Automotive aluminum recycling at end of life: a grave-to-gate analysis

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Executive summary

Need

The aluminum industry and its stakeholders need to collect quality data and information to achieve a comprehensive understanding on the recycling of end-of-life automotive aluminum. Aluminum demand is increasing in the automotive industry. Yet the recycling of the material at the end of useful life has not been well understood due to the complexity of the automotive recycling value chain and the absence of quality statistical data and information. This has led to confusion and speculation about the fate of the metal – whether it is well recycled or permanently lost. Recycling is a critical step for the sustainability of a man-made metal like aluminum since it significantly saves both energy and scarce natural resources. Therefore, efforts must be made to gain quality data and information to examine the efficiency and effectiveness of the automotive aluminum recycling value chain.

Project goal

The objective of this study is to obtain a more quantitative understanding of the fate of automotive aluminum at the end of its service life. This project will determine the recycling rate of aluminum and its alloys within the United States' automotive sector. A holistic and detailed understanding of the processes, technologies and their effectiveness, regarding the collection and recovery of aluminum from end-of-life automobiles, and the resulting material flows must be pursued and reported. The information and results of the study are intended to be utilized by both the aluminum industry and its stakeholders for environmental assessment, process efficiency improvement, design for the environment (DfE) and other sustainability-related purposes.

Methodology

A grave-to-gate process material flow analysis (PMFA) approach is used to determine the recycling rate of automotive aluminum/aluminum alloy metal units. Three operations contribute to the total aluminum metallic loss to the landfill after an automobile enters a dismantling operation. These include shredding, downstream separation, and scrap melting. Process specific surveys were distributed to two types of material collection operations, auto dismantlers and downstream separation systems (DSSs), as well as metal recovery process operations (*i.e. secondary smelters and re-melters*) in order to investigate the percentage of aluminum metal unit loss and process material flow quantifications through the entire recycling system for this commodity. Grave-to-gate, within the system boundary of this study, spans the moment an automobile enters a dismantling yard to the moment the aluminum metal units are completely recycled and enter back into life as an input material for any application requiring aluminum (open loop recycling).

The amount of material processed through this system reaching the gate of a new life cycle is not compared to an input value to the PMFA system because end-of-life vehicles and automotive aluminum scrap are exported so frequently and these values are not monitored accurately for the entire market in the US. In other words, this study does not utilize a mass-balance analysis. The amount of end-of-life vehicles that retire on an annual basis is only used in this study to determine the market share covered by each survey respondent and the market share of the respondents as a whole. The recycling rate is determined by combining a material collection rate with the recovery process efficiencies as applicable to the material that flows through each step in the recycling process.

Results/discussion

The overall recycling rate for automotive aluminum was found to be 91%. The distributed surveys covered 5% of the United States' dismantling industry considering the amount of end-of-life vehicles entering the survey respondent's lots, 32% of the downstream separation system industry based on volumetric throughput and 60-70% of the secondary aluminum production industry based on market share responses. The weighted average material collection rate for end-of-life vehicles that flow through a dismantling operation and a downstream separation system is 99.7%. The major detriment on the automotive aluminum recycling rate derives from the recovery processes. Aluminum in the form of aluminum oxide is delivered to landfill from these processes. When a heavy gauge scrap class is charged, referred to in this study as a heavy recovery process, a metal yield of 95% is attained. Light gauge scrap melting is estimated to result in a metal yield of 91%, and this process is referred to a light recovery process throughout the report. The majority of automotive aluminum is charged as a light gauge, mixed, shredded scrap. It has been estimated that 86% of obsolete auto-aluminum is charged in this form.

A sensitivity analysis was conducted to determine a minimum and maximum automotive aluminum recycling rate percent (RR%) for the US. This RR% range is 80% - 98%. The weighted average of 91% falls within this range and is estimated to be much more representative of the entire industry in comparison to these extremes. This analysis gives an understanding of the variability of the secondary aluminum production industry pertaining specifically to automotive aluminum collection and recovery.

Introduction

The demand for aluminum in the automotive sector in North America is projected to grow through 2025. Ducker Worldwide reports a 39% increase of aluminum weight per North American light vehicle over the next decade. The major driver for the increase is the added content in body sheet and closures with continued content growth in casting and extruded auto-components[1]. The growth of aluminum is partly driven by the benefit of vehicle light-weighting to meet the Corporate Average Fuel Economy (CAFÉ) standards. Aluminum is a lighter automotive material compared to conventional heavier materials with the same or greater strength. Lighter material allows for building lighter vehicles with the same or improved safety performance while increasing fuel economy[2]. The increased use of aluminum in automotive not only helps improve vehicle fuel economy but also reduces overall energy consumption and greenhouse gas emissions from a full vehicle lifecycle point of view, shown in multiple life cycle analysis studies[3,4].

The overall benefits of automotive light-weighting with aluminum cannot be fully achieved without the material being efficiently and effectively recycled and reused at the end of its service life since the metal is a relatively energy intensive material to produce. Like most other man-made materials, recycling is a significant requirement for aluminum to be responsibly and sustainably used to serve human needs. The metal is highly recyclable and can be repeatedly recycled and reused. Recycling aluminum only consumes about 8 percent of the energy of virgin aluminum production[5].

It has been a long-held belief that that aluminum along with other automotive metals is readily recycled as long as the vehicle itself is properly recycled after its service life. Yet details of the recycling have been traditionally poorly understood by both the aluminum industry and its stakeholders. This is due to the complexity of automotive recycling itself, as well as the absence of statistical data and large scale quality studies. There have been many published academic papers on the topics of automotive aluminum recycling and the broader automotive material recycling. However, these studies have been either focused on different regions and countries rather than the United States or North America, or on individual cases that are not representative of the general situation and the average practice of the entire industry. Questions such as how effective aluminum recovery can be during the recycling processes and what recycling rate can be achieved have never been satisfactorily answered. Such reality has prompted the Aluminum Association to sponsor this research project in order to get a comprehensive understanding of the fate of automotive aluminum at the end of its service life.

Goal of the study

The objective of this study, as stated previously, is to obtain a more quantitative understanding of the fate of automotive aluminum at the end of its service life. Through the study, the Aluminum Association intends to gain representative and scaled data and information on how aluminum is separated and recovered during the end-of-life vehicle (ELV) recycling processes. Consequently, the Association aims to estimate a representative aluminum recycling rate for automobiles. The information and results of the study are intended to be utilized by both the aluminum industry and its stakeholders for environmental assessment, process efficiency improvement, design for the environment (DfE) and other sustainability-related purposes.

In order to achieve the goal of the study, the project team decided to adopt a process material flow analysis (PMFA) approach to develop an analytical model to examine the losses of metal aluminum and its alloys during the recycling processes. Empirical data is designed to be collected from each of the relevant processes throughout the automotive recycling industry. Consequentially, a recycling rate is calculated based on the model and its data, incorporating reasonable assumptions and the industry's best knowledge.

System boundary of the study

The input to the system encompasses passenger automobiles, from sub-compact to light trucks, which reach end of life and are collected for recycling in the United States of America. This value is in excess of 12.6 million vehicles annually[6]. The process material flow model begins with the dismantling operation on end-of-life vehicles and is completed when the automotive aluminum is recycled and enters a new life cycle as a recycled aluminum product (*i.e. open loop recycling*).

The following sections will introduce the flow system for processing end-of-life vehicles. There are three material collection stages, namely dismantling, shredding and downstream separation systems. Recycled auto-components either enter into a new life cycle as a recycled product for further manufacturing or as reusable auto-parts that begin new productive lives immediately but eventually reach a recovery process and become a recycled product. **Figure 1** lays out the process stages and defines the products that are typically dismantled or recycled during each processing step.

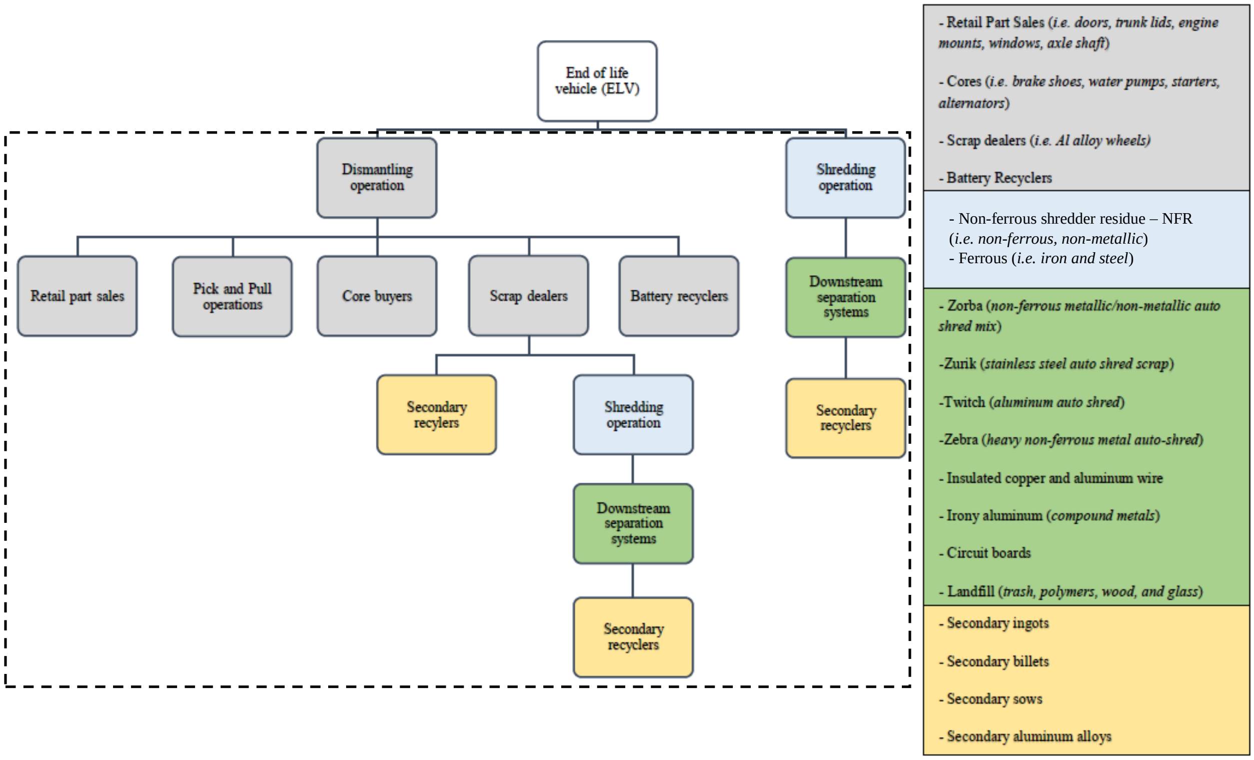

Figure 1: End-of-life vehicle process flows with process-specific product outputs.

Process descriptions

Material collection processes

Dismantling operations

In 2014, the average lifetime for a passenger car and light truck were 16.9 and 15.5 years, respectively[7]. After de-registration, the delivery of the ELV to a dismantling operation initiates this study's process material flow analysis. Once on the dismantler's lot the remaining fluids (*i.e. oils, lubricants, washing fluids*) are drained and high value and hazardous components are removed and distributed to the appropriate consumers or handlers (*i.e. core buyers, battery recyclers, scrap dealers, retail part sales*). Core buyers are interested in purchasing parts that can be refurbished, rebuilt and reused such as brake calipers, water pumps, starters, and alternators. Scrap dealers will purchase anything of known composition such as aluminum alloy wheels and in some cases mixed scrap streams chasing the buy low, sell high concept. This purchased scrap can be sent to auto-shredders, specialty shredders, or directly to a recovery operation. The products, predominantly Al-alloy wheels and bumpers, sent directly to a recovery process will be referred to as heavy gauge scrap.

Dependent on the age and model of the vehicle, dismantling operations determine the fate of the remaining ELV's recoverable weight. If the car's reusable parts are not in high demand, then the

ELV could be delivered to a "pick and pull" where members of the public can pay a small fee to recover auto parts for reuse or it is crushed into an auto hulk and delivered to a shredding operation. If the retired parts are in demand and entering back into a new lifecycle is feasible then the company will inventory the ELV and the auto parts become available for retail sale. In summary, a dismantling operation in this study is defined as a process at which, in addition to hazardous materials (*i.e. airbags*) being removed and excess fluids drained, metallic car components may be removed, sold and reused.

Shredding operations

The next step in the material collection process of aluminum from an ELV is shredding. Once all reuse value and hazardous materials have been removed from the ELV, crushing into the auto hulk/flat form and shipment to auto-shred plants sequentially occur. A market-driven recipe of light iron (*i.e. end-of-life white goods, home appliances*) and auto hulks is mixed on a conveyor belt directed towards a hammermill to be shredded into workable size pieces. Scrap metal from other industrial sectors like building/construction, machinery/equipment, and packaging/containers can also be added as ingredients to the mixed, obsolete metal recipe dependent upon market conditions and fluctuating value. Magnetic separation is commonly, if not always, utilized at shred plants to separate ferrous from non-ferrous/non-metallic scrap metal components. A conveyor belt containing the scrap, after shredding, is fed near another conveyor belt that magnetically attracts the ferromagnetic portion (steel and iron) of the shredded mixture. The non-ferrous/non-metallic stream remains on the initial belt and falls into a collection bin/pile or continues to a downstream separation system.

Shredding operations and downstream separation systems are differentiated throughout this study. Although infrequent, in some cases shredding operations do not separate beyond magnetically sorting ferrous and non-ferrous/non-metallic auto-shred scrap. This point of separation sets the limit between the two operations. Air separation, eddy-current separation, density separation and radiative techniques are all categorized into downstream separation systems. For those shredding systems that incorporate air separation prior to magnetic separation, this ejected stream is assumed to be processed at a downstream separation system to recover the sheet/plate-shaped and smaller sized light metals like aluminum. Hence, this flow is still considered and the loss monitored and analyzed in the same resulting landfill flow.

Loss strictly from shredding auto hulks is non-existent as there is no direct landfill flow from this portion of the process. The hammermill does not consume any metallic content. As just stated, any air-separated light material will be processed further to recover as much aluminum metal content as possible. After magnetic separation, it is assumed that all aluminum/aluminum alloy content resides in the non-ferrous shred residue that is delivered to another processing site or continues to a downstream separation system onsite. Material flow to landfill results at different points during downstream separation and will vary as a function of plant specific processing techniques.

Simply put, the landfill product combines at the end of complete treatment (*i.e. shredding and separation*) at a scrap processing yard. The research team asked the scrap processors to analyze or share their data regarding the aluminum alloy content in this combined product at the end of their entire material collection process. It should be noted that all scrap processors surveyed partake in some form of downstream separation beyond magnetic and air-separation. The entire landfill flow, after combination at the end of the entire process, is typically processed through a specific recovery system for this material stream or reprocessed a second time through the same collection system to recover the maximum metal auto-shred.

Downstream separation systems

Downstream separation systems (DSSs) are operations that utilize dry and/or wet automated sorting technologies to upgrade scrap in value and by-product specification. In most cases, shredding operations take part in some form of downstream separation. However, some operations focus solely on downstream separation and do not incorporate hammermill shredders. These companies purchase pre-shredded metallic scrap mixtures and further sort at their separation facility. Automotive shredded scrap can be sorted based on size, color, weight, magnetic properties, electrical conductivity, density and chemical composition, to name a few. Downstream separation systems incorporate the appropriate technologies that target the metallic constituents that fit their process-specific business models.

The non-ferrous residue (NFR) enters these operations as a mixed non-ferrous, non-metallic scrap stream after shredding, magnetic and, in some cases, air separation. NFR can be composed of plastics, rubbers, wood, stones, dirt, glass, foam, fabric, non-ferrous metals, circuit boards, insulated wire and some stainless steel. The concentration of the contaminants (*i.e. dirt, foam, plastic, rubber etc.)* is dependent upon the degree of air separation prior to magnetic separation. Some scrap processors target the wire and circuit board content prior to shipment of non-ferrous residue, therefore, this content is variant as well. The dominant non-ferrous metals are aluminum, copper, magnesium, brass and zinc along with non-magnetic stainless steel. DSSs incorporate technologies to target NFR's constituents, collect and sell them to further downstream consumers. These specific technologies are discussed in more detail in **Appendix A: Downstream separation system technology**.

From NFR, the majority of the aluminum content is ejected during eddy-current separation. The Institute of Scrap Recycling Industries (ISRI) classifies this scrap stream as Zorba. Zorba is a fragmented, non-ferrous mixture of metals including aluminum, copper, lead, magnesium, stainless steel, nickel, tin, and zinc. It predominantly consists of various grades of aluminum alloy. This material is generated by the following processing methods in any combination: eddy current, air separation, flotation, screening or other segregation techniques. The material must have passed through a magnet at least once to reduce or completely remove free iron (*i.e. scrap iron particulates*) or large iron attachments. This scrap class typically contains ~65% aluminum alloy by weight[8]. From Zorba, Twitch or Tweak is extracted dependent upon processing technique. Twitch, as defined by ISRI, is a floated, fragmented scrap stream derived from a dry or wet density separation technique that must be dried after processing and may contain no more than 1% free zinc, 1% free magnesium, 1% of free iron. There must be less than 2% non-metallic content and 1% free rubber and plastic. Twitch typically contains 90-98% aluminum alloy by weight[8]. Tweak is another fragmented auto-scrap class derived from either mechanical or hand separation. This material must be dry and cannot contain more than 4% free zinc, 1% free magnesium, 1.5% of analytical iron and more than a total 5% of non-metallic. Tweak is typically referred to as "long-throw" since it is recovered by controlling the distance of ejection during eddy current separation. Twitch and Tweak are charged into recovery furnaces to be re-melted/smelted for reuse. The recovery of these scrap classes will be referred to as light gauge scrap melting due to their size distinction from heavier, larger sized scrap charge discussed previously (*i.e. heavy gauge*). Please see **Figure 2** for the definition of both shredding operations and downstream separation systems as defined by this study.

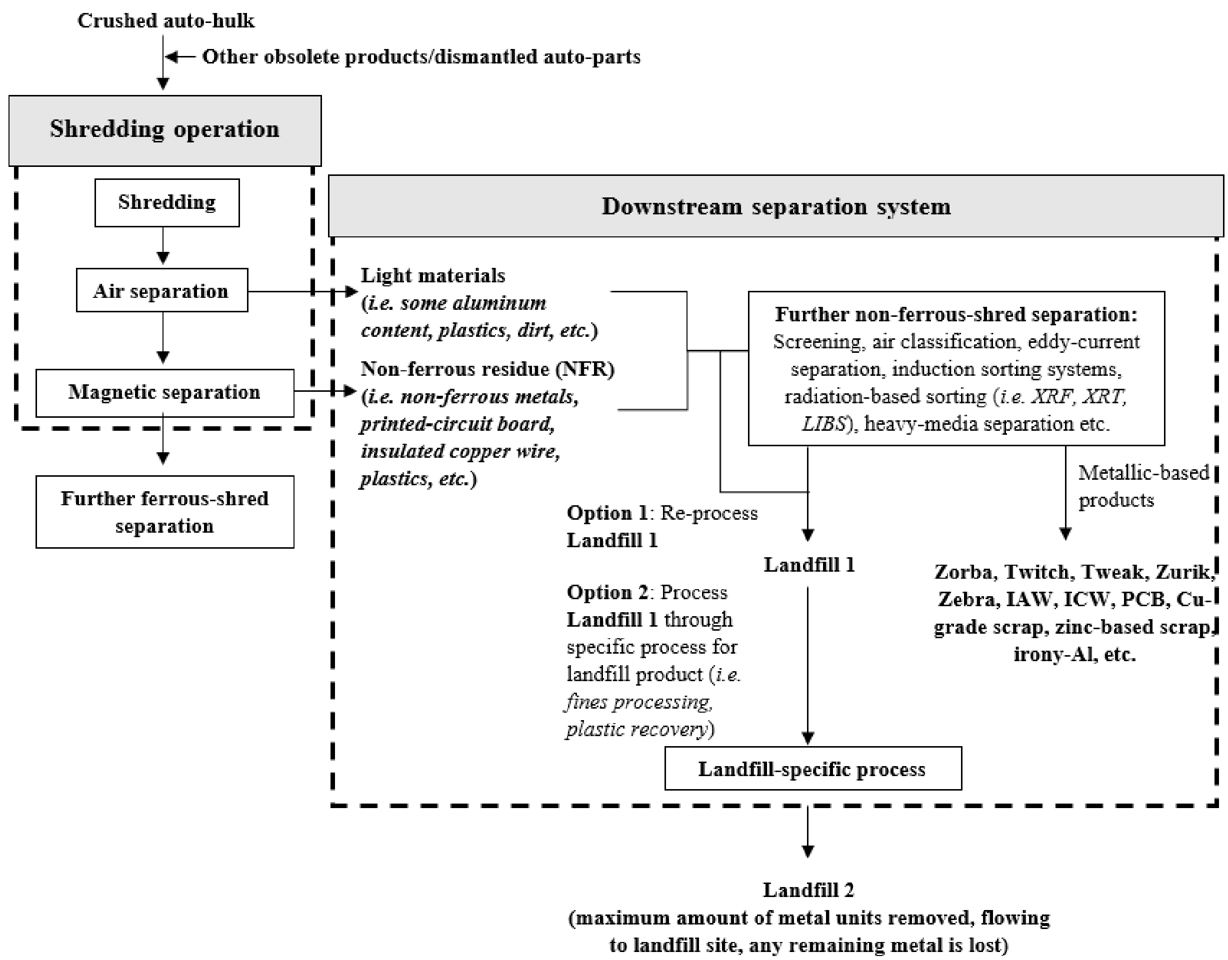

Figure 2: Shredding operation and downstream separation system definitions.

Recovery processes

Secondary aluminum recovery facilities convert collected aluminum-containing scrap into a fully recycled, reusable product. These products are either in the metal ingot form (*i.e. extrusion billet, ingot, sow etc.*) or in the semi-fabricated product form as castings, extrusions or sheets for further shaping and finishing. The feedstock to these plants is typically pre-treated through a cleaning process involving heat or chemical treatment to reduce contamination due to impurities like carbon from polymers, paints, and lacquers in the mixed stream.

Light gauge vs. heavy gauge scrap recovery processes

Throughout this report references will be made to light gauge and heavy gauge recovery processes. This classification is made as a reference to the size and surface area of the scrap class that is being charged into the re-melt/smelting furnaces. Light gauge scrap (*i.e. auto-shred Twitch*) will be smaller in size and has a high surface area to volume ratio. Heavy gauge scrap (*i.e. Al alloy wheels, Al bumpers*) is larger in size and has a lower surface area to volume ratio in comparison to light gauge scrap. This classification must be made because dross formation increases as the surface area to volume ratio for the scrap charge increases. This has been proven in previous studies[9,10,11]. Dross is a by-product that forms naturally during aluminum smelting. Aluminum reacts with oxygen to form aluminum oxide at an increased rate during the melting process due to the heightened processing temperature. During liquefaction of aluminum scrap, the aluminum oxide films on the surface of the individual particulates float to the top of the molten volume. This by-product is skimmed and sent to a dross processor for further metallic recovery (discussed in **Appendix A: Downstream separation system technology)**. Black dross is the by-product of an aluminum melting process when a salt flux is used as an additive to breakdown the oxide film in order to release the entrapped aluminum metal units. White dross is a dross type that forms when no salt flux is used during the original melting. Salt cake is a by-product of white dross processing and consists of similar composition to that of black dross. A similar composition results because a salt fluxing agent is used during white dross processing to extract aluminum metal units. Salt cake and black dross consist of varying compositional proportions of aluminum, aluminum oxide and salt flux[12,13].

An increase in dross production increases the aluminum metal unit loss, therefore decreasing the recycling rate of automotive aluminum. A fluctuating limit is always reached pertaining to the maximum amount of aluminum metal that can be recovered from this waste stream. Many factors attribute to this limit including cleanliness of the melt and, as discussed, surface area to volume ratio. Mixtures of aluminum scrap classes, possibly mixed with primary aluminum, (*i.e. 25% Twitch, 50% Al alloy wheels, and 25% Al turnings*) are commonly charged together to produce the required secondary aluminum alloy chemistry. Secondary aluminum recovery processors understand and quantify the metal yield expected from each charge and identify how each mixture constituent affects this yield. Due to the variable nature of these charge mixtures, distinguishing them into two categories, heavy and light recovery processes, although not processed separately in most cases, allows for an appropriate melt yield to be attributed to the scrap class that is being recovered to form a new aluminum product.

Methodology and model

Process material flow system

The recycling rate of **a metal in a product** (e.g. aluminum and its alloy in automobiles) is defined as the ratio of the quantity of material recycled or recovered to the quantity of material generated or available[14]. The latter term – material generated or available – is also known as the real material content in the product.

$$\boldsymbol{Recycling\ rate\ of\ material\ in\ product} = \frac{\boldsymbol{Material\ Recycled\ or\ Recovered}}{\boldsymbol{Material\ Available\ (Material\ Content)}} \times \mathbf{100}\%$$

Although the definition is simple, to estimate a recycling rate for a material in a highly complex product like an automobile is no easy task. The complication comes from the reality that statistical data has not existed for both the numerator and denominator. This is due to the complexity of the product itself and its recycling system. An automobile is a multi-material product that has a very long service life. Both the content of material and the actual service life of the product vary greatly by vehicle model, production year and individual cases. When retired from service, automobiles are recycled in very large quantity in a very complex value chain. To make the matter more complex, automobiles are also often recycled together with other products such as home appliances and other machinery. The materials recovered from the recycling system are very likely to be mixed with materials from other recycling systems in the downstream scrap trading processes as well. Therefore, for automobiles, the task of figuring out accurate annual numbers on the quantity of a specific material recycled as well as its availability for recycling (the material content) is very complex.

Instead, one has to find a different path to understand material recycling in automobiles. To do so, it's required to peel the onion layer-by-layer and conduct empirical analysis. The recycling rate of automotive material is influenced by three distinctive factors: the collection rate of the product itself (*e.g., automobiles*), the collection rate of the material (*e.g. aluminum and its alloys*) and the recovery process efficiency (*e.g. re-melting to form a new product*). The rate can be estimated by the following equation:

$$\boldsymbol{Recycling\ rate\ of\ material\ in\ product\ (RR\%)} = \boldsymbol{Product\ collection\ rate} \times \boldsymbol{material\ collection\ rate} \times \boldsymbol{recovery\ process\ efficiency}$$

In this study, the focus is on analyzing the material collection rate and recovery efficiency of automotive aluminum while assuming that the collection rate of the product – ELVs – to be 100% since the system boundary is set from the point when ELVs enter the dismantling stage. This treatment allows the study to be simplified by eliminating the uncertainties related to the "hibernation" of ELVs. The hibernation of ELVs refers to the situation in which vehicles are temporarily, or in some cases permanently, "lost" for recycling. This may be caused by vehicles being abandoned in remote locations, lost ownership, being collected as antiques, or being smuggled out of the country.

The "hibernation" of vehicles, although happening in reality, is supposed to be in very small proportion. Given the legal and regulatory environment, the market value of materials for ELVs, as well as other circumstances, most of the temporarily hibernated ELVs will be ultimately recycled. It is only a matter of time.

Based on such a critical assumption and the drawing of the system boundary, a grave-to-gate material flow analysis system is developed to focus on analyzing the material collection (***MC***) and material recovery efficiency (R_i) of the system to determine the recycling rate for automotive aluminum. This system is open loop and spans from a retired automobile entering into the system to the completion of a scrap re-melt/smelting process where a secondary recycled semi- or final product is formed. The material recovery process efficiency will vary based upon the scrap form that is charged. The subscript, i, designates the scrap form that is charged at the recovery process site (*i.e. secondary smelter*). If the subscript is L, the scrap form charged is light gauge (*i.e. Twitch*) and if the subscript is H, the scrap form is heavy gauge (*i.e. Al alloy wheel, Al bumper*). The type of material charged must be differentiated because the recovery efficiency rate varies between the two forms.

When examining material collection rates and recovery efficiencies, the losses of aluminum and its alloy throughout each recycling process is analyzed by collecting empirical operation data from industry-wide operators. The efficiency is initially assigned a value of 1 and aluminum metal unit losses are accounted for as the ELV auto-aluminum flows through material collection and recovery operations specific to its form, size, cleanliness and compositional variance. The data provided by each company from each operational tier is weighted appropriately as a function of their market share in terms of ELVs processed per month for dismantlers, an estimation of the automotive aluminum scrap mass throughput for the DSSs and the estimated market share percentage for aluminum recyclers that they reported. The weighted datasets calculate each operation's collection/process efficiency as a function of aluminum metal unit loss to landfill and input/output material flow in the specified heavy/light form of obsolete automotive aluminum scrap.

The light recovery process material flow value is designated l and the heavy recovery process material flow value is designated h. Determining these process material flow values allows for the appropriate material collection rate(s) and recovery process efficiency to be applied based on the amount (as a percent) of the auto-aluminum that flows through each respective operation.

System model

Figure 3 displays the flow model that is used for this study. As mentioned, the process material flow system boundary begins at the dismantling operation. It is assumed that all end-of-life vehicles enter this initial material collection process. From here, the material flows h and l are differentiated. Flow h, from the dismantler (D), flows into the heavy recovery process directly (R_H). Flow l, from the dismantler, flows through a downstream separation system (S), the second material collection process for this stream, into the light recovery process (R_L). By combining the percent of aluminum that is fully recycled from both recovery process' material flow streams, the recycling rate percent (RR %) is determined for automotive aluminum.

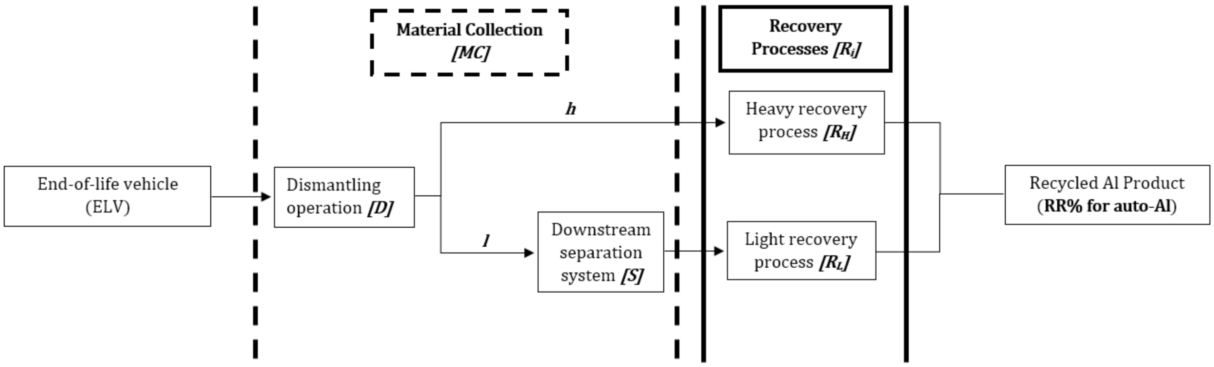

Figure 3: Automotive aluminum material flow model: grave-to-gate (auto-aluminum parts at a dismantling yard to a recycled Al product).

Equation 1 is the model equation that combines process material flow values with the material collection and recovery process efficiencies, appropriately. This equation is the numeric form of the *Recycling rate of material in product (RR %)* equation mentioned previously. It is critical to separate the aluminum scrap product that is charged in the light gauge scrap form from that of which charged in the heavy gauge scrap form. The light recovery material flow is represented by the first bracketed term and the heavy recovery material flow is represented by the second bracketed term.

Equation 1: Recycling rate (RR %) equation for automotive aluminum.

$$RR\% = ([MC] \times R_L) \times Light\ recovery\ material\ flow \ + \ (MC \times R_H) \ \times Heavy\ recovery\ material\ flow$$

$$RR\% = [([D \times S] \times R_L) \times l] + [(D \times R_H) \times h]$$

D is the process efficiency term for the dismantling material collection process. ***S*** is the process efficiency term for the downstream separation system material collection process. $\boldsymbol{R_L}$ is the process efficiency for the light gauge scrap recovery process. $\boldsymbol{R_H}$ is the process efficiency for the heavy gauge scrap recovery process. Each process efficiency term defined above is calculated under the same assumption. Automotive aluminum metal unit flow (reported as a weight %) to landfill accounts for the only reduction in the specific process efficiency value. Each process is initially assigned an efficiency value of 100% and the reported aluminum metal units flowing from each material collection and recovery process to landfill reduces this value proportionally. Worth noting is that this study does not utilize a mass balance to determine each process efficiency since the input of aluminum mass into the system is unknown. Also, this study does not consider aluminum metal units that are miss-sorted into other commodity streams (*i.e. ferrous, stainless steel, ICW, PCB etc.*) as a loss or reduction in process efficiency. These aluminum metal units are considered collected within the system boundaries of this study as they are not deposited into the landfill.

Data collection and market share analysis

The research team surveyed shredders, DSS operators, and scrap re-melters/smelters through both personal contacts and project committee member contacts. In addition, the Automotive Recycler's Association (ARA) helped distribute the dismantler survey to its national membership. The research team asked 6 survey questions (see **Appendix B: Dismantling operation survey questions**) that aimed to determine net metal loss, aluminum metal unit loss, ELVs processed per month and downstream sales relationships for the process material flow determination. The multiplication of the net metal loss by the aluminum metal unit loss results in the estimated amount of aluminum and its alloy flowing to a landfill from these operations. The analysis was conducted this way due to the size-restrictions faced by dismantlers when it comes to metal-type differentiation in the landfill stream. These fragments are too small to determine the metal type, but the weight of net metal loss is recorded and within this net loss the aluminum alloy content is estimated. The size of the operation is taken into account for data weighting purposes but did not affect the population that is targeted for the survey. Each respondent's specific market share is calculated, summed and divided by the average number of ELVs reaching end of life annually. The weighting calculation is based upon ELVs processed annually for the individual company in proportion to the total number of ELVs processed annually by the complete collection of survey respondents.

The research team surveyed committee member contacts as well as personal contacts to collect the required information from downstream separation systems. A total of 4 questions were sent to these operations to determine the process specific efficiency and process material flow to re-melt/smelting facilities (see **Appendix C: Downstream separation system survey questions**). The mass production percent of the landfill flow multiplied by the weight percent of aluminum metal units within this flow, after appropriate weighting, determines the process efficiency for these operations. Each respondent's specific market share is calculated and applied to their reported data to normalize the dataset based upon auto aluminum scrap processed in 2014.

Recovery processes were surveyed through phone interviews conducted by the research team (see **Appendix D: Recovery process survey questions**). The committee supplied contacts for this phase of the secondary aluminum production line. Questions regarding metal yield for heavy and light gauge scrap classes were answered as well as the percentage of aluminum metal units recovered via dross processing for each respective scrap charge. Each respondent's specific market share was reported by them and is applied to their reported data to weight the dataset appropriately.

Sensitivity analysis

A sensitivity analysis was conducted in order to determine the minimum to maximum range for the automotive aluminum recycling rate. Although the weighted RR% calculated is accurate and representative as a weighted average, it is worthwhile to show the range within which this value can fall as the critical variables within the system are set to minimum and maximum values.

As described in **Table 1**, a minimum RR% scenario determined the minimum automotive aluminum recycling rate. Each variable deemed critical to the final RR% was set to the lowest possible value or the value that results in the highest amount of Al metal unit loss based on true survey response without any weighting or averaging factors.

Similarly, a maximum RR% scenario determined the maximum automotive aluminum recycling rate. Each variable deemed critical to the final RR% was set to the highest possible value or the value that results in the lowest amount of Al metal unit loss based on true survey response without any weighting or averaging factors.

Table 1: Sensitivity analysis scenario definitions.

Scenario	Description	Critical variables
Minimum RR%	This scenario determines the minimum automotive aluminum recycling rate. Each variable deemed critical to the final RR% is set to the lowest possible value or the value that results in the highest amount of Al metal unit loss based on true survey response without any weighting or averaging factors.	• *Al process material flow from dismantling operation (i.e. total collection percent)* • *Al metal unit loss at dismantling operations* • *Al metal unit loss at DSSs* • *Al process material flow to light recovery processes* • *Al process material flow to heavy recovery processes* • *Al metal unit loss at light recovery processes* • *Al metal unit loss at heavy recovery processes*
Maximum RR%	This scenario determines the maximum automotive aluminum recycling rate. Each variable deemed critical to the final RR% is set to the highest possible value or the value that results in the lowest amount of Al metal unit loss based on true survey response without any weighting or averaging factors.	

Results and discussion

Market share analysis

Dismantling operations

As mentioned, there are approximately 12.6 million vehicles reaching end of life in the US annually. Based on this, the survey response received from the dismantling operations represents approximately 5% of the market. The scale of operation from the responsive companies varies in size from 1-9 ELVs processed per month to 10,000 – 99,999 ELVs processed per month. A total of 21 companies responded from various regions across the US. The weight of each company compared to the total responsive population as a function of annual ELV processing is not reported to maintain the confidentiality of each company's reported data.

Downstream separation systems

In April 2015, Recycling Today released a market analysis study on the top 20 largest non-ferrous scrap processors in North America[15]. These rankings are a function of volumetric non-ferrous throughput. The research team acquired these data supporting this study in order to appropriately weight the collected data from DSS companies in the US. If a company responded to the research team's DSS survey but was not reported in the Recycling Today study, the volumetric non-ferrous annual throughput was acquired from company specific websites or shared during interviews.

Table 2 defines the values used in **Equation 2** to determine the total downstream separation system market covered. The individual contributions to this total are used for data weighting purposes. The total DSS market covered is approximately 32%.

Equation 2: Total market share percent covered in the study for DSSs.

$$Market\ share\ \% = \frac{\sum V_{NF} * Al\% * T\% * A\%}{T_{ELVs} * W_{ELVs} * DSS_{in}}$$

Table 2: Downstream separation system's market share percent variable description.

Variable	Description	Value
$\Sigma\, V_{NF}$	Volume of non-ferrous scrap material handled by scrap processors in 2014 that participated in this study[15]	~4.7 billion lbs.
$Al\%$	Percent of non-ferrous material estimated to be aluminum (aggregate for industry)[15]	67%
$T\%$	Percent of recycled secondary aluminum that originates from	42%

	the transportation sector in old scrap form[16]	
$A\%$	Aluminum end-use manufacturing percent that Auto & Lt Truck represents within entire transportation industrial sector[17]	65%
T_{ELVs}	Total vehicles reaching end of life in the US annually[6]	~12.6 million
W_{ELVs}	Average total aluminum weight in light ELVs (1999)[18]	251 lbs.
DSS_{in} (1)	Process material flow of auto aluminum into downstream separation systems (**Table 4**)	0.86

As for weighting the DSSs respondents against one another in order to normalize these data, the individual contribution for each specific scrap processor ($V_{NF,\,j}$) was set to the numerator of **Equation 3** below and divided the summed volume of non-ferrous scrap material handled by scrap processors in 2014 that participated in this study (ΣV_{NF}). The subscript j refers to the scrap processor referenced to within each weighting calculation. Weighting the survey responses, through normalization, allows for each scrap processor to affect the recycling rate appropriately based upon their individual market share. The calculated values for individual respondents are not reported to maintain the confidentiality of the DSS survey respondents.

Equation 3: Market share percent for each DSS survey respondent.

$$Market\ share\ (\%)_j = \frac{V_{NF,j}}{\sum V_{NF}}$$

Recovery processes

Based on conversations with secondary aluminum producing companies in the US, the market coverage for this portion of the study falls within the range of 60-70%. The companies interviewed re-melt/smelt a wide range of aluminum scrap and reported each individual charge constituent's effect on melt loss.

Aggregate survey results

Dismantling operations

The material collection efficiency of dismantling operations in the US is determined as a function of loss. Losses from these operations include aluminum metal unit flow to landfill as a result of cutting, refurbishing, refinishing and repurposing operations onsite. The weighted average efficiency is 99.9%. This material collection's process efficiency ranges between 99.75% and 99.99%. Although losses are not evaluated to this degree of accuracy, for differentiation purposes within the sensitivity analysis these values are reasoned appropriate. The survey questions regarding loss were multiple choice and allowed respondents to choose a range if any loss is observed at their respective operation or to input their own value. If a loss is reported and a loss range option selected, the research team used the upper limit of the range in the efficiency calculation. The appropriate data weighting, based on ELV annual intake, was applied for each individual response.

Dismantlers report 0.58 or 58% of their intake weight being crushed into auto hulk form and being delivered to a shredding operation. This flow was determined by asking the monthly weight of auto hulks or flats being delivered to shredders and subtracting that from the monthly average ELV weight entering their lot. The difference is the average weight that is being delivered to core buyers, scrap dealers, entering a new life cycle or being re-melted/smelted. The remaining process material flow value is therefore 0.42 or 42%. A further breakdown of this remaining process material flow is required to differentiate between the ***l*** and ***h*** flows to their respective recovery processes. This breakdown is discussed and determined in the following section: *Process flow analysis from dismantling operations.* It has been assumed that from a shredding operation, 100% of the shredded material flows to a downstream separation system of some degree.

Process flow analysis from dismantling operations

The process material flow from a dismantling operation is needed to determine the amount of material that is sent directly to heavy gauge scrap melting or to light gauge scrap melting through a downstream separation system. This analysis was conducted in three different ways.

1. **Expert opinion**: The first analysis conducted to determine the breakdown of the remaining 0.42 or 42% of auto aluminum material flow from a dismantler was completed by interviewing an aluminum recycling expert. Sarah Willcutts, of Andersen's Sales and Salvage, Inc., manages a dismantling/shredding/separating system at one site in Greely, CO. She claims, as an industry average, 10% of the dismantled auto-aluminum weight is sent directly to a heavy recovery process from the dismantling site. Therefore, 0.32 or 32% of the dismantled aluminum weight will eventually be shredded and sent to a light recovery process totaling a material flow value of 0.90 or 90%.

2. **Statistical analysis:** The second analysis conducted to determine the breakdown of the remaining 0.42 or 42% of auto aluminum material flow from a dismantler was completed through a statistical analysis. This analysis utilizes data collected by the United States Geological Survey (USGS). **Table 3** shows the adjusted consumption values in the year 2013 for 4 types of old scrap. The adjustment made is that 27% of the old scrap consumed originates from the auto and light truck transportation sector. This 27% value is calculated by multiplying the $A\%$ (65%) and $T\%$ (42%) values from **Table 2**.

Table 3: Adjusted old aluminum scrap consumption value in USA (2013)[19].

Scrap Form	USGS Reported Consumption Value (lbs.)	Adjusted Consumption Value (lbs.)
Old Cast	586 million	158 million
Old Extrusion	478 million	129 million
Other Wrought	730 million	197 million
Auto-shred	214 million	58 million

Summing the entire adjusted consumption value column does not account for all the auto-aluminum scrap processed in the US through dismantling operations and DSSs. This is a result of a significant amount of automotive scrap being exported to foreign markets where further processing is more economically viable. According to the United States International Trade Commission, ~4 billion lbs. of non-used beverage container (non-UBC) aluminum scrap was exported in 2013[20]. Combining the adjusted consumption values for old cast, old extrusion and other wrought scrap aluminum totals the amount of automotive aluminum that flows to a heavy gauge scrap melting operation in the US (~484 million lbs.). This value divided by the average auto-aluminum available around the year 2013 (total ELVs reaching end of life annually multiplied by the weight of aluminum in ELVs from 1999; 12.6 million * 251 lbs. = 3,160 million lbs.) tells us how much auto-aluminum is charged in the heavy gauge scrap form for this high-level statistical analysis. This fraction represents approximately 0.15 or 15% of the total obsolete automotive aluminum. The other 0.85 or 85% is assumed to be charged and re-melted/smelted as a light gauge scrap class. Therefore, 0.27 or 27% of the originally dismantled auto-aluminum parts will eventually be shredded and delivered to a light gauge recovery process.

3. **<u>Component-based analysis:</u>** The third analysis conducted to determine the breakdown of the remaining 0.42 or 42% of auto aluminum material flow from a dismantler was completed through an automotive aluminum component analysis. Considering the average lifetime of a light vehicle, the aluminum component breakdown for vehicle in the year 1999 is used for this analysis. Ducker Worldwide reports an average of 251 lbs. of aluminum per light vehicle in the year 1999. Of the 251 lbs. of automotive aluminum, the research team, based on conversations with dismantling experts, determined that aluminum alloy wheels and bumpers are the most frequent components charged and re-melted/smelted in a heavy gauge scrap form. These components, in combination, make up approximately 18% of the total automotive aluminum weight from 1999 (~44 lbs.)[18]. Therefore, this sets the maximum amount of aluminum that flows to a heavy recovery process. The remaining 24% is assumed to be shredded and processed as a light scrap form which brings this process material flow to 0.82 or 82%.

For the minimum recycling rate (RR%) sensitivity analysis, the process material flow breakdown set by the expert opinion is used (0.10 or 10% to heavy recovery process). For the maximum RR% sensitivity analysis, the component-based breakdown is used (0.18 or 18% to heavy recovery process). For the weighted average analysis, the average of all three analyses is used (0.14 or 14%).

Downstream separation systems

The aluminum metal unit loss at the processing site of a downstream separation system results from the production waste flow to landfill. The aluminum metal units lost here are simply too small in size for effective collection. The landfill flow is typically reprocessed at these yards to extract the maximum amount of metal weight and is closely monitored for its metallic content. The aluminum metallic loss percentage is determined by multiplying the mass production percent of each company's landfill flow by the reported aluminum metal unit percentage in this flow. A marginal loss of 0.2% aluminum metal unit from these operations has been determined. The DSS-specific process efficiency is therefore very high at 99.8%. The range of process efficiency for this material collection process is set between 99.75% and 99.97%. As shown in **Figure 1**, many different metal and material type streams are produced at DSS operations. The aluminum/aluminum alloy content in each of these streams is not investigated individually. The research team is not accounting for miss-sorts into other metallic streams as aluminum loss; only material failed to be collected from landfill waste affects the operating efficiency. The assumption is made that the end use consumers for other material streams (*i.e. non-aluminum based*) will either utilize the aluminum content in their specific recovery process or extract the aluminum as an impurity and deliver the extracted content to a light gauge recovery processor. Once in the shredded, separated state, 100% of this material flows to the light gauge recovery process.

Recovery processes

A significant difference in metal yield when melting heavy vs. light gauge scrap was determined from the interviews conducted with scrap aluminum recovery operations. Heavy gauge scrap processing is reported as having a higher process efficiency when compared to light gauge processing. On average, 95% of the charged heavy gauge auto-scrap is fully recovered. After dross processing, an additional 0.5 – 3% of aluminum metal units can enter into a new life cycle. A safe efficiency to use for heavy gauge scrap melting, according to the advice given by the survey participants, falls within the 95 – 96% range. The heavy gauge scrap recovery process is determined to be, on average, 95% efficient. The heavy recovery process has a reported minimum efficiency of 91% and a maximum process efficiency of 98%.

The average light gauge scrap recovery efficiency is 90% prior to the dross processing step. On average, about a 1% efficiency increase is accomplished by recovering aluminum metal units from the dross. This recovery process efficiency is averaged at 91% and has a reported minimum efficiency of 81% and a maximum efficiency of 98%.

Weighted average recycling rate for automotive aluminum

The process efficiency for each operation only applies to the flow of material processed through that operation. **Table 4** shows a summary of all the data collected, aggregated and modeled from the results reported in previous sections. These are the values that are inserted into **Equation 1.**

Table 4: Weighted process material flow and process efficiency values.

Weighted Average RR% Analysis	
d	1
h	0.14
l	0.86
D	99.9%
S	99.8%
R_L	91%
R_H	95%
Recycling Rate (RR %):	**91%**

The material collection rate for automotive aluminum is 99.7%. This accounts for the aluminum metal unit loss through dismantling and after downstream separation. The major aluminum metal unit losses occur during the recovery process. When including these process efficiencies and incorporating their respective process material flows, the overall weighted average automotive aluminum recycling rate is determined to be **91%**.

Sensitivity analysis – minimum and maximum recycling rate for automotive aluminum

Table 5 below shows the values used for the minimum and maximum scenario sensitivity analysis for the automotive aluminum recycling rate. For the minimum RR% analysis, the flow to the light recovery process is maximized as this is the least efficient process in the system. This same value is minimized for the maximum RR% analysis to ensure that the largest amount of auto-Al metal units flow into a heavy recovery process and avoid the losses accrued at the DSS. The weighted average RR% analysis value falls within the minimum/maximum range calculated at 80% to 98%. The weighted average RR% analysis is most representative of the secondary aluminum production industry pertaining to auto-aluminum in comparison to the two extremes set here.

Table 5: Sensitivity analysis results.

Critical system variable	Minimum RR% Analysis	Maximum RR% Analysis
d	0.98	1
h	0.1	0.18
l	0.9	0.82
D	99.75%	99.99%
S	99.75%	99.97%
$\boldsymbol{R_L}$	81%	98%
$\boldsymbol{R_H}$	91%	98%
Recycling Rate (RR %):	80%	98%

Figure 4 shows the process material flow diagram that summarizes the grave-to-gate processing of end-of-life automotive aluminum. Each process within the scope of this analysis is within the dashed boundary enclosure. Each material collection and recovery process reports the average and range of aluminum loss to landfill.

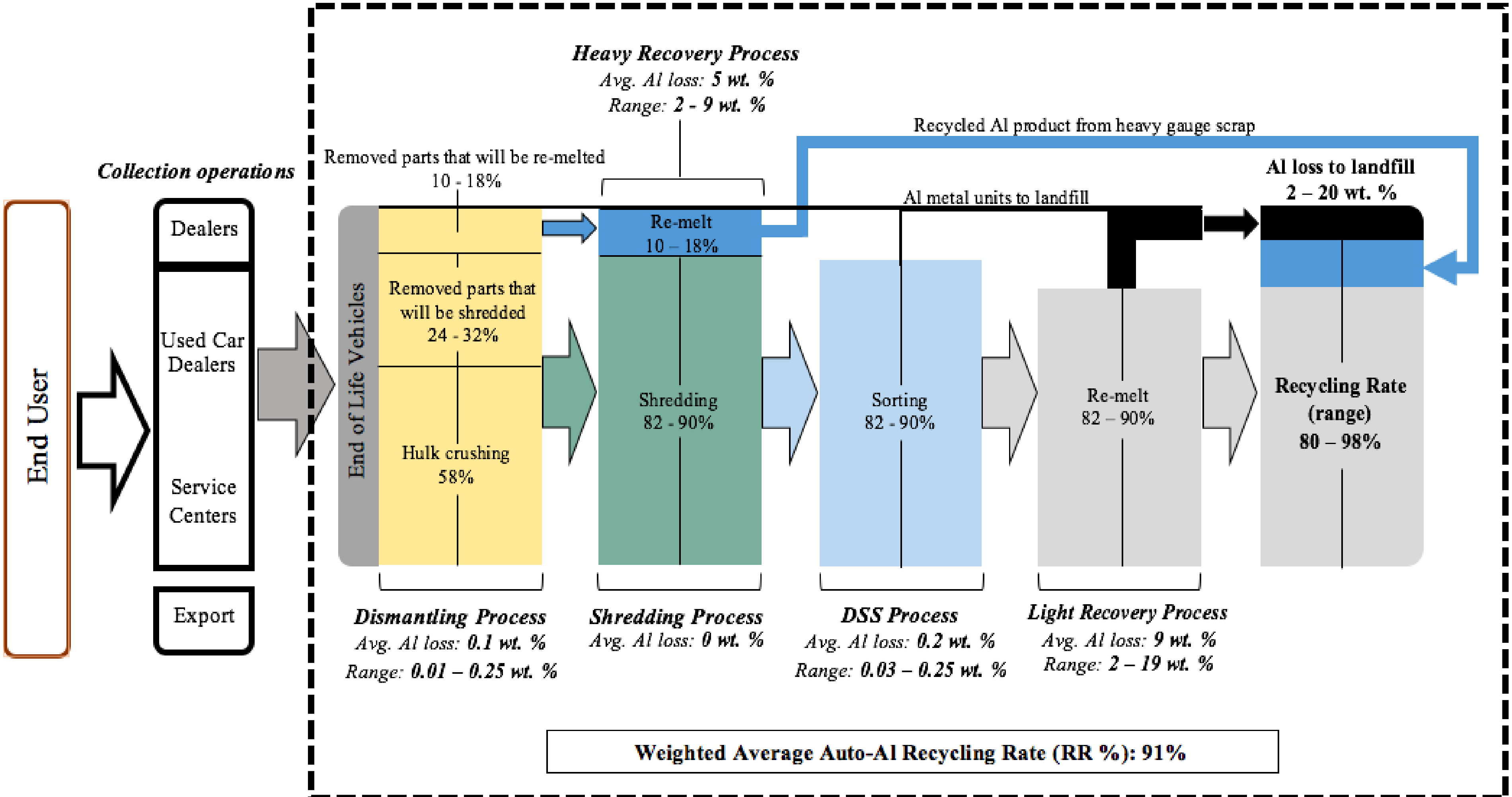

Figure 4: Process material flow analysis for automotive aluminum.

Conclusions

In the Introduction, we highlighted the need for the aluminum industry and its stakeholders to collect quality data and information to achieve a comprehensive understanding on the recycling of end-of-life automotive aluminum. This study addressed this need by examining the fate of end-of-life automotive aluminum, focusing on analyzing the material flows during the ELV recycling processes to identify aluminum alloy metal unit losses. The study provides one of the best quantifications to date of the average percent (91%) of aluminum currently being recovered by the recycling systems in the US. This level of metal recovery is considered highly efficient and effective.

The efficiency and effectiveness are largely driven by the economic value embedded in aluminum metals. There is clearly a concerted effort to recover this valuable light weight commodity from end-of-life vehicles. Throughout the survey and investigation processes, we found that maximizing the rate of metal unit recovery is the most important indicator of all companies' business operations. Metal unit losses to landfill, in the form of scrap fragments and aluminum oxide residing in dross, decrease profit margins within the industry. Thus optimizing these processes is a forefront priority for both material collection and recovery processors. The marginal percentage of aluminum metal units reaching landfill is a result of process size and aluminum recovery limitations faced during separation and dross processing, respectively. Clearly, the recycling rate determined by this study completes the beneficial notion of using aluminum as a lightweight alternative to aid in fuel economy increase and gaseous emission decrease.

While the data and information collection process was massive in scale and covered a significant proportion of the industry, gaps still exist for future improvement since the ELV recycling system is very complex, involving multiple levels of internal and external trading activities, massive amount of material flows and storages, as well as thousands of independent firms and players and thousands of workers. The information gaps and areas for possible future improvements include the following.

One of the critical assumptions used for this study was that the loss of end-of-life vehicles to the landfill would be very rare and that these so-called hibernating vehicles will ultimately end up in a recycling system somewhere. The validity of this assumption could be further examined and investigated. Such an investigation could help complete a holistic picture of the entire automotive recycling system in the US.

The second important assumption in this study was that aluminum alloys diverted to other material streams during the recycling processes, e.g. ferrous metals, were assumed to be recovered. An investigation would be worthwhile to find out both the level of diversion to other recovery systems and the fate of those aluminum fragments.

Finally, this study did not track the end-use of the recovered aluminum metal units. The long-held contention by the industry is that the majority of the metal would end up being used by the automotive industry again for wheels, bumpers, engines and transmissions. An independent study could be done to examine the end-use to identify where and how the recycling system can be further improved to add more value to the recycled metals. This would be particularly valuable and necessary in the very near future as the use of aluminum in automotive is increasing exponentially.

Given the complexity of the automotive recycling industry and the data collection challenges we experienced during this study, none of the above suggested potential study topics would be easy. However, our opinion is that it would be worth the effort to help continuously improve the recycling processes since, as mentioned in the very beginning of this report, recycling is a critical component of sustainability.

Appendix A: Downstream separation system technology

Air separation

Air separation technologies will vary at different recovery plants. Some common types are wind-sifting, air-knives, elutriation, winnowing and air columns[21]. The mixed material stream introduced in **Figure 1**, defined as non-ferrous-shredder residue (NFR), is the flow stream that will be exposed to this level of separation on the non-ferrous side of recovery. Vertical air separation is a common technique used at this stage which involves feeding the recycled material down a vertical column where air nozzles are dispersed throughout releasing compressed air aiming to remove the lighter materials like plastic and wood. The metals are collected at the bottom as, tactically, not enough force is used to eject these heavier components. One drawback of this separation technique is that light metal components are displaced into the landfill stream and a further processing is required for near-complete metallic recovery.

Eddy-current separation

Eddy-current separation (ECS) is used for further separation of NFR. This technology utilizes the large range of electrical conductivities within the mixed metal steam. A rotor lined with NdFeB magnets, with alternating north and south poles produces an external magnetic field that repels non-magnetic, electrically conductive materials. These materials get expelled from the scrap stream leaving behind only the non-conductive/non-metallic particles and ferrous scrap pieces that did not sort properly at first exposure to magnetic force. This magnetic field can be altered with an adjustment in rotor speed. Varying conductivity leads to varying eddy currents and this variation leads to different metals being ejected calculable distances. This allows for possible separation as a function of the base metal. Separation to this point allows for the derivation of the Institute of Scrap Recycling Industries (ISRI) classified Zorba. Zorba is a non-ferrous mixture of metals including aluminum, copper, lead, magnesium, stainless steel, nickel, tin, and zinc. It predominantly consists of various grades of aluminum alloy. However, the weight percentage of each metal within the mixture is agreed upon between buyer and seller. This material is generated by the following processing methods and in any combination: eddy current, air separation, flotation, screening or other segregation techniques. The material must have passed through a magnet at least once to reduce or completely removes free iron or large iron attachments. This scrap class typically contains ~65% aluminum alloy by weight[8]. By using the calculable ejection distances, “long-throw” or tweak aluminum shredded scrap forms can be recovered here.

Sink-float (heavy-media) separation

Sink-float (heavy-media, density) separation is a wet process that utilizes the known specific gravities of water-based slurries to separate non-ferrous metals and plastics with varying densities. As an example process, first, fine particles are be screened out of the mixed metallic stream. Conveyor belts carry the Zorba scrap stream to a rotating drum where the first slurry, a 2.1-2.5 specific gravity bath, is used to separate out the magnesium and denser plastics from the other metals. The control of the bath’s specific gravity is attributed to the use of magnetite or ferrosilicon powder[21]. The final bath (3.1-3.5 specific gravity) is used to float out the cast and wrought aluminum while the heavier metal components such as copper, zinc and lead sink to a different conveyor belt. The lighter aluminum scrap mix is classified by ISRI as Twitch (floating fraction) and the heavier metals as Zebra (sinking fraction). Twitch is derived from a dry or wet density separation technique, must be dried after processing and may contain no more than 1% free zinc, 1% free magnesium, 1% of free iron. There must be less than 2% non-metallic content and 1% free rubber and plastic. Twitch typically contains 90-98% aluminum alloy by weight[8].

X-ray transmission separation

X-ray transmission (XRT) separation aims to accomplish the same sorting effectiveness (Zorba upgraded to Twitch and Zebra) as the wet, heavy-media separation previously introduced but as a dry method. XRT is used to sort metals according to atomic density. After the non-ferrous scrap stream moves through ECS, a conveyor belt system carries the scrap to the XRT equipment's feed mechanism (*i.e. vibratory platform, rotary ejection etc.*). The controlled feed allows for proper scrap distribution on the analysis belt. A scanning mechanism (*i.e. laser, 3D camera, weighing scale*) is used to alert the x-ray source and ejection method of the individual scrap piece's belt location. An x-ray source tube and an x-ray detection system are positioned below and above the conveyor belt, respectively. Once the belt location and density are known, the ejection system is alerted to either fire the compressed air or pneumatic hammer system to induce separation or to allow the scrap piece to fall if the material's density does not meet the pre-programmed criteria[22].

Laser-induced breakdown spectroscopy (LIBS)

The chemical analysis of metals using this method has been intensely studied. LIBS has been described as a method for quantitative compositional analysis on industrial Al alloys[21,23,24]. A sensor first detects the presence of a specific particle, then this particle is hit with a laser pulse. These pulses create local, luminous plasmas (*i.e. atomic emissions*) that are detected[24]. This emitted light, upon its breakdown, is analyzed spectroscopically using an optical fiber, a polychromator and a photodiode connected to a computer system for an instantaneous elemental composition detection[24,25]. Werheit et al. have researched a 3D scanning LIBS system for aluminum cast and wrought alloy recycling. Sorting measurements of Al post-consumer scrap were taken in this study. After 20% of the data was discarded as outliers, wrought and cast, low and high silicon Al scrap samples were identified with an accuracy greater than 96% correct identification of the alloy. The second study conducted by this group involved the sortation of 8 different Al alloys of production scrap that required a high analytical precision. A mean identification correctness was reported as greater than 95% for wrought alloys[23].

X-ray fluorescence (XRF)

X-ray fluorescence technology is used to determine the chemical composition of unknown scrap metal pieces in real-time. This technology utilizes x-ray fluorescence detection from an unknown scrap particulate to identify particular alloying elements and their respective weight percentages or fluorescence signal intensity. In more detail, low energy x-ray radiation is fired at the scrap streams which leads to the excitation of low-energy electrons causing them to eject from orbit. Then, higher energy electrons quickly fill the vacancies at the lower energy states and with these jumps, elemental specific fluorescence is released. An energy dispersive x-ray sensor is used to detect this release of fluorescence and alerts the computational system of the chemical composition. The fluorescence signal intensity correlates to the chemical composition of all heavy elements (*i.e. not Al, Si, Mg*) detected within the scrap piece[26].

Dross processing and recovery

There are two main dross processing states, liquid and solid, that are processed to recover the maximum amount of aluminum metal units during recycling. The liquid dross state calls for a continuous process that takes advantage of the energy used to melt the original charge and the other process involves reheating the dross to liquefy the cooled, solid-state by-product. The most common technique used for dross processing involves charging this by-product, in either state, into a rotary salt furnace (RSF). A RSF typically operates as a batch process but can accommodate a continuous charge if the dross is delivered directly to it from the melt. Dross and/or dross concentrate is mixed with a fluxing salt similar to the original melting step. This additive again aids in breaking the oxide skin around the molten aluminum as the furnace is heated. This allows for the aluminum to coalesce and increase metal unit recovery. The furnace rotates to allow for the heated refractories to drop below the melt line and surpass the poor thermally conductive molten salt layer at the top of the melt[12].

Appendix B: Dismantling operation survey questions

1. What percentage of the total metal content purchased by your operation is not recycled or reused/resold?
    a. 0%
    b. 0%-1%
    c. Other (please specify)
2. How much of this non-recycled metal content (from question #1) is aluminum or aluminum alloy?
    a. 0%
    b. >0% - 10%
    c. >10% - 25%
    d. >25% - 50%
    e. Other (please specify)
3. On average, how many end-of-life vehicles enter this operation per month?
4. What is the monthly average of total auto hulk weight leaving this operation? (please specify units)
5. Who do you sell your parts and aluminum scrap to? (check all that apply)
    a. Retail part sales for repurposing
    b. Scrap dealers
    c. Core buyers
    d. Re-melting processes
    e. Other (please specify)
6. If allowed, please list the contact names and phone numbers for the operations that you send your parts/scrap to. (*i.e. core buyers*, *scrap dealers*, *smelters etc.*)
    a. Core buyers
    b. Scrap dealers
    c. Smelters
    d. Other

Appendix C: Downstream separation system survey questions

1. Does your company produce Twitch?
2. If so, what percent of Twitch is sold to secondary smelters vs. continuous casters/secondary foundries?

   (This question was originally asked because two melt losses were going to be accounted for if Twitch was sold to a secondary smelter first then that recycled secondary ingot to a secondary foundry or continuous caster. Upon final review with committee, it was agreed that only one melt loss needs to be accounted for so the research team modeled the amount of heavy gauge scrap (*i.e. Al alloy wheels*) versus light gauge scrap (*i.e. Twitch*) that is charged during melting as there is a distinguishable difference in metal yield as a function of this variance in charge composition.)

3. What percent of mass production does your landfill flow represent?
4. What is the weight percent of aluminum/aluminum alloy in this landfill flow?

Appendix D: Recovery process survey questions

1. What is the metal yield when heavy gauge aluminum scrap is charged?
2. What is the metal yield when light gauge aluminum scrap is charged?
3. What percentage of aluminum is recovered during dross processing of a heavy gauge auto-scrap charge?
4. What percentage of aluminum is recovered during dross processing of a light gauge auto-scrap charge?
5. What is your company’s market share as a function of secondary processing capacity?

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