Dematerialization and Secondary Materials Recovery in the U.S.

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Complexity in individual materials as well as the diversity of materials used in industrial and consumer products leads to problems both in isolating material components and retaining the value embedded in material goods, posing problems for effective materials recovery. Secondary materials processors must respond to contemporary challenges arising from materials complexity and diversity if they are to serve their proper function in minimizing the environmental disturbances associated with expanding material consumption.

INTRODUCTION

"Dematerialization" refers to the absolute or relative reduction in the quantity of materials required to serve economic functions.[1] This phenomenon, to the extent that it is occurring, possesses implications for the environment as well as natural resource use.

The primary materials lying beneath the earth's surface are not in danger of exhaustion,[2] and Figure 1 shows the intensity of materials use in the U.S. economy from 1900.[3,4] As the century opened, traditional structural materials such as steel and lumber were of great economic consequence; as the century closed, the relative importance of these materials has significantly diminished. Plastics and aluminum, both highly versatile materials, have grown considerably in economic importance since the middle of the century. More "exotic" materials such as gallium, beryllium, and lithium have become integral to economic activity, although they have consumption levels measured in kilograms rather than tonnes. In general, the reliance on traditional bulk materials has lessened and a more diverse menu of materials is being called upon to serve in the modern economy. A paradigm shift is under way: Although they once solely provided structure, materials are now expected to serve smarter, more intrinsic functions.[5] This, in turn, has made secondary recovery increasingly complex.

The objective of secondary materials recovery is, essentially, to escort materials to the places they have already been. The system's ability to do so successfully can be affected at any of four stages—extraction, production, consumer end use, and waste disposal. Developments in the mining and exploration sector, for example, affect the price differential between primary and secondary sources of materials. The means by which raw materials are transformed into industrial end products can greatly facilitate or severely hinder recovery. Finally, consumption patterns and waste-management decisions can determine the suitability and accessibility of material resources for reprocessing. Developments at all stages have profound effects on general material consumption rates, even if the material flow is only one way.

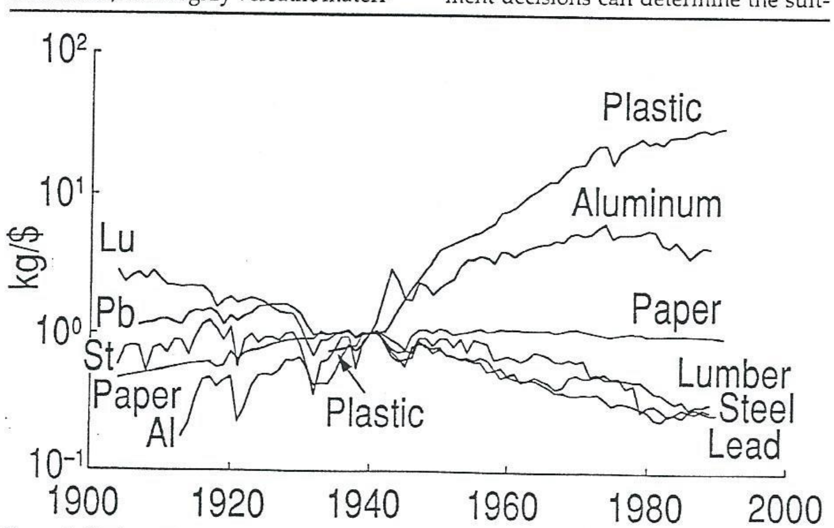

Figure 1. The intensity of materials use in the United States from 1900–1990. Production data for all materials are divided by gross national product in constant 1982 dollars. The figure is normalized to 1940 because it marks the beginning of the second period of sustained economic growth during this century.[4,13]

STEEL

The evidence for dematerialization in the case of steel is strong. Greater upstream efficiency and secondary materials recovery have both played roles in achieving this result.

Data[3,4] on U.S. primary and electric arc furnace (EAF) steel production show the marked drop in primary steel production over the last two decades (Figure 2). Imports account for some of the drop, but other factors have contributed as well, including a maturing infrastructure, reduced demand for new applications, materials substitution, and greater scrap consumption.

The rate at which fresh steel must be supplied to replace old stock can be described by the metals rate of replacement (MRR):[6]

$$MRR \propto (1/t_1 - R_t)$$

where t_1 is the metal's application lifetime and R_t is the technical mass reduction rate (an empirically determined rate at which technical advances allow for reducing the mass necessary to serve that function). Consistent gains in metallurgy and related fields have yielded metals and metal products with longer lifetimes. For instance, the use of large steel ingots (monoblocks) to forge entire turbines for power plants eliminates the problem of cracking at welded joints, a condition that shortens the operational life of older turbines.[7] As an example of technical mass reduction, castings for automotive and truck parts made of austempered ductile iron are 30 percent lighter than conventional steel parts and have the same utility.[8]

Throughout the structural metals industry, innovative processes have improved product quality and stimulated greater overall material efficiency. Alloys having tensile strengths well beyond those found in elemental metals as well as methods that increase metal strength directionally allow for a smaller cross-sectional area and less material to support loads. New diagnostic methods have enabled metals processors to moni-

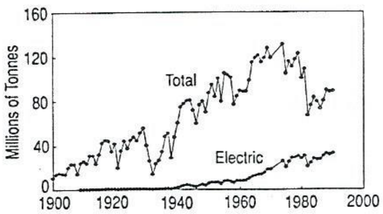

Figure 2. Primary and EAF steel production in the United States from 1900–1990.[3,4]

tor the migration of impurities to grain boundaries, measure porosity in castings, and increase the precision of alloy composition ratios. As a result of better process monitoring, industry can now provide products with properties very close to listed values. Additionally, near-net-shape processes such as powder metallurgy contribute to greater materials efficiency by reducing the amount of metal initially used as well as the home scrap generated during machining.

Substitution has also contributed to the decline in steel production. In the automotive industry, for example, the average U.S. car in 1992 was roughly 315 kg lighter than one made 20 years earlier. Much of this "downmassing" has resulted from the decreased use of carbon steel and the introduction of high-strength, low-alloy (HSLA) steel, plastics, and composites (Figure 3).[9]

Recovering the steel already stored in the economy plays a fundamental role in furthering the dematerialization of steel. EAF production has climbed steadily throughout the century. Because it relies primarily on scrap as an input, it is a reasonable proxy for scrap steel consumption. (Up to 25 percent of primary steel is produced with scrap.) In recent years, however, EAF production has begun to show signs of stagnating at about 40 percent of all production; this plateau may be related to a trend in scrap supplies.

One of the vexing problems encountered by manufacturers of EAF steel is the presence of trace amounts of contaminants in scrap piles. Zinc coatings, for example, can cause inconsistencies in steel bars manufactured from scrap even when present at levels of tens of ppm. Copper or tin can alter metal properties when present in similarly minuscule quantities. Reprocessed steel consumers, such as hanger manufacturers, have tight tolerances for the metal they use, and they can reject an entire batch of steel wire due to slightly low ductility or high brittleness—factors that can be affected by the low contaminant levels described above.

Contaminants are an even greater problem when attempting to achieve precise alloy composition ratios. Specialty steels, such as the 300 and 400 series of stainless steels, can tolerate lower impurity levels than carbon steel and are sensitive to elements such as lead when present at 10 ppm. Superalloys have an even lower tolerance to contaminants. For this reason, a major difficulty for recycling these materials lies in the absence of effective separation processes to segregate scrap piles. Nonetheless, unusually homogeneous scrap, such as home scrap and metal used in bulk applications within the industry, may avoid this difficulty—of the 25,000 tonnes of superalloys recycled in 1986, 70 percent were restored as the same alloy. Only 20 percent was downgraded to lower-value metal.[10] Thus, if use of a given material is confined to a controlled environment, high return rates may be achieved, even for advanced materials.

Returning to steel scrap, the concentration of unwanted elements can be sufficiently diluted to regain the desired composition ratio. Using dilution or other methods to recover the value found in mixed scrap must always be judged in terms of its profitability against the cost of using primary material sources. Including environmental value in this cost-benefit analysis can result in a lower input of virgin materials and the development of more efficient recovery processes. In the event that metal recovery or dilution is not feasible, mixed scrap can be reprocessed, often resulting in a downgraded product. Regardless of the material, the presence of high-value materials in mixed scrap often implies downgrading as the common last resort.

Hence, as steels become more physically and chemically complex, greater ingenuity will be required to balance the properties desired throughout the life cycle, including reuse.

SELECTED NONFERROUS METALS

As Figure 4 shows, aluminum consumption has grown in recent decades, primarily because of its appealing properties and suitability for applications requiring high strength, low density, and good thermal conduction. The sharp rise in secondary recovery that occurred in the early 1940s shows that a nation mobilized for war can quickly become very efficient in its use of materials. At this

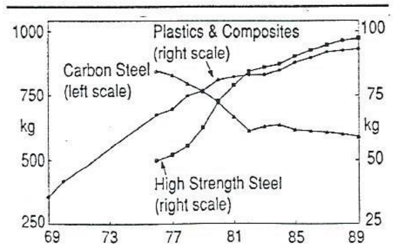

Figure 3. The weight of carbon steel, stainless steel, composites, and plastics in the average U.S. automobile from 1969–1989.[9]

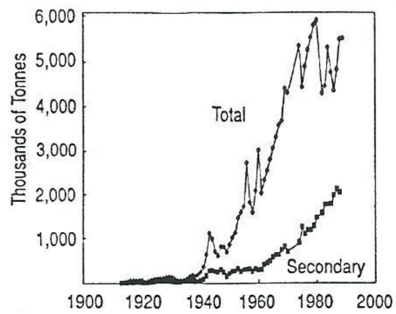

Figure 4. Primary and secondary aluminum production in the United States from 1900–1990.[3,4]

time, access to ore bodies was restricted, and price did not matter. Despite a decline in secondary recovery after World War II, the last two decades witnessed a marked increase in secondary aluminum recovery. Currently, secondary metal accounts for nearly 40 percent of all production. Primary aluminum production is roughly 20 times more energy intensive than production from secondary sources. Thus, escalations in the price of energy, like those of the early 1970s and 1980s, serve as strong motivators for increased secondary consumption and closing the materials loop for aluminum.

Used aluminum beverage cans (UBCs) have a recycling rate that is approaching 70 percent. UBCs provide an excellent example of how a system-wide approach to recycling can yield superior results. On the production end, can design was altered in the late 1970s from three to two pieces. The new design required less soldering and simplified the recycling process. The alloys used for the end and body pieces were chosen to facilitate a fully closed recycling loop. On the consumer side, a standardized, widespread system of collection promoted a high return rate for cans. Also, individual can weight has declined from the use of lower-gauge sheet and by the development of structural design changes that maintain can strength while using less metal (Figure 5).[11]

Aluminum-lithium alloys, titanium-based alloys, and composites typify materials that can compete effectively with polymers for specialized markets, such as aerospace parts. One drawback with aluminum-lithium alloys, however, is that its the component elements must be separated before reprocessing due to the highly reactive nature of lithium.

Separation of distinct materials "woven" together on a microlevel presents a new assortment of challenges to the recovery industry. Due to their unique physical compositions, novel recycling problems are associated with advanced materials. Melting or grinding down composites can destroy their valuable structural properties, which generally relate to average fiber length. Beyond difficulties associated with fiber length, fibers of boron, germanium, and silicates are reactive when elevated to the melting point of their host metals. This precludes melting the host and filtering out the fibers as a recycling option. For polymer composites, the difficulties associated with melting are greater still.

On the other end of the spectrum is lead, which enjoys a recovery rate approaching 70 percent. This high rate is partly due to the ease of isolating and collecting lead from spent batteries. In addition, dissipative uses of lead in many products (e.g., paint and gasoline) has been discontinued over the last few decades due to the adverse environmental and health effects associated with such use. One development clouding the future of lead recycling is the presence of contaminants in the battery waste stream. Industrial batteries containing high levels of antimony as well as nickel-cadmium batteries (attractive due to higher energy densities and excellent cyclability) must be manually separated and receive special handling at the smelter.[12] Cadmium is a toxic substance, and its use and disposal are heavily regulated. Its presence during lead smelting generates hazardous dust, leading to high disposal costs. In addition, the presence of cadmium or antimony in lead, even in small amounts, affects hardness. The manual separation required for these batteries inevitably drags down the recycling rate.

POLYMERS

From the introduction of Bakelite, the first synthetic thermosetting resin, in 1909 to today's ubiquitous polyethylene terephthalate (PET) beverage containers, the use of plastics for a wide range of applications has grown rapidly (Figure 6).[13,14]

Perhaps *the* material of the 20th century, polymer plastics are truly manufacturer friendly. Generally speaking, they are easily made into complex geometric forms, chemically inert, electrically insulating, and less dense than many traditional materials. Based on these characteristics, this low-density material has caused a substantial shift in

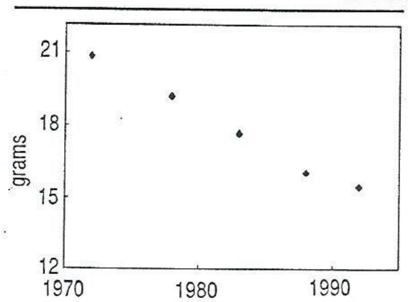

Figure 5. The downward trend in aluminum beverage can weight in the United States since 1973.[11]

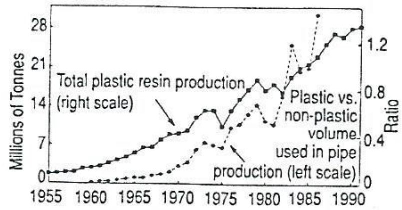

Figure 6. Total U.S. plastic resin production[13] and volume ratio of plastic versus other materials for pipe manufacture.[14]

the complexion of U.S. materials demand (Figure 1). In fact on a volume basis, the United States consumes more plastic than all metals combined.

One result of this trend is that the volume of structural materials consumed in the United States has grown over the last two decades (Figure 7).[15] The abundance of petrochemical feedstocks associated with the U.S. energy reliance on oil and gas is substantially related to the plastics demand. The oil crises of the early and late 1970s caused reversals in both material volume consumption and gross national product. Still, these declines were followed by resumption of the upward trends fewer than five years after each crisis.

Although polymers come in literally thousands of different varieties, eight commodity polymers satisfy more than 80 percent of U.S. demand and constitute a like amount of post-consumer plastic waste. This fact gives some hope of tractability for the problem of plastic waste. Currently, less than two percent of discarded plastics in the United States are recycled.[16] As a percentage of production, the figure is lower than one percent.

Several problems plague the nascent plastics recycling industry. They are separation, decontamination, and property degradation during reprocessing.

Separation is not critical for all types of plastics recycling. In the case of plastics packaging, separation is sometimes impossible. For instance, some potato chip bags can contain nine separate plastic layers over a thickness of approximately 0.05 mm.[17] Plastic types that are mixed together, either in one product or in the general waste stream, can be recycled for lower-grade uses such as plastic lumber. However, individual resins fetch much higher market prices. Hence, separation is important to polymer recycling if it is to become an economically viable option.

The manual separation of plastics has met with some success. Curbside collection programs have achieved respectable recovery rates, although they rarely achieve complete isolation of a given polymer type. For industry, however, manual separation is simply not cost effective. The development of technology for automated plastic separation is still in the initial stages. In this regard, methods being investigated include exploiting the density disparity between polymer types (e.g., polyethylene is ~0.95g/cc and polyethylene terepthalate is ~1.35 g/cc) and utilizing the signature x-ray spectra of chlorine atoms to isolate polyvinyl chloride samples. Research is also being done on optically tagging polymer types to facilitate automated separation. One strategy that may stimulate greater recovery rates by streamlining the separation process is the adoption of a universal polymer coding system such as the one recently established by the Society of the Plastics Industry.

Contamination by lids, labels, adhesives, and chemical additives (e.g., colorants and stabilizers) is another problem facing this industry. A starting point for addressing this obstacle may rest with the manufacturer. If recyclability was considered during the initial design phase, many recovery problems could be obviated. Using a more uniform mix of materials for product manufacture as well as considering post-consumption disassembly would enhance a product's ultimate recyclability. Producers could profit by homogenizing their inputs, reducing disposal costs, and gaining a better environmental profile as well.

One problem that cannot be remedied by changes in procurement, however, is the nature of the polymers themselves. With few exceptions, polymers are unable to sustain the high temperatures normally used for reprocessing. For example, the temperatures required to comply with U.S. Food and Drug Administration standards for food-package sterility would damage most plastics too severely for reuse. For this reason, PET bottles, which have an effective collection system and constitute a relatively homogeneous waste stream, cannot be reused as is and must first be downgraded.

While metals seem to have reached maturity and show some signs of dematerializing, polymers appear young and

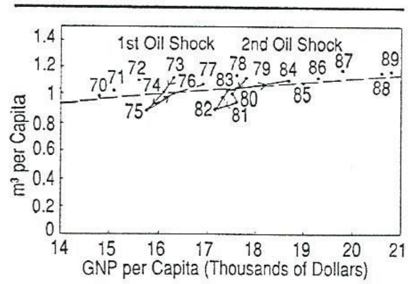

Figure 7. Total physical structural material consumption in the United States from 1970–1989. Volume is calculated using average material densities and is plotted against gross national product in constant dollars. The solid lines show the short-lived effects of the oil shocks, and the dashed line represents a linear best fit of the data.[15]

aggressive. Their role as a central structural material will almost certainly grow.

CONCLUSION

By design, today's downsized, high-performance products use a mix of materials to achieve less mass and improved properties. Each material acts to optimize the overall product performance and can add to product complexity. Once the product's life is spent, however, such mixes often pose significant problems for separation after disposal and reduce the economic feasibility of recovering individual materials. If product complexity continues as the rule, not the exception, products from spacecraft to food packages can be expected to embody an increasing heterogeneity of materials that are not easily isolated.

The competition in today's materials markets is increasingly a competition of properties. Hence, the objective of any comprehensive recycling strategy must be not only the recovery of materials but also the retention of the materials' properties. However, recovering the value embedded in products is often troublesome due to the custom properties that make them especially valuable for a given application. Thus, if ease of collection, component separation, and reprocessing are considered during the design process, significant savings in labor, energy, and capital could be realized.

With regard to dematerialization, we are faced with countervailing forces whose net effect is unclear. Population and economic growth call forth more materials. Greater efficiency within individual material sectors and through material substitution enables offsetting dematerialization. However, a number of problems are associated with effectively reprocessing many of the advanced materials characteristic of our era. If the obstacles to materials recovery can be overcome, then the combination of high-performance materials, coupled with a responsive secondary materials industry, could key a new, more environmentally benign materials era.

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