Assuring the Continued Recycling of Light Metals in End-of-Life Vehicles: A Global Perspective

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Editor's Note: This paper is based on the author's lecture presented at the Light Metals Division Luncheon during the 2004 TMS Annual Meeting in Charlotte, North Carolina. A hypertext-enhanced version of this article is available on-line at www.tms.org/pubs/journals/JOM/0408/Gesing-0408.html

This article reviews issues and technologies in recycling, both current and future, with a focus on end-of-life vehicles (ELVs) and their increasing light material content. Discussion includes the issues involved in designing for recycling, the existing global scrap recycling system, and interactions between different types of recyclables and different sections of the global market. A review follows of current scrap recycling technologies and compares the vehicle recycling regulations in the United States, European Union, and Japan. Finally, opinions are presented on useful, and some not so useful, global and local recycling regulations and initiatives.

THREE Rs AND OTHER RECYCLING PARADOXES

We all know the three Rs—reduce, reuse, recycle—yet are we as a society giving them any attention? The three Rs are ordered according to their priority. The list starts with reduce, but our affluent society's love affair with pick-up trucks, SUVs, and monster homes demonstrates that the North American consumer is not ready to reduce—and over 2.5 billion Asians are in the process of joining the consumption rat race. This has enormous impact on the world economy, the need for fuels and commodities, and on the global demand for recyclables.

Reuse extends the lifetime of components and hence decreases the market for new products, which does not particularly interest most original equipment manufacturers. Reuse has a potential to recover the full value of the item or its components. (A new car sells for less than its cost in replacement parts, and antique dealers often sell items at premium to their original value.) One example of successful reuse is multi-modal shipping containers. These have slashed global transportation costs for manufactured goods and enabled global shipping of low-value scrap. As a result, Asian hand sorting is competing successfully against the technologically advanced sorting of the North American and European recycling industries. There is no competition between reuse and recycling—anything reused will still need to be eventually recycled to recover the value of the materials of construction.

In spite of the fact that reduction is more effective in mitigating humanity's impact on the environment than recycling, and reuse recovers more of the value, it is recycling that globally is the cause celebre of environmentalists and regulatory agencies. But what is recycling? Recyclability, recycled content, recycling rate, and recycling all come into play, but these are not synonyms.

Recyclability refers to the potential market for the scrap of a given composition—the purer the scrap, the more market options there are. Consequently, pure metal from primary smelters can be considered the most recyclable metal composition.

Recycled content depends on the compositions of the desired alloy and of the scrap. Higher element concentrations in the alloy permit use of more scrap. If the scrap is purer than the alloy, then it can be batched from 100% scrap. Some alloys are specifically designed to be batched with high recycled contents. For aluminum alloys the three most common examples are:

- 380 series foundry alloys: an average composition of today's scrap mix of all common alloys
- 3105 painted sheet alloy: an average of low copper and zinc wrought alloy mix
- 3004/3104 can body alloy: a prime diluted composition of can body and can lid mix

Recycling rate and fraction recycled are ill-defined, nebulous concepts when applied to a class of long-lifetime post-consumer products like vehicles. While there are statistics on the number of end-of-life vehicles (ELVs) processed, the vehicle lifetime is uncertain. Many no-longer-registered vehicles are not immediately scrapped and spend years in backyards and farm fields, and later in dismantling yards. These are not disposed of, they are just retired and join the growing pool of reusable and recyclable materials in consumers' hands. The number of vehicles available for recycling is unknown, and thus the fraction of the number of available ELVs actually recycled—the recycling rate—cannot be determined.

Fraction recycled is the weight fraction of the recycled ELVs that ends up in recycled products. This can be determined during a recycling process test by a material mass balance. Unfortunately, it is impractical to operate the entire recycling system in a mass balance test mode at all times. An occasional test will demonstrate the recyclability potential of the best recycling process in the high-recovery test mode. This will have little relation to the material losses from the small shredders or scrap processors who optimize their processes for high throughput and high product grade to maximize profits. A better measure of fraction recycled would be (weight recycled)/(weight recycled +

loss to the landfill). The weight recycled is known from the recycling plant output, and the loss to the landfill can, and should, be statistically monitored for all landfills by sampling the residue.

Recycling—the act of material recovery from scrap—depends on the existence of a complete recycling system. This includes legislation, regulation, education, collection, technology, and, finally, a market for all types of recovered scrap. All these components need to be present for an efficient recycling system.

The sidebar on pages 20 and 21 describes how the three Rs can be incorporated into vehicle design.

REQUIREMENTS FOR A SUSTAINABLE LIGHT METALS RECYCLING SYSTEM

To be sustainable, a recycling system needs a sufficient market for the scrap-derived product to consume all the manufacturing and post-consumer scrap. It also needs appropriate technologies to manage the alloying elements (impurities) so that the scrap products can access this scrap market.

A low-cost, sustainable metal recycling system requires:

- Relatively pure prime alloys to act as diluents for the inevitable impurity pickup in the recycle loop, and to provide a means to upgrade the secondary alloy composition without needing to resort to melt refining
- A few large-volume secondary alloys with high recycled content to provide a sufficient market for all the recycled scrap
- Low-cost technology and a system for managing the alloying elements in scrap and using these elements to alloy new metal. In recent years it has been an eye opener that manual inspection combined with low wages and transportation costs, as is the case now in Asia, can successfully compete with the current best separation and sorting technologies developed in North America and Europe.
- Unrestricted flow of metal scrap between market segments and geographical locations. The free-market mechanism automatically least-cost optimizes the distribution of metal among the markets and customers. Closed-loop recycling of each product or alloy, the highest-cost option, is not necessary to ensure complete recycling of scrap.

The current metal recycling system already satisfies these requirements. Additional regulations need to take care not to require high-cost recyclability that does not necessarily increase recycling. Regulators need to facilitate a level playing field for all the recycling and scrap-market participants. The system should not be locally skewed through lack of, or non-enforcement of, health and safety or environmental regulations; nor through excessive duty barriers, tax incentives, or skewed currency exchange rates; nor through corrupt accounting and financial practices.

GLOBALIZATION OF THE WORLD ECONOMY: THE IMPACT ON RECYCLING

The adoption of English as a global language of business, the rise of global multinational corporations, instant global electronic transfer of information and funds, computers sharing common software, and multi-modal shipping containers have all contributed to changing the world of the 21st century into a global village.

For recycling, the shipping container is especially important. This versatile, reusable packaging globalizes world economies and manufacturing as well as the scrap market by slashing the cost of transportation of manufactured goods. Since the container is reusable, it needs to be returned to the point of origin to continue its cycle. Ships, trains, and trucks that transport these containers also make the round trip. This enables virtually free transport of recyclables and scrap on a global scale as the cost of the round trip is already pre-paid by the importer of the manufactured goods.

It is interesting to follow the evolution of global markets over the centuries while concentrating on the importance of transportation costs. In the Euro-Centric world of the 16–19th centuries, sea transport was very expensive, which resulted in Europe importing mainly treasures such as gold, spices, silk, and cotton. Europeans were net exporters of people and manufactured goods.

In the second part of the 20th century, multi-modal shipping containers slashed the shipping costs for manufactured goods, enabling globalization of manufacturing and its transfer to Asia; containers on the return trip often carry raw materials and scrap. The United States changed in the second part of the 20th century from being a net exporter to net importer of manufactured goods and fuel (and a net exporter of recyclables and scrap).

The 21st century is showing another major shift. Asia already holds the world's largest producers of steel, copper, zinc, aluminum, and magnesium, as well as metallurgical engineers. Asian cheap labor has attracted a majority of the world's manufacturing plants for consumer items manufactured from these raw materials. Further, as this manufacturing activity is generating real wealth, Asians are quickly becoming the largest consumers of manufactured goods, raw materials, and fuel. Most of the major multinational companies are competing for this rapidly growing market, investing and building manufacturing plants. The result is a staggering growth rate: in 2003, the automobile production rate in China grew by 87% from 2 million to nearly 4 million vehicles.

Low wages in Asia permit manual scrap processing. High custom duties on prime metals raise the domestic metal prices, and since this tends to set the value for the sorted scrap products, it allows scrap importers to pay higher prices for mixed scrap in Europe and North America than the local value of the sorted scrap products.

In China, government-licensed recyclers receive refunds from a 15% value added tax (VAT). This, in the Chinese market, gives them significant advantage over any potential non-government-sanctioned competition. Also, since the Chinese market sets the world price of scrap, the VAT refund gives the licensed recyclers an advantage in purchasing scrap from North America and Europe. The tax also encourages further profits from creative reporting of the scrap values for VAT refunds, additionally offsetting already low processing costs.

Table I. Products with Least-Demanding Specifications that Set the Lower Limit on Scrap Value

Product	Scrap/Residue	Value ($/t)
Alternate daily landfill cover	Building demolition nonmetallics Auto shredder nonmetallics Shredded tires	1~2
Reinforcing rod	Steel scrap	100
38X foundry alloys	Aluminum scrap	1,000
Al can body hardener	Magnesium scrap	1,000

Lax or non-enforced occupational health and environmental regulations in Asia further drive down scrap processing and residue disposal costs in comparison to North American and European markets.

Another factor is the exchange rate between the dollar or euro and the Chinese yuan being fixed at an artificially low level (by up to 40% according to the U.S. National Association of Manufacturers). This eliminates the automatic wage rate correction mechanism that operates when the free market sets the exchange rates.

This results in Asian importers being able to pay higher prices for mixed scrap in the United States and European Union than the value of the sorted nonferrous (NF) metal components of that scrap on the U.S. and E.U. markets. The ever-growing exports of U.S. aluminum scrap shred to Asia driven by the previously described factors are causing metal scrap shortage in the European Union and the United States. Historically, because of the shortage of scrap for batching aluminum foundry alloys, secondary remelt foundry ingot has in the last three years frequently sold at a premium to prime. Under these conditions of foundry scrap shortage, there exists very little financial incentive to sort out wrought alloys from the foundry mix and to sell these separately.

The next decade is likely to see a change in these skewed economics. As Asian economic growth continues, Japan's history of the post-World War II economic boom is likely to be mirrored on the mainland. As wages rise and the expectation of the population for good life, health, and clean environment increase, the playing field is likely to level out for both the manufacturers and the recyclers. Serious questions remain, answers to which are far beyond the scope of this paper: Will there be any North American and European players left to enjoy this level field? Where will the raw materials and resources come from to satisfy the Asian hunger for western-style wealth?

RECYCLING COSTS AND SCRAP VALUES

Lightweighting is increasingly shifting the vehicle composition from steel to light metals and plastics. This is already affecting the value of the ELV. For example, in a 2000 automobile, nonferrous metals comprise ~10% of the vehicle weight, but account for more than half of the scrap material value.[1] The nonmetallic components still have a small negative value reflecting the cost of disposal charged by the landfills for use of the residue as the daily landfill cover.

The relative abundance of the metals

VEHICLE DESIGN AND THE THREE RS

Giving manufacturers the responsibility for recycling of their own products is a mixed blessing. It encourages consideration of recycling during design and manufacturing cycles, but it also encourages setting up of inefficient parallel recycling systems by manufacturers with little interest or understanding of the scrap business.

A vehicle design engineer has key input in determining the ease of processing of the end-of-life vehicle (ELV) for reuse and recycling. The third-priority status of the design for recycling is appropriate. The first design priority should always be to reduce—reduce accidents by optimizing handling and safety features, and reduce fuel consumption and associated air emissions. The second design priority should be reuse. Extend the vehicle lifetime by eliminating corrosion and facilitating dismantling and maintenance of each component. This will also pay off for ELV dismantling and the re-manufacture of parts for the spare parts market. The current recycling system is already built to deal with and to separate various construction materials, hence it imposes less demanding and appropriately third-priority design constraints. Nevertheless, since the focus of this paper is recycling, the most important design considerations for recycling are as follows.

- Eliminate the toxics. These include chromium 6+, mercury, lead, halogenated polymers—polyvinyl chlorides, polychlorinated biphenyl, etc. Heavy/toxic metals on shredding get distributed throughout the shredder residue and thus make it more difficult to use as a daily landfill cover or a source of heat. During combustion, chlorinated and fluorinated polymers can lead to emissions of some of the most toxic and ozone-layer-destroying air pollutants.
- Design key structural components from prime alloys with a maximum property-to-weight ratio. For example, reduce the weight of AlSi-A356 wheels, AlZn-7029 bumper and structural extrusions, and AlMg-5754 sheet structural stiffeners. Choose from the standard alloy families based on the common alloying elements Al, AlCu, AlMn, AlSi, AlMg, AlMgSi, and AlZn. Forget uni-alloy vehicles, but where possible minimize the part count and minimize the number of materials/alloys in any one part.
- Avoid exotic alloying elements. Exotic alloys can have enticing properties. The addition of lithium gives high specific stiffness, and tin enables super-plastic forming. However, the concentration limits for these elements in common alloys is <0.05%, and a small number of components with exotic alloying additives can poison the aluminum recycling system. There is a related issue in the AlSi foundry alloys with the alloying elements used to refine and modify the Al-Si eutectic structure. The west uses Sr, Ca, and Na additives, while Asia uses Sb. The systems are incompatible as the combination of additives precipitates out. Millions of Asian-built ELVs are shredded in the west with local ELVs, increasing the treatment costs for secondary foundry alloys.
- Provide an appropriate market for any recycled materials in the transportation sector. Metal concentrate from the shredders already contains aluminum from all industrial sectors including buildings, packaging, appliances, machinery, etc. There is no need to segregate the ELVs at the shredder. Design some high-volume components with high recycled content. Structural castings are another desirable example. In the aluminum-intensive vehicle there is an increasing use of structural thin-wall castings in suspension components and structural pillars in body in white. Foundry alloys have higher alloying element concentrations and lower formability requirements than stamped sheet components. This allows higher recycled content and provides a continuing market for recycled aluminum. Structural castings are designed to consolidate

recovered from scrap shredder nonmagnetic metal concentrate has steadily evolved over the years. In the 1980s it was dominated by zinc, copper, and brass, which combined to make up over 70% of the total. Today aluminum dominates. Even after many shredders remove an aluminum fraction for direct sale to secondary smelters, the remaining metal concentrate still averages over 70% aluminum. The stainless-steel fraction is also growing, while the remaining sink metals continue to lose their share of the shredded scrap market.

In the recycling of both aluminum and magnesium, recycling processing costs are a small fraction of the prime reduction costs. The energy consumption per tonne of recycled aluminum ingot is ~2 kWh/kg—about 5% of the cost of mining, alumina refining, and aluminum reduction. The capital costs of a secondary smelter and upstream scrap processing are ~$500 per annual tonne of aluminum—again, about 5% of the costs of a prime smelter, power plant, and alumina refinery.

The cost of remelting scrap aluminum or magnesium is lower than that of electric-arc-furnace production of steel from scrap. This is mainly due to the lower melting temperatures of the light metals than steel. This comparison is especially attractive for light metals on a per-volume basis. In lightweighting, material substitution is never done on kg/kg basis; it is more often closer to a cc/cc basis. In this way, recycling significantly favors the substitution of light metals for steel in lightweighting applications.

There is, however, a widely held misconception concerning the value of scrap and secondary metal. Hopeful buyers figure that since the light metal recycling costs are low, the recycled metal should be sold at significant discount to prime. This has not been the case in the past several years of scrap shortages. For any particular application, the value of scrap is set by the component it replaces in the furnace batch. Typically, this is the most expensive component, which for any alloy with less than 100% recycled content is prime. Therefore, as long as prime is displaced by scrap, the value of that scrap to the secondary smelter is set by the price of the prime, adjusted for the processing costs during recycling. Since these recycling costs are a small fraction of the prime price, the value of the light metal scrap is also high and close to prime.

Collection and dismantling costs in Europe and Japan are paid for by deposit programs and by additional end-of-life treatment charges paid by the manufacturer/customer at the time of purchase or registration. The residue disposal costs in Europe and Japan are excessive due to abnormally high landfill dumping fees; these at times threaten to make the ELV hulk worthless. In North America, the free market value of the parts for reuse and materials in the

Table II. Comparison of Impact and Benefits of Use of the Nonmetallic Fraction of ASR for ADLC vs Incineration with Energy Recovery

	Energy Recovery	Alternate Daily Landfill Cover
Landfill solids	Ash–0.3 t ($100)	ADLC 1 t $2
Energy	30 GJ $70	
Greenhouse gases	CO_x–2 t	
Airborne pollutants	NO_x, dioxins, Furans – ~0 t	
Net gain	($30)	$2

several joined stamped metal components. This reduces the number of multi-material joints, adhesives, and fasteners. Do not stop with metal components; look for filler and additive-tolerant applications for recycled rubber and plastics. Heat, sound vibration, and impact isolation require a high volume of hidden material with lax mechanical property requirements that can consume and add value to crumb rubber, plastics, and seat foam. Products include roof, floor, trunk, and hood liners as well as undercoating formulations.

- Promote development of markets for recyclables from ELVs in any industrial sector. Wrought-cast separation of aluminum alloys and alloy-sorting technology is already producing 3105 building siding and 3104 can body alloys from the aluminum recovered from auto shredder metal concentrates. Non-automotive markets have the potential to consume all the rubber and plastic from all forms of scrap including ELVs. Tire rubber and plastic chips can be used in civil engineering fill and erosion control; agricultural mulch; playground, arena, and parking lot surfaces; or as filter and bulking media. Crumb rubber and plastic can be used as binders or fillers for rubber/polymer modified asphalt concrete or for molded/extruded components. However, active promotion of these markets is necessary through education, elimination of contrary local regulations, development of scrap products (including standards and specifications), and investment in the infrastructure to effectively use these products.
- Design so that shredding generates mono-material pieces. This can be done by consolidating components and reducing permanent joining of different materials. Plastic snap fasteners that attach the headliners to the sheet steel are shredder- and recycling-friendly, as they break or unfasten when shredded. Attaching the sheet by welding incompatible alloys or using self-piercing rivets, however, is detrimental to recycling. Consider an aluminum sheet vehicle body with 2,000 steel rivets. There are ~250 kg of wrought aluminum metal in the vehicle body. On shredding, ~20% of the particles are too small to economically alloy sort and there are few rivets in this fraction. Larger particles average 25 g/piece. Particles with rivets usually contain only one rivet. Thus, out of 8,000 particles, approximately 2,000 would have rivets. A high-intensity magnet can remove the particles with rivets, but this results in a 25% reduction in high-value alloy recovery. Particles with rivets can be re-shredded to small sizes or sweat-furnace melted. In either case the product is only suitable for high-iron foundry alloys.
- Use composite materials judiciously, for example, where in-use energy savings justify end-of-life use as daily landfill cover. Fiber-reinforced plastics, metal-matrix ceramic composites, and other exotic combinations can have physical and functional properties providing significant in-use benefits. All too often separation of these materials into their components for recycling is not technically feasible or economically viable.
- Encourage source segregation and minimize mixing of scraps. Design new manufacturing plants with separate scrap handling for aluminum and steel, and, if practical, for individual alloys. Examples are stamping plant processing steel, 6111 outer skin, and 5754 inners.

There is no need to include recycled content in every vehicle component. This closed-loop recycling is the highest-cost option and is not necessary for an efficient recycling system. It is most effective to have few large-volume components suited to accept high recycled content and to allow free flow of scrap and recyclables from one product to any other.

hulk was sufficient to fund required de-pollution, and the U.S. Environmental Protection Agency (EPA) approval of the use of treated shredder residue (ASR) as landfill cover made the ASR a product with value to the landfill operator, reducing ASR tipping fees.

All potential recycling routes must compete economically with the lowest-cost option of directing the mixed residue scrap to the alloy having the widest composition limits. The large volume products listed in Table I have the least demanding specifications and thus set the lower limit on the value of the scrap and the residue.

DAILY LANDFILL COVER

The EPA requires a landfill cover of six inches of sandy soil daily or an alternate daily landfill cover (ADLC). Since landfills are sited in clay, sandy soil is not usually available locally, resulting in significant costs to the landfill operator to purchase and truck in the sandy soil. This soil also takes up valuable volume of the landfill. Consequently, landfill operators are happy to offer discounts on dumping fees to the suppliers of the materials that can be used as ADLC.

The following items are approved for use as a municipal daily landfill cover throughout the United States, including California: treated auto-shredder residue, shredded demolition residue, shredded tires, de-watered water treatment sludge, mulch, foam, and tarps.

Since there is a significant environmental benefit in controlling disease vectors (i.e., rats and gulls) and wind-blown garbage, ADLC can be considered as a legitimate albeit low-value use of shredder residue's nonmetallic fraction. The costs and value of recovering plastics and combustibles from shredder residue need to be compared to the benefit of their use as ADLC. Table II shows an example comparing the combustion of the nonmetallic portion of the shredder residue with energy recovery against its use as ADLC.

Without considerable additional treatment, a shredder residue's nonmetallic portion combusts, leaving ~30% ash in which residual heavy metal ions are in toxic leachable form. Current U.S. regulations require that such ash be disposed as hazardous waste at costs in a range of $300–500/t. The value of any energy recovered does not compensate additional landfilling costs, and this does not even take into account greenhouse gas emissions and the costs of air pollution controls. Use of shredder residue as fuel for cement kilns and/or iron smelting has also been proposed. In these processes, the ash becomes part of the cement product or the steelmaking slag. However, copper and/or iron oxide are undesirable impurities in iron and cement, respectively. The cost of ridding the shredder residue fuel of these difficult-to-separate impurities must be weighed against the fuel value. In the United States, ADLC is the preferred use. In Europe, however, where regulations are increasingly banning shredder residue from municipal landfills, there are some cement kilns burning shredder-residue-derived fuel and claiming this as satisfying the E.U. requirements for car recyclability.

CURRENT INTEGRATED MATERIAL RECYCLING SYSTEM

After being de-polluted and stripped of spare parts by a dismantler in a junkyard, the ELV joins an integrated global material recycling and production system. Figure 1 attempts to summarize the major recycling loops in present aluminum production, use, and recycling. The aluminum portion of the global material manufacturing/recycling system needs to consider more than just post-consumer aluminum.

In-house prompt and manufacturing scrap streams combine to be nearly as large as the post-consumer scrap flow. These prompt scrap recycling loops have a significant impact on the relative economics of the materials competing for the various applications. For example, near-net-shape casting gives foundry alloys a significant advantage over stamped sheet alloy components, which generate scrap at direct chill ingot casting, hot and cold rolling, blanking, and stamping stages. During production and component manufacture, the alloys are known, and it is usually feasible to maintain source segregation of the scrap by alloy. Source segregation is always less expensive than subsequent sorting of the combined scrap mix.

The aluminum components are usually a minor fraction of the final assembled vehicle, building, machine, or packaged product. Just as assembly and construction has to deal with all the component materials, so does post-consumer disassembly and recycling. Whereas the recycling of production and manufacturing scrap can concentrate on a few known aluminum alloys, the post-consumer recycling system must, as it is already set up to do, process and recycle all the material components of the end-of-life items, vehicles, and buildings.

Aluminum is still a minor player in this system. When steel scrap prices tumbled from $100/t down to $50/t, shredders quit shredding cars and building demolition residue. With no steel scrap being generated, there was also no recovery of nonmagnetic metals and other recyclables. Any recycling system has to account for this essential commingling of materials in the post-consumer recyclables. There are virtually no aluminum or steel recycling yards—only junkyards and scrap yards. The car shredders shred much more than cars; they shred any metal-containing item or debris. A recycler must market all product streams to remain profitable.

PROCESSING OF ELVS AND OTHER POST-CONSUMER END-OF-LIFE ITEMS

As depicted in Figure 2, the North American post-consumer metal recy-

Table III. Processes Used to Upgrade Light Metal Scrap[2]

Separation	Process
Steel separation[2]	Magnetic
Non-magnetic metal-nonmetal separation[2]	Size screening
	Conductivity–eddy current separation (ECS)[3,4]
	Density–air suction/elutriation
	Density–sink-float[2,3,5,6]
Al-other metal separation	Sink-float and ECS
Al-Mg separation	Sink-float, ECS, and color sort[7,8]
Chemical-composition-based Al alloy batching	Laser-induced breakdown spectroscopy[9–13]

cling industry consists of less than 6,000 scrap collection and dismantling yards, about 200 scrap shredders, close to 10 sink-float plants, and one metal sorter (Huron Valley Steel Corporation). Why this inverted pyramid structure? Collection needs to be widely distributed in individual localities. This layer is controlled by small, usually family-run, enterprises.

These figures reflect the sequential removal of the recycled materials from the shrinking mixed recyclable stream and the highly mechanized, productive material separation and scrap-sorting plants. In Europe there is a similar structure with the addition of a more vertically integrated ownership structure. A recent attempt to gain control of the scrap collection system by the Ford Motor Company was quickly abandoned due to the complexity and manual labor intensity of the junk collection, dismantling, and baling business. The material volume is steadily decreased as the stripped vehicle hulks are flattened, transported to shredders, and converted to fist-sized pieces.

Shredders recover steel and may skim off a portion of aluminum with an eddy current separator. They in turn sell the nonmagnetic metal concentrate to sink-float plants to separate float

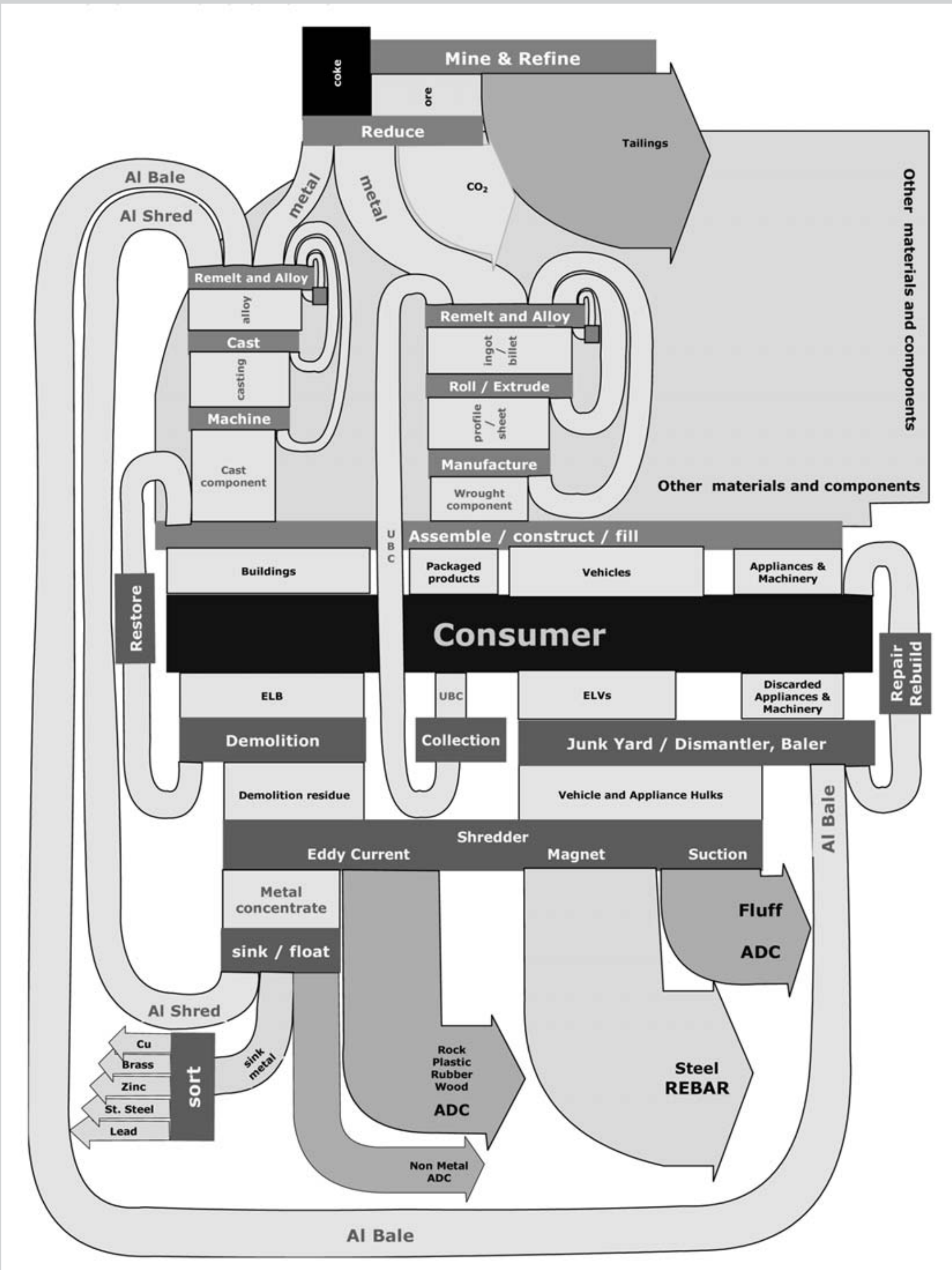

Figure 1. The interaction in aluminum production, use, and recycling.

aluminum and sink metals from nonmetallic particles. Huron Valley Steel Corporation has a nonmagnetic metal sorter to separate Al, Mg, Cu, Zn, brass, stainless steel, and lead—a highly mechanized and highly productive system. However, it is currently more profitable to sell the mixed sink metals to Asia for hand sorting there than to sort the sink metals and market the products in North America and Europe.

Dismantling and Shredding

End-of-life vehicles or other items are dismantled for parts re-build and re-use or removal of dangerous/toxic substances such as liquids (e.g., gasoline, oil, coolants, and refrigerants), air bag propellants, and lead batteries. Stripped hulks are shredded for material recovery. Shredding is essential for efficient scrap sorting. The process liberates mono-material pieces enabling material separations, densifies the shredded product enabling cost-efficient transport of the relatively low-value residue, and generates a predictable size and shape of particles enabling mechanical handling and sorting.

Dismantling and shredding are complimentary; dismantled parts need to be shredded for cost-efficient handling, storage, transport, and material recovery.

Upgrading Light Metal Scrap

There are many processes practiced commercially in Europe and North America to upgrade light metal scrap—all of which are characterized by high productivity, low processing costs, and negligible energy requirements (as shown in Table III). Huron Valley Steel Corporation publications,[2,5,6,7,9,10,11] and those by authors from Delft University of Technology[3,4] have described nonproprietary aspects of these technologies. An inspector can manually perform all but the last separation (chemical-composition-based alloy batching).

Table IV. Al In-Use Pool (~year 2000)

Al prime adding to the pool	~20,000,000	t/y
Losses (destructive, melt & landfill)	3,000,000	t/y
Net Al pool growth	17,000,000	t/y
Total Al pool	**>500,000,000**	**t**
Vehicle pool	~500,000,000	Vehicles
Net increase in Al in in-use vehicles	~4,000,000	t/y
Pool of Al in vehicles	**~40,000,000**	**t**

GROWING LIGHT METAL POOL

As customers use products containing light metal components, they are adding to a growing pool of light metals (see Table IV)—a veritable above-ground mine of end-of-life items. The change in metal reserves in this mine is best estimated by the difference between the source (global primary production) and losses (global losses to the permanent metal sinks). These losses include:

- Destructive uses—steel deoxidants, powders, pigments, and metallized packaging and foil laminates (<400 kT)
- Metal oxidized upon remelting (<750 kT)
- Metal buried in municipal landfills (<1,850 kT)

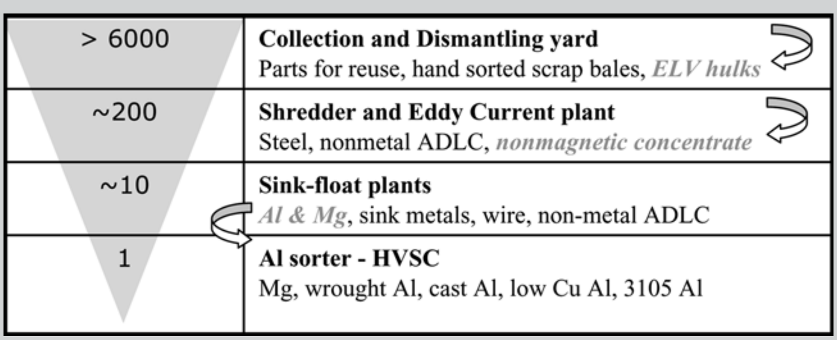

Figure 2. Global aluminum production—primary and secondary.

The accumulation of aluminum in the pool of in-use products began in earnest in the 1940s with World War II. Integrating the net annual additions over time gives a current estimate of the aluminum reserves in this mine at ~0.5 billion t. Coincidentally, 0.5 billion is also the number of vehicles driving around the globe. These vehicles already store ~40 million t of aluminum—approximately two years of production of the entire world's primary smelters.

Magnesium will soon add significantly to this mine. While the aluminum industry is mature, magnesium is at the beginning of an explosive growth curve. On a percentage basis, magnesium is the fastest-growing metal market.

Figure 3 illustrates the growing importance of recycled metal in satisfying the global demand for aluminum metal. Figure 4 illustrates that although aluminum used in transportation is the fastest-growing market segment, it still represents a minor portion of the above-ground mine. The recycled metal average composition reflects the metal recovered from this mine and not the current input to the in-use pool. This is a major consideration in determining the average composition of recycled metal and underlines the importance of the free flow of recycled metal from the above-ground mine to any current market.

Figure 5 illustrates that transportation drives the growth of aluminum consumption, but Figure 6 shows that the ELVs are an even larger fraction of the metal recovered for recycling.

NEED FOR SCRAP SORTING

For over a decade various publications have warned of potential problems in maintaining complete recycling of aluminum scrap due to composition incompatibilities of the alloys used in various markets (e.g., see References 1,

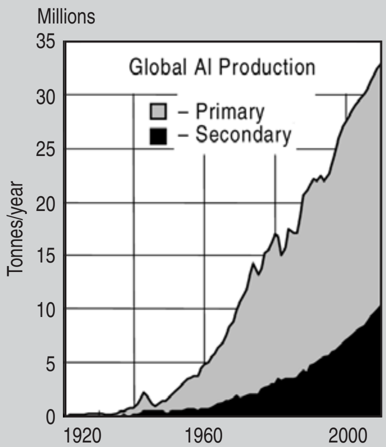

Figure 3. Global in-use aluminum—auto and other uses.

14, 15, and 16). For example, wrought alloys tend to have high magnesium content while cast alloys are usually high in silicon. As the formability and property requirements of new applications become more stringent, alloy designers tend to tighten the alloying element and impurity concentration limits, while the melt composition of the mixed alloy scrap is suitable only for the least-demanding secondary foundry alloy applications.

Table V quantifies this warning in the transportation sector. In 1999 metal from recycled cars could not satisfy the secondary cast demand of the rapidly expanding aluminum engine block and transmission case market; 500,000 t needed to be sourced from non-ELV aluminum scrap sources. This table also shows current predictions for 2009 accounting for the rapidly growing Asian car production and domestic car market and faster-than-expected market penetration by aluminum cast components. Wrought aluminum has penetrated the luxury car market with Jaguar, Audi, and Honda leading in the use of wrought aluminum components. The penetration of the mass-production car market by aluminum sheet components awaits optimization of continuously cast sheet and a related drop in the sheet price. At the same time, penetration of aluminum foundry alloys into drive-train components continues unabated. Even with these adjustments, the total scrap recovered in 2009 is likely to exceed the market for Al38X engine blocks and transmission cases. About 1,500,000 t of metal may become available for other applications and there will be a demand for ~5,900,000 t of higher-purity aluminum-alloy applications in the transportation sector. Clearly, a means of upgrading aluminum scrap metal will be useful.

However, let us consider what would happen if there were no means of upgrading the aluminum scrap mix. Would that make aluminum non-recyclable? Of course not. For the first time we would be in the position where the supply of aluminum scrap exceeded the demand for the particular scrap category. Economics would dictate that the price drop to a point where demand would match supply. An increase of aluminum 38X foundry alloy consumption of only 20 kg/new car would be necessary to consume the available 1,500,000 t of scrap. This could be easily achieved by substitution of aluminum block engines and/or transmission cases in a few of the mass-market car models still using iron power trains. A price drop in aluminum foundry alloy is the most likely change to induce car manufacturers to adopt now well-proven aluminum engine technology.

Further, technology already exists for upgrading light-metals scrap. Since the integrity of the metal scrap recycling system in the next decade does not depend on scrap upgrading, the degree to which these techniques are adopted will be strictly driven by economics and the market demand for alloys with recycled scrap content.

ELV RECYCLING REGULATIONS

The European Union, Japan, and Korea are moving forward with a wide-ranging set of regulations for recycling of ELVs. In the United States, the EPA regulates air and water pollution, affecting how end-of-life products are recycled and disposed of, but recycling decisions are left to the free-market economics of the recycling industry. In this section we compare these approaches. They all share the same goal: prevention of waste and encouragement of reuse, recycling, and other forms of recovery. They differ in what they regulate and how they implement these regulations

The U.S. EPA requires de-pollution

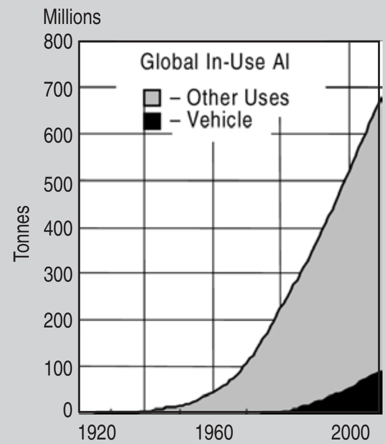

Figure 4. Global aluminum consumption—vehicles and other sources.

of the ELV before shredding by removal of all liquids (refrigerant, coolant, gasoline, and oil), removal of the lead-acid battery, and deployment of air bags. The EPA also requires that the ASR be stabilized prior to landfilling to pass metal-leachability tests. Stabilized ASR is approved as an alternate daily landfill cover.

Japan's Automotive Recycling Law sets up a separate vehicle recycling system. It separates the recycling of valuable metals from items costly to recycle: ASR, airbags, and refrigerant liquids. The customer pays a recycling fee in advance to cover the costs of recycling these three items. This subsidy reduces the de-pollution costs, thus increasing the value of the ELV. There are ASR recycling targets requiring a 30%, 50%, and 70% decrease in ASR landfill by 2005, 2010, and 2015, respectively.

The E.U. Directive on ELVs requires for new car designs no toxics (Pb, Hg, Cd, or Cr^{6+} with some exceptions); design for dismantling, reuse, and recovery of components and materials; increase recycled content of vehicles to provide a market for recycled materials; de-pollution in licensed facilities; and specific reuse and recovery targets (85% of the ELV weight by 2006, 95% of the ELV weight by 2015).

How are these regulations implemented? The U.S. system works with minimum government interference, driven by the inherent economic value of the spare parts and recycled materials. De-pollution is usually done by the

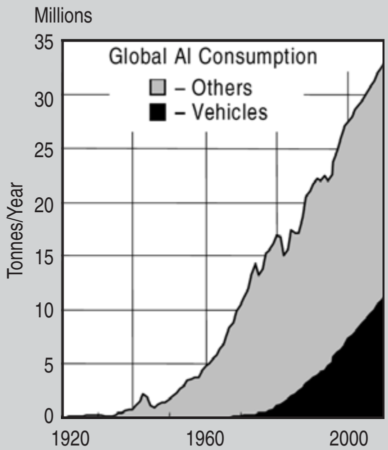

Figure 5. Global aluminum recycling—vehicles and other sources.

dismantler and the cost is calculated into the value of the ELV hulk.

Japan's Automotive Recycling Law registers and licenses recycling business operators, sets up an electronic manifest system, and collects recycling fees from owners and distributes them to the recycling business operators recycling ASR, airbags, and chlorofluorocarbons.

The E.U. Directive on ELVs requires: free take-back from the last owner; a certificate-of-destruction as a condition of de-registration; licensed collection and treatment operators; producer be responsible for design that will allow achievement of reuse/recovery targets; producer/manufacturer be responsible for recycling of the ELVs; and that producers bear the costs of ELV collection and dismantling of hazardous components.

QUESTIONABLE ASPECTS OF ELV REGULATIONS

The European and Japanese regulations are being used to construct dedicated local car recycling systems. This conflicts with the interdependent, global nature of existing vehicle manufacturing and scrap recovery systems. Metal scrap, other material production, and parts manufacturing are all quickly being exported from Japan, European Union, and the United States to mainland Asia. The European Union and the United States are thus left with the low-value ASR. Manual dismantling for material recovery is not economical in Japan, the European Union, or the United States; however, low transportation costs to China and India make it economical there. One possible solution would be to sell to Asia de-polluted, un-flattened ELV hulks, stripped of all re-usable/re-manufacturable parts. Manual dismantling of plastics, glass, interior liners, etc. would be economical there due to low labor costs.

The European and Japanese regulations imply setting up a recycling system dedicated to ELVs. These are currently handled by multipurpose junkyards that handle all other types of scrap from demolition residue, furnishings, appliances, machinery, etc. There are common techniques for recycling all these items. Segregating the potentially most profitable and largest volume stream from the rest is likely to make it less economical to recycle the smaller, less profitable streams. Unless care is taken, an increase in the car-recycling rate might result in an overall decrease in recycling of other items.

In the present integrated, globalized car-recycling system, specific recycling and recovery targets for ELVs are impossible to quantify and are hence unenforceable. They are almost always translated to recyclability, which is not the same. Building a new, separate recycling system to be able to monitor these targets is counterproductive. Achievement of reuse/recovery targets depends on further development of non-automotive uses of non-metallic ELV scrap, but car manufacturers usually lack expertise and interest in non-automotive products.

The specific recycling targets both in Japan and the European Union could be met by limiting the concentration of high-value metal recyclables in the ADLC and recognizing ADLC as a low-value "recovered product," as it is already done in the United States.

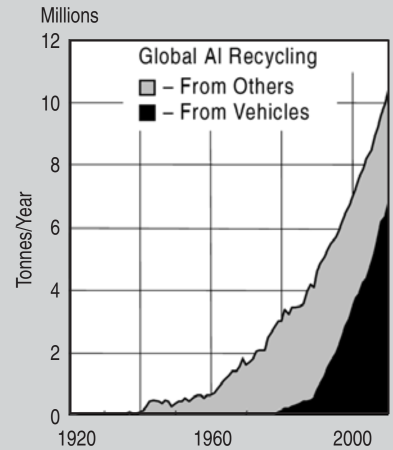

Figure 6. The North American post-consumer recycling industry.

Development of higher-value recovered products to be used outside of the landfill for selected groups from the non-metallic portion of the ASR should be encouraged.

Car manufacturer expertise is better utilized in optimizing vehicle safety and fuel efficiency by maximizing the performance-to-weight ratio. Over the vehicle life, this reduces the environmental impact of the vehicle by more than the energy cost to produce its materials of construction. Cars should be constructed from recyclable materials, but the responsibility for recycling is already well taken care of by the existing recycling industry.

In Europe, automakers are made responsible for recycling, plus collection and de-pollution costs. Manufacturers control only a portion of the recycling system. Scrap recycling rates are determined by a combination of system constraints that are not under the control of vehicle manufacturers. These include environmental regulations and their enforcement; import duties, taxes, and

Table V. Global Estimates for Prime and Secondary Al Alloy Use in Transportation Sector Illustrating an Opportunity for Al Scrap Sorting

	1999	2009	
Transportation Al market	6,600,000	10,900,000	t
Number of new vehicles	55,000,000	70,000,000	
Number of ELVs	40,000,000	55,000,000	
Recycled Al from ELVs	75	120	kg/ELV
	3,000,000	6,600,000	t
Secondary cast Al market	64	71	kg/new car
	3,500,000	5,000,000	t
Needed from non-auto scrap	500,000		t
Auto scrap available for sorting		1,600,000	t
Wrought and prime cast transportation Al	3,100,000	5,900,000	t

exchange rates; transportation costs; lack of education on possibilities and inertia of potential scrap users; existing standards, existing system infrastructure, and high cost of change; and also political patronage in landfill, recycling, construction, and paving contracts

European Union regulations impose excessive part marking and uneconomic dismantling requirements where shred sorting does the separation more economically.

The imposition of unnecessary, expensive bureaucratic regimes of regulations, fees, and subsidies does not necessarily improve the recycling system. On the contrary, they simply add cost without necessarily improving on the existing global system.

USEFUL RECYCLING INITIATIVES

Some aspects of the Japanese and E.U. regulations are beneficial to the recycling system. For example, they encourage prompt ELV disposal by continuing vehicle registration fees until transfer of responsibility by sale or issue of "certificate–of-destruction." This could be further improved by paying the fair market value of the ELV to the last owner during the cost-free ELV disposal at a de-pollution facility.

Other regulatory initiatives that would be beneficial include:

- Keep high-value recyclables out of the landfill by banning landfilling of ELVs, white goods, electronics, etc. (Regulations to that effect already exist in many localities. For example Michigan recently banned cans, soda pop bottles, and tires from the trash imported from Toronto.)
- Require processing by shredding and separation of valuable recyclables
- Encourage setting up of shredding and segregation plants at landfills (shredding densifies the residue preserving the landfill space)
- Regulate maximum metal content for ASR (1–2%)
- Use and expand existing recycling infrastructure: junkyard re-user and de-polluter, shredder, sorter, secondary smelter, or processor
- Seek synergies; use expertise from and expand upon existing large recycling initiatives and technologies covering areas such as municipal solid waste, demolition residue, tire recycling (15% of scrap tires come from ELVs), road surface repaving, wastewater treatment and sewage sludge, white goods and machinery, and electronics

Finally, to optimize the global recycling system, the field needs to be leveled for all players by taking the following steps:

- Addressing round-trip transportation charges for manufactured goods
- Lowering the import duties in Asia on prime and sorted metals
- Eliminating the VAT
- Challenging monetary exchange rates fixed at unfair levels
- Regulating and uniformly enforcing global environmental standards

Unless the European Union and United States succeed in addressing these issues, the flow of scrap raw materials, manufacturing plants, and jobs from the European Union and the United States to Asia will continue and local recycling initiatives and recycling industries will continue to suffer. A breakdown of any part of the global recycling system reduces the efficiency of the whole recycling effort.

CONCLUSION

There is not, nor should there be, a specific mandated ELV recycling system. There is an existing scrap recycling system that draws scrap from all scrap supply markets and sells to all scrap-consuming markets. This is already a globally integrated system with scrap flowing freely from the developed countries to the third world. Trying to set up a system that monitors closed-loop recycling within any portion of the system is not likely to add value or result in any more recycling. Adding closed-loop constraints is sure to add costs and increase recycled material prices. A more fruitful approach is to monitor and set metal, rubber, and plastic maximum content limits on any residue streams from the recycling system. Moreover, we should continue and expand monitoring and control of the other effluents of the recycling facilities. Air should be monitored for both toxics (dioxins, furans, and polycyclic aromatic hydrocarbon) and for green gas emissions. Water should be checked for contamination from liquid residue streams and by leachate from solid residue.

Doing that, one might easily find that it may be more environmentally friendly to use the PVC-contaminated mixed plastics as daily cover to the municipal waste landfills than to generate airborne toxics, greenhouse gases, and hazardous ash in attempts at pyrolysis or incineration with energy recovery. Laws and regulations for doing this are already in place in some jurisdictions. The challenge facing the worldwide system is to level the playing field by uniformly applying these regulations.

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