the rapid pace of change in many aspects of our lives.

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Table 1. Greatest Engineering Achievements of the 20th Century

1.	Electrification	11.	Highways
2.	Automobile	12.	Spacecraft
3.	Airplane	13.	Internet
4.	Water supply and distribution	14.	Imaging
5.	Electronics	15.	Household appliances
6.	Radio and television	16.	Health technologies
7.	Agricultural mechanization	17.	Petroleum and petrochemical technologies
8.	Computers	18.	Laser and fiber optics
9.	Telephone	19.	Nuclear technologies
10.	Air conditioning and refrigeration	20.	High-performance materials

I also encourage students to think about the growth in the planet's human population. The year 1927, the year of Lindbergh's solo Atlantic flight and Babe Ruth's 60th home run,[6] is identified as the year the planet's human population reached 2 billion.[7] The year 2011 is identified as the year the planet's human population reached 7 billion.[8] Our ingenuity, our sheer numbers, and the consequences of both have propelled us to the edge of the Anthropocene Epoch and have greatly influenced and expanded the anthroposphere, which, in turn, has impacted the biogeochemical cycles of the planet.

The relevance of the size of the human population to this discussion is demonstrated by an examination of the so-called Kaya identity, which has been applied to reducing energy demand and CO_2 emissions by Allwood et al.[9] Equation 1 quantifies the role of human population and its relation to sustainable practices.

$$CO_2 \text{ emissions} = \text{population} \times \frac{\text{GDP}}{\text{population}} \times \frac{\text{energy}}{\text{GDP}} \times \frac{CO_2 \text{ emissions}}{\text{energy}} \quad (1)$$

INDUSTRIAL ECOLOGY AND ANALYSIS OF THE ANTHROPOSPHERE USING MATERIAL FLOW ANALYSIS

Industrial ecology is a relatively new academic discipline. The 1991 publication of the book *Metabolism of the Anthroposphere* is credited with helping to launch this academic discipline.[2] In a 1998 *Chemical & Engineering News* article[10]the discipline of industrial ecology was described as a "little known" but "rapidly emerging field".

One of the primary goals of industrial ecology is the analysis of anthropogenic material cycles. The payoff is a detailed snapshot of how a raw material is extracted, chemically transformed (e.g., into its elemental state), fabricated into useful products, used, and finally discarded. Major stages are often broken down into substages (e.g., in the areas of production and recycling of manufacturing scrap).[11] The environmental impact of the cycle is also illuminated; greenhouse gas (GHG) emissions and energy consumption are tabulated. It also reveals the amounts of in-use stocks of the material. This detailed picture of the anthropogenic material cycle points the way to implementing more sustainable practices in the anthroposphere.[12]

Material flow analysis (MFA) is a technique developed to illuminate the detailed material cycle. It identifies and "quantifies the flows of materials into, out of, and through a system of interest, balancing all flows by conservation of mass."[13]

Since the start of the 21st century, one finds a dramatic increase in studies employing MFA. Many of these studies focus on metals. One place to find these studies is to search the ACS journal *Environmental Science & Technology*. These studies demonstrate that a significant movement of metal from the lithosphere into the anthroposphere has occurred.[12] Further, a sizable cache of the metal is often present in in-use stocks in the anthroposphere. While the discussion that follows is confined to aluminum, recent studies have focused on a variety of metals including copper,[14] iron/steel,[15] and scarce/precious metals[16] among others.

MFA STUDIES OF ALUMINUM

The second most produced metal is aluminum, albeit a distant second compared to steel: 1088 million metric tonnes for steel (2008) vs 45 million metric tonnes for aluminum (2007).[17] In 2013 Cullen and Allwood published a global map of aluminum flow.[17] Among the highlights of this study and several other recent MFA studies on aluminum were the following findings:

- Between 1950 and 2007, end-user demand for aluminum has increased 30-fold:[17] a more dramatic increase than for any other metal.[18]
- Primary aluminum production (from bauxite ore) accounts for roughly half of all aluminum that is made, and secondary aluminum production (from recycled scrap) constitutes the other half.[17]
- Primary aluminum production (using the Hall–Héroult process) consumes 3.5% of global electricity and generates 1% of CO_2 emissions.[17]
- Between 1900 and 2010 the global in-use stock of aluminum has reached about 10% of presently known bauxite reserves. These in-use stocks are concentrated in the developed countries (e.g., the U.S. accounts for 28% of the total).[12]
- The material efficiency of the aluminum industry is poor: half of all cast aluminum ends up as manufacturing scrap, which is returned to the refiner.[17]
- Under the most favorable set of circumstances, preparing aluminum from scrap requires 95% less energy than aluminum prepared from bauxite. However, when recycling cast aluminum alloys complications arise.[17]
- The journey of contemporary global anthropogenic aluminum through its transformation from bauxite ore to a final product has recently been mapped.[19]
- The end uses of aluminum can be divided into four broad categories: vehicles, industrial equipment, construction, and metal products. When further subdivided to give a dozen more narrow categories, it is found that cars (17.5% of the total) are the largest subcategory. Electrical cable and drink cans are 8.4% and 7.3% of the total, respectively.[17]
- Global unit carbon emissions for the aluminum industry are nearly 13× greater than the iron/steel industry.[20]

INCORPORATING MFA FINDINGS INTO CLASSROOM DISCUSSSIONS OF CHEMICAL PROCESSES AND SUSTAINABLE PRACTICES

For the first time in a thirty-five year career of teaching general chemistry this author recently incorporated the MFA results for

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aluminum outlined above into a 1.5 h lecture on aluminum. An outline of the PowerPoint presentation used in this lecture is provided in the Supporting Information. The effectiveness of this new approach was assessed by comparing the results of a baseline survey prior to and exam questions after the lecture on aluminum and after the students finished a two-week lab on anodizing and coloring aluminum.[21] The assessment results are summarized in the Supporting Information.

The author also brought into the lecture on aluminum the recent announcements by Ford Motor Company and General Motors that some of their 2015 vehicles will use substantially more aluminum to reduce the weight of the vehicle and improve gas mileage.[22,23] The new 2015 Ford F-150 pickup truck will contain ~1000 lbs of aluminum and weigh 700 pounds less as a result of increased reliance on aluminum.

■ ELEVATING OUR DISCUSSION OF SUSTAINABLE PRACTICES

The value of the global map of aluminum flow[17] and related maps addressing global aluminum production[12,19] is that they offer a level of detail unavailable heretofore. If one wants to address the sustainability of converting bauxite or aluminum scrap into a finished aluminum product, one is now obliged to refer to these maps. Failure to do so opens the nonuser to legitimate criticism as ill-informed and amateurish in their approach.

The global map of aluminum flow[17]produced by MFA also links the worlds of chemistry and engineering. Both chemists and engineers work with matter. However, chemists view matter on a molecular scale while engineers are primarily concerned with the bulk properties of matter. Engineers are interested in what material best meets a particular need. In the case of metals, chemists focus on the physical and chemical properties of a pure metal. Engineers work with metals too, but rarely pure metals. They work with wrought and cast alloys. On the left-hand side of the Sankey diagram of the global map of aluminum flow[17] reside alumina and the electrolysis of molten aluminum salts. On the right-hand side of the same diagram is a list of the end-use products made of wrought and cast aluminum alloys. In the middle of the diagram pure molten aluminum is recast to give aluminum alloys that before fabrication are hot rolled, cold rolled, extruded, drawn into wire, or shape cast.

Both chemical educators and engineering educators are guilty of portraying their discipline as a distinct, isolated island of knowledge and practice. They are not! The global maps of aluminum (and other metal) flows clearly demonstrate that they are not. With the availability of these maps we need to share with our students the big picture; we need to complete the story of aluminum by traversing the map completely from left to right. This new information will allow us to more fully appreciate that anthropogenic material cycles are having a huge impact on the chemistry of the planet. To do otherwise is to shortchange our students.

■ ASSOCIATED CONTENT

Supporting Information

Baseline aluminum survey; multiple choice exam questions about aluminum; outline of PowerPoint slides used in lecture on aluminum. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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