End-of-Life Recycling for Vehicles of the Future: Roadmap Update 2006

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I. INTRODUCTION

Automobile recycling[1] is the final productive use of end-of-life vehicles (ELV). Obsolete cars have been a valuable source of recycled raw materials and useable parts for repair since cars have been mass produced. In North America, 94 percent of vehicles that reach the end of their useful service life are profitably recycled by the existing recycling infrastructure. That infrastructure includes automotive dismantlers who recover useable parts for repair and reuse; automotive remanufacturers who rebuild a full range of components including starters, alternators, and engines to replace defective parts; and scrap processors who recover raw materials such as iron, steel, aluminum, and copper. The remaining auto "hulk" is typically shredded along with other consumer goods. The shredded material is sorted to recover ferrous and non-ferrous metals, and the remaining portion is landfilled.

Today, the metals which constitute over 75% of the weight of the obsolete car are profitably recovered and recycled; the remainder is landfilled. The recyclability[2] of ELV is presently limited (1) by the lack of commercially proven technical capabilities to cost-effectively separate, identify, and sort materials and components and (2) by the lack of profitable post-use markets. Over the next 20 years, both the number and complexity of ELV are expected to increase, posing significant challenges on the existing recycling infrastructure. The automobile of the future will use significantly greater amounts of lightweight materials (ultralight high-strength steels, aluminum, plastics, composites, etc.) and more sophisticated/complex components. New recycling technology is and will continue to be needed to improve vehicle recyclability.

ELV Content Recycled is 85%

Material breakdown of an obsolete vehicles is[3]:

- *75% metal*
- *15% plastic*
- *10% other (glass, fluids, dirt, and other miscellaneous materials)*

Over the past 15 years, the original equipment manufacturers (OEM)—Ford, GM and DaimlerChrysler—through the Vehicle Recycling Partnership (VRP) and other organizations including the Aluminum Association (AA), American Plastics Council (APC), the Institute of Scrap Recycling Industries (ISRI), the Automotive Recyclers Association (ARA), the Automotive Parts Rebuilders Association (APRA), and the federal government have been working both collaboratively and independently to address technical, institutional, and economic issues that currently limit the recycling of ELV. Progress has been made in understanding some of these issues, and promising new technologies are currently being developed in anticipation of the recycling challenges presented by future vehicle fleets.

[1] Recycling is defined as products, parts, or materials that are cost-effectively diverted from the waste stream and returned to use as a functional part or raw material for the manufacture or assembly of a new product. For the purposes of this document, recycling is defined in its broadest sense and therefore includes thermochemical conversion of materials (e.g. pyrolysis), energy recovery, parts and components re-use and remanufacture, and materials recycling.

[2] Recyclability is defined as the wt% of the obsolete object that end up being recycled.

[3] The material composition of ELVs is not expected to change much by 2025.

The automobile recycling community seeks to improve ELV recyclability. The automobile recycling community includes the following:

- Automobile companies (i.e., OEM)
- Suppliers of materials and components
- Recycling industries involved in reuse, remanufacturing, and material recovery
- Industries that use recycled materials (end markets)
- Researchers at national laboratories, universities, and institutes who can help solve the technical challenges

In 2000, the U.S. Department of Energy's FreedomCAR and Vehicle Technologies Program (formerly the Office of Transportation Technologies), along with the Argonne National Laboratory, published *A Roadmap for Recycling End-of-Life Vehicles of the Future*. This roadmap was used as a reference for the ELV recycling community to guide research and development activities. This 2006 roadmap is an up-to-date version of the original roadmap. This edition is based on lessons learned and outlines new opportunities for improving the recyclability of future ELV.

Specifically, this roadmap presents:

- Goal and objectives to improve recyclability
- Challenges impacting automobile recycling in 2025
- Strategies for increasing recyclability
- Priority R&D and non-R&D needs to improve recyclability
- Next steps for implementing roadmap priorities

Appendix A provides an overview of the roadmap development processes. Appendix B provides a list of contributors and acknowledgements, and Appendix C contains definitions of terms and acronyms used in the Roadmap.

II. GOAL AND OBJECTIVES FOR ELV RECYCLING

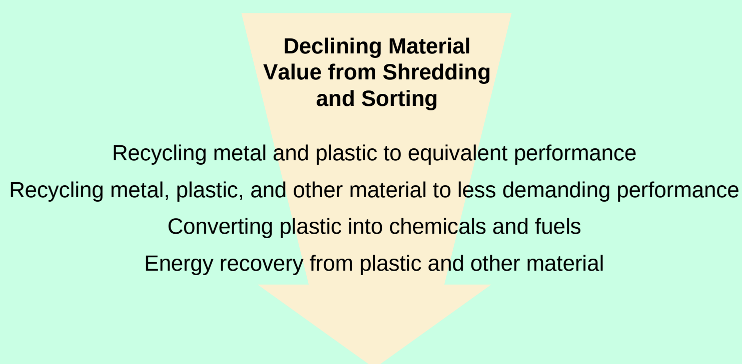
The recycling community has set out to identify, develop, and demonstrate the best technologies that recyclers can use to maximize the amount of material and components that can be profitably recycled and to maximize the total lifecycle value of an ELV. Exhibit 1 ~~2~~ presents the goal and objectives of the recycling community. The technologies selected at any point in time will depend on the commercialization of scientific and technological advancements; federal, state, and local regulations; and cost-effective opportunities for recyclers in the market.

Exhibit 1. Goal and Objectives for Maximizing ELV Recycling

Goal: To identify, develop, and demonstrate the best available technology to maximize recycling given the market and current regulations.

Objectives:

1. Design automobiles for the entire life cycle to improve the fuel economy, optimize material use, and minimize landfill
   - Evaluate the environmental impact across the automobile life cycle to identify the area(s) with the greatest potential for improvement
   - Continuously improve the life cycle design to reduce the environmental burden and promote sustainable material use
2. Maximize the lifecycle value of component and materials in ELV
   - Define the value streams for ELV components and materials so recyclers can determine the tradeoffs among options and maximize the economic and environment value
3. De-pollute automobiles to remove contaminants
4. Maximize dismantling through reuse/ remanufacturing and bulk material recovery
5. Maximize shredding and sorting to attain the greatest material value
6. Minimize landfill of post-shred material



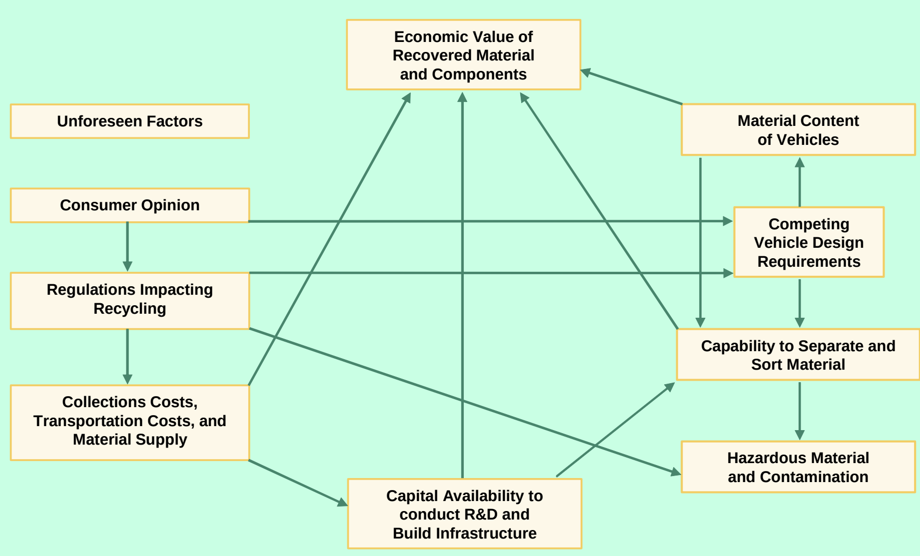
III. Challenges Impacting Recyclability in 2025

Numerous challenges exist that impact automobile recycling. The recycling community's success at addressing these technical, economic, institutional, and social challenges over the next two decades will impact the viability of ELV recycling in 2025. The top factors affecting vehicle recycling are listed in Exhibit 2. The ELV material constituency in 2025 (as a percent of vehicle weight) is expected to be similar to today's vehicles, as indicated in Section 1. This implies that the challenges and key factors that will affect ELV recycling for the next 20 years are similar to the key factors and challenges that the recycling industry faces today. The relationship among the top factors is presented in Exhibit 3. The success of material and component recovery depends on these complex interrelationships. Key issues associated with the top factors affecting vehicle recycling are highlighted below.

Exhibit 2.
Top Factors Affecting Automobile Recycling
For the Next 20 Years

- Economic Value of Recovered Material and Components
- Material Content of Vehicles
- Competing Vehicle Design Requirements
- Capability to Separate and Sort Material
- Hazardous Material and Contamination
- Capital Availability to Conduct R&D and Build Infrastructure
- Collection Costs, Transportation Costs, and Material Supply
- Regulations Impacting Recycling
- Consumer Opinion
- Unforeseen Factors

Exhibit 3.
Major Interrelationships Among the Top Factors



▸ *Economic Value of Recovered Material and Components*

The types of materials used in vehicles determine recovery options. Even small changes in the vehicle material content will have a significant impact on the economics of the recycling stream. For example, the trend towards more plastics and composites with less metal in vehicles means that the hulk may be less valuable at end-of-life. The high cost and scarcity of specialty materials used in advanced vehicles will require raw material management and this will encourage recyclability to offset the virgin material.

Design for recyclability is not emphasized. Most OEMs have design for recycling and dismantling guidelines that engineers use. However, when ranked against other things such as safety or fuel economy recyclability has less importance. With the passing of the RRR amendment to type approval for the EU in 2005, recyclability has taken on a new importance to the auto companies.

The economic value of recovered materials and components will shape the future of the recycling business. Markets for most non-metallic recovered materials do not exist today. Development of viable markets for recovered materials and components is critical to achieving any significant increase in the current level of ELV recycling. Without clear market drivers, creating the market pull needed to significantly improve recyclability will be impossible. Further emphasis on technologies to further extract more metals from shredder residue for which markets already exist could affect greater ELV recovery by weight as they are currently commingled with the non-metallic fraction.

Some composites and commingled incompatible materials do not have secondary use markets. Alternative uses for materials may exist but recyclers are not aware of the opportunities. Market development strategies for fines and glass, for example, could identify new uses, benefits and promote recycling. End-market consumption of reprocessed material and parts will determine the economic viability of the industry. Their value as "green" products is not expected to create significant market impact.

New technology is needed to make material recovery cost-effective. Low-cost raw material from nature competes with recycled material. Today, except for ferrous and non-ferrous metals, the cost of collecting, sorting, recovering and/or chemically converting some recyclable materials such as plastics exceeds the cost of virgin material. For some materials, current technology does not produce recycled materials with the same characteristics and performance levels as new materials. Advancements in technology are likely to reduce the cost and improve quality of recovered materials and, therefore, increase recyclability. For example, chemical recycling of some polymers can now produce plastics with properties equivalent to virgin resins.

Changes in original material properties over time, while in original use or through multiple recycled uses, also affects the recyclability of materials. Ultimately, some materials ~~will~~ could reach a point at which they have no post-use value due to chemical and physical property changes.

There are no industry standards for material performance because materials are selected for competitive advantage in specific applications. Material specifications and part performance standards are used to determine if recovered and recycled content materials can be used for automotive applications. Most auto companies require that recycled content materials meet the same performance specifications as virgin materials. Establishing specifications and part testing can be expensive. Lot-to-lot sampling techniques for material qualification are required to establish quality consistency. Increasing the use of recycled plastics in vehicles may require duplicate testing and development costs to assure equivalency of performance. Availability of recyclate streams, in sufficient quantities is needed. Nevertheless, rewritten standards and product verification tests are necessary to increase the amount of recycled material in vehicles and other applications.

A systems perspective to ELV recycling management does not exist. Managing recovered material and components systematically throughout their lifecycle is complex. Solutions can take many forms such as a new recycling technology, a new end-use concept, and/or a new regulation. New opportunities often create new challenges. Currently, there is limited knowledge of how the interface of technology and policy affect recycling and management throughout the lifecycle. This know-how is needed to optimize where and how an effective intervention can be introduced.

How recycling is defined and perceptions impact material management. Stakeholder interests in a recovered material are usually material-specific. For example, a steel user is typically only interested in the purity of recovered steel. Collectively, these interests have shaped the way recycling is viewed. Many potential end users of recovered materials do not have accurate information on the value of recycled material. In the United States, recycling is not a high priority for policymakers. Because of the complexity of the ELV recycling life cycle, policy makers often have incomplete information.

▶ *Material Content of Vehicles*

The diversity and complexity of the materials used in vehicles make sorting bulk material and shredder residue challenging. Although OEMs have made efforts to decrease the absolute number of different materials used in cars, the trend is toward increased use of materials that currently have limited recyclability (e.g., plastics, composites) relative to traditional metals. This trend is driven by the need to cost-effectively meet increasing performance and safety specifications. As the number of incompatible materials increases, separating and sorting materials is more costly. Lot-to-lot material property variability increases, which impacts the success of an individual recycling stream. ELV's are also recycled with other durable goods which make up a large percentage of the non-metallic materials recovered.

Complete information on some of the types of material in vehicles is may not available. This information, along with material labeling such as resin type on plastics, could facilitate bulk material and post-sort recovery. However, even if one had the information on materials in an automobile that would not help after the vehicle has gone through a shredder with other goods such as old appliances. Many Some durable goods industries are not focused on recycling. As a consequence, material designs for components used across industries are not focused on recycling. Material and component suppliers must respond to multiple regulatory requirements and customer demands, and meeting recycling requirements are not a priority.

The impact on recycling from a change in the materials used is often not understood. The recycling community must continuously respond to the impacts from design tradeoffs. For example, new glass window technology reduces the weight from 80 pounds to 40 pounds, but now the windows are laminated with a polymer interlay, such as polyvinyl butyral (PVB), a new material which is also recyclable. How new lightweighting technologies alter recyclability is not well understood.

Recovering components containing hazardous materials and eliminating contaminated material in the shredder residue is difficult and made more complex as new materials are introduced. For example, flat panel displays used in entertainment and navigation systems contain heavy metals (i.e. mercury) and are expected to grow in popularity; uncertainties exist about the impact of traditional car batteries, hybrid car batteries (which contain Ni/MH, Li-ion, Li-polymer, vanadium, rare earth, and other advanced materials), and hybrid powertrains; contamination from the auto seat flame retardant pentabromodiphenyl ether (PentaBDE) will persist for some time to come, and the impact of its alternatives is unknown. Similarly, substances, such as bromine and lead, need to be monitored and removed. PCBs is another substance of concern that needs to be addressed before materials in shredder residue can be recycled.

ELVs, appliances and other items are mixed during the shredding process. Defining vehicle recycling narrowly (as oppose to using a broader, more accurate definition i.e., material recycling) restricts the development of solutions. Recycling autos separately, i.e. not mixing them with other durable goods, may not necessarily produce the best stream of recycled materials. That is, the combination of materials which we have in a vehicle arte there for performance reasons, not for an optimal material mix.

▸ *Competing Vehicle Design Requirements*

When producing vehicles, vehicle designers must balance consumer demands such as safety, cost, and performance with regulatory requirements. Although the OEMs are committed to using recycled materials in their vehicles, design for reuse, remanufacturing, disassembly, and material recycling is not emphasized as heavily as other concerns such as safety and fuel economy. Increasing pressure is placed on OEMs to provide warrantees of greater length and make vehicles less costly to repair. Intelligent disassembly is not expected to be available for the mass fleet. The environmental impact from competing design requirements is not well understood. Manufacturing practices and priorities are expected to continue to significantly impact vehicle recycling.

▸ *Capability to Separate and Sort Material*

Cost-effective technologies to separate and sort non-metallic material from shredder residue are emerging. The capability to economically recycle today's SR has not been proven on a large scale yet, at least not in the U.S. market. Some operations such as Galloo in Europe, where disposal cost is high, has been successful in recovering some plastics from SR. In the United States, considerable research has been conducted by the VRP, APC, Argonne and others to develop advanced technology to separate SR into recyclable constituents. Quality plastics have been recovered. While the technology developed at various organizations shows promise, full-scale commercial operation has yet to be demonstrated. The technology requirements to recycle more complex materials such as those used in hybrids and fuel cell vehicles have not been defined. Historically, the dismantling industry has been very creative in recycling vehicles they have never seen prior to entering the market. New processes such as marking plastic parts by resin type will facilitate sorting.

There is also a lack of awareness of the technology that is available and what it can yield in terms of value (e.g., alternative product stream technology). In the future, the development of innovative recycling technologies that are independent of material content and design may preclude the need for sorting. Predictive separation models and technology will be needed to develop this capability but fasteners could still remain an issue.

Strong material fastening methods are required to withstand vehicle demands, but joining techniques can complicate or preclude cost-effective recycling. Fastening and assembly methods are done for safety and performance and not for disassembly. Once disassembled, cost-effective, accurate material identification and sorting techniques for non-metallics and commingled metallics do exist, however, it is time consuming and labor intensive. As a result, pieces of mixed material must be sorted by hand or else they will contaminate the recovery stream. The purification and cleaning technologies for metals and plastics are inadequate and often non-existent, resulting in contamination of recovered materials (e.g., removal of paint, formulated performance additives, pigments, etc.). As a result, cleaning and purification of recycled materials is necessary in order to meet purity and part performance requirements for high end applications.

▶ *Hazardous Material and Contamination*

Contamination of the shredder residue with toxic materials such as polychlorinated biphenyl (PCB) and heavy metals poses a significant challenge for material recovery. Unless they are prevented or eliminated up stream, these hazardous materials must be eliminated, managed, and processed by recyclers. Recycling technology for some contaminated parts such as plastic gasoline tanks do not exist, except if the recovered plastics are used for low end applications. Contaminated SR entering landfills and incineration are restricted by regulations that vary by region and are subject to interpretation. Environmental concerns (e.g., dioxins) and capital costs necessary to make energy recovery facilities environmentally acceptable may limit energy recovery.

Cooperation between dismantling and shredding operations can increase the recovery of usable components and materials. Information needs to be exchanged between these operations to improve the recycling process. For example, removing non-metal parts for recycling at the dismantling facility should increase the value of the "hulk" because the shredder will have less SR to dispose of. In the present practice the "hulk" is sold to the shredder by weight and removing materials from it reduces its value.

As new materials enter the market, the technology in use and in development may no longer be solutions or sufficient. For example, the introduction of carbon fiber, titanium, sulfur, chlorine, and other materials can thwart the use of existing technology and new technology in development.

▶ *Capital Availability to Conduct R&D and Build Infrastructure*

Expanding vehicle recyclability will depend on the widespread use of yet-to-be-developed recycling technology. There is a lack of investment capital to launch technology R&D. R&D costs to create new processes are high and testing and development will take time. This reluctance to invest could be due to the perceived lack of economically recoverable value in SR.

Commercialization of new technology must keep pace with the new requirements of ELV recycling. Technology investments for recycling are significant. Without economic or policy drivers, it is difficult to successfully transfer pre-competitive technology into commercial practice. There is ~~also~~ limited capability to demonstrate an improved on-going recycling operation or new technology, which is needed to convince recyclers of opportunities.

A lack of financial return for recyclers has led to technology inertia for facilities and tooling (F&T). There are limited incentives to use new technology, especially considering the weak markets for some recyclable materials. Existing infrastructure will need to be expanded significantly to increase material recovery and adapted as different technologies enter the ELV stream, such as fuel cells and hybrids. These new technologies pose new challenges for the recycling infrastructure. Opportunities for entrepreneurs will need to be fostered and capital has to be raised to build the infrastructure. Innovative industry interfaces such as mobile shredders or granulators for plastics are needed to encourage a viable industry.

Recyclers and researchers cannot anticipate where and when advanced materials will show up in the recycling infrastructure. As a result, investors in recycling infrastructure do not know when material value will occur (i.e., in remanufacturing, dismantling, or shredding). This restricts investment in needed infrastructure. Likewise, researchers need clear priorities to focus recycling R&D as changes in the ELV recycling industry occur. Some advanced composite materials are already on the road today in vehicles, e.g. Corvettes, Saturns and Mack truck cab bodies.

▶ *Collection Costs, Transportation Costs, and Material Supply*

An economically viable recycling industry will depend on cost-effective collection, transportation, and sufficient material supply. Parts and material must be collected, transported and consolidated. With over 15,000 dismantlers in the United States there is an insufficient quantity of materials, beyond what is being recycled, to allow the operation to be economical, and to provide consistent feed streams. The recycling infrastructure is also not available in some regions of the country. Reverse logistics (e.g., collection, participation), transportation economy, and landfill capacity will impact the ability to change the ratio between scrap and waste.

▶ *Regulations Impacting Recycling*

In the United States, recycling of ELV is market driven. In Europe and Japan, a regulatory approach to eliminate most landfilling and encourage recycling is being used with recycling standards varying by region. These approaches are costly and their success is debated. There is concern that the strategies used abroad may influence U.S. regulators or public opinion, leading to less than optimal choices for the U.S. recycling industry. As good corporate citizens, most OEMs are promoting recycling to avoid landfilling and a costly regulatory approach to recycling. As international companies, OEMs are challenged with meeting the requirements of each country.

The recycling market is to some extent not well understood today, and uniform definitions of recycling needed for clear communication do not exist. In some cases, consistent interpretations of regulatory definitions do not exist. (e.g., recycled content verses recyclability), and some regulatory definitions have been counter productive. In addition, metrics for recycling performance are not well defined (e.g., what is the objective, how can recyclability be measured such as energy savings and life-cycle cost). The lack of clear definitions of short and long term recycling strategies inhibit the development of innovative and optimal solutions. Despite these difficulties, there is a thriving recycled material market out there. In the case of materials derived from shredder residue, what is needed is market drivers and consistent volumes and quality of recovered materials.

Federal regulations and state and local regulations that vary from region to region significantly impact the recycling process. These regulations impact fluid recovery by dissemblers, emissions from incineration that prevent energy recovery, and allowable material content in landfills, for example. The regulations are often not coordinated despite the interrelated impact of the requirements (safety, environmental, others). The outcome is less-than optimal recycling solutions. There is increasing pressure to find alternatives to disposal due to decreasing landfill space. Competing environmental goals could influence the trend towards recycling. For example, opposition to mining raw materials that recycled materials could displace. Safety requirements have led to joining methods that pose significant challenges for recycling. An improved understanding of substrate and joint failure mechanisms could increase joint durability and facilitate recycling. The inability to predict future regulations and subsidies has a significant impact on recycling economics and material recyclability, especially for plastics.

▸ *Consumer Opinion*

Consumer opinion and concern for recycling could become significant drivers. The public has broad concerns about the environmental impact of vehicles and is concerned over the types of materials ending up in landfills and the impact of energy recovery through incineration. The public likes "green" products. However, the public won't pay more for it. In addition, there tends to be a perception that reused, remanufactured, and products with a "recycled content" are of lesser value or quality than new parts/products. Consumers and citizens will determine what is acceptable and influence future regulations. Among material industries, there are misconceptions about what can be recycled. For example, the composite, steel, and other industries often perceive that plastics are not recyclable.

▸ *Unforeseen Factors*

Unforeseen technical, economic, and social factors could influence vehicle material content and the future of recycling. For example, fuel price increases impact trends toward more energy-efficient vehicles and increase the expected vehicle life. A trend toward increased leasing versus vehicle ownership could impact product and material recovery and impact recycling activities. A significant development in energy storage technology may change vehicle technologies. Major changes outside the automotive industry could modify some of the drivers for recycling such as if methane hydrates become feasible.

The adoption of new recycling technology leads to new unpredicted challenges (even after the technology appears to be successfully implemented) due to the introduction of new automotive materials and processes. Flexible and innovative over-arching recycling strategies (i.e. mechanical recovery, chemical recovery) are needed to more effectively address existing, new, and unexpected challenges that impact vehicle recycling.

IV. Strategy for Increasing Recyclability

The variability in the way recyclability is defined throughout the world is a significant obstacle. For example, the definition of recyclability is different in North America, the European Union, Japan, Korea, and China. Some recyclability definitions target the vehicle design, not the content. This impacts the content of the shredder residual produced (prohibiting reuse) and the efficiencies of post-shred recovery and recycling technologies.

The North American recycling infrastructure currently handles 94 percent of all ELVs.

Overcoming all the challenges to improve recyclability will require a carefully crafted strategy, dedication from the recycling community, and on-going dialogue to track progress. The relationship among the top challenges facing recyclability is presented in Exhibit 3. The success of ELV recycling depends on these complex interrelationships. The strategy outlined below will help maximize the value recovered from ELV.

- Come together as a unified recycling community to cost-share the development of required new technology, to develop a baseline assessment of technology and operations, and to promote recycling infrastructure development.
- Incorporate reuse, remanufacturing, and recycling into the design phase for cars whenever possible. This may include rationalization of some materials where feasible, and facilitation of component and material removal.
- Recycle as early in the recycling stream as possible while relying on the market to optimize the value and amount recycled at each step. Base recycling decisions on fully accounted costs.
- Maintain a flexible recycling process that can adapt to diverse automobile model lines fabricated with different techniques and materials from various suppliers.
- Consider the recycling requirements of new automotive technologies entering fleets as early as possible.
- Develop automated ways to recover bulk materials.
- Encourage the development of innovative technology options that enable cost-effective recycling.
- Understand the technology and policy options for achieving diverse recycling objectives such as optimizing for life-cycle material use or energy use reduction.
- Emphasize R&D on post-shred material identification, sorting, and product recovery because this will have the greatest impact on raising the market value of the SR and help avoid landfilling and incineration.
- Focus R&D efforts on materials not recycled today by sorters (e.g., post-shred glass, rubber, fluids, textiles, plastics)
- Foster the development of economically viable uses for recovered materials (whether in the same or different applications) and develop material testing specifications.
- Encourage investment in the infrastructure needed to recover value from ELV recycling. Build on the existing infrastructure.

- Develop a means to prevent the entry of PCBs and other hazardous materials into the recycling stream and promote acceptable limits in the SR.
- Foster effective communication between dismantlers, processors, and auto manufacturers to bolster recycling, especially for new material streams.
- Educate the public, policymakers, and industry so they have an accurate understanding of how ELV are recycled and the opportunities and challenges.
- Understand the limits of a market-driven recycling industry and the limits of technology-driven solutions. Develop a plan for the gaps.

V. Priority Needs for End-of-Life Vehicles Recycling

The major goals of this research are to (1) enable the optimum recycling of all automotive materials, (2) ensure that advanced automotive materials that improve the life-cycle energy use of vehicles are not precluded from use as a result of a perception that those materials are not recyclable, and (3) continue to enable market-driven vehicle recycling. The automobile recycling community identified the priority R&D and non-R&D activities needed to improve recyclability by 2025. They are presented in Exhibit 4. Activities exist across the recycling spectrum, including design, dismantling, reuse and remanufacturing, post-shredder, and end-use. The needs are categorized as top, high, and medium priority and by the time frame in which useful results can be expected. For technology development, the timeframe is for production-ready technology with proven economies-of-scale and feasibility in real-world commercial applications. Many of these activities have been on-going since the inception of the CRADA and some even before by the recycling community. The rationales for the priorities outlined in Exhibit 4 are discussed briefly below.

Proactive Industry-Wide Action

While the CRADA team provides a core of expertise, cooperation with other organizations is key to achieving the overall program objectives. It is considered a high priority to continue with an effective outreach program to solicit the participation of the recycling community and other stakeholders. In the United States, a market-driven recycling infrastructure is in place. The CRADA team will continue to pursue cooperation with organizations and companies that are a part of the recycling infrastructure and with other stakeholders. A website was launched to provide for better communication and networking with stakeholders and other research teams and interested parties: http://www.es.anl.gov/Energy_Systems/CRADA_Team_Link/Index.html. The website provides an update of the CRADA progress and provides access to relevant information and publications including a bibliography of technologies for recycling automotive materials. The CRADA team held a media event for *America Recycles Day*. It was attended by a number of media organizations. Several presentation and publications were made to further communicate with interested parties. Meetings with representatives of the Institute of Scrap Recycling Industries (ISRI) and the Automobile Recycling Association (ARA) were held to brief them on the CRADA objectives and projects and to elicit their participation. Reviews of the CRADA projects and ongoing efforts are held regularly. The CRADA team will continue to pursue active outreach efforts to share information with and seek the participation of all stakeholders and interested parties including potential users of the recycled products.

Members of the recycling community formed an alliance to help implement the 2000 Roadmap with the formation of the U.S. ELV CRADA. This alliance brought together automobile companies, suppliers, recycling industries, national labs, and universities to discuss challenges, set priorities, and cost-share and co-manage activities. Many other alliances among these groups exist today. By sharing the risk and creating a common voice, the United States will be able to improve recyclability. The U.S. CRADA Team is working to assure that research plans are pursued with knowledge of other related activities, and that follow-up meetings are held regularly, especially as new technologies mature and enter the automobile market. Key non-R&D recycling issues have been pursued as well. This roadmap identifies the need for a web-based information exchange service for the recycling industry, the development of effective communication documents and strategies to educate stakeholders, and for a strategy to work with consumer good industries to reduce the contamination of post-shred material recycling. The CRADA team website (http://www.es.anl.gov/Energy_Systems/CRADA_Team_Link/Index.html) forms the basis for such a service, as an on-going effort, by adding appropriate links to it as they become available.

Industry-Wide Analysis

In order to make judicious tradeoffs among material selection, vehicle design, recycling technologies, and recycling process operation parameters one needs to understand their impact on recyclability and the environment. Currently, the status of technologies used, existing process capabilities, and the mass balance flow of automotive materials at end-of-life is not known with the level of confidence needed to assure that the industry is making the best choices to optimize recyclability. Development of a better understanding of the interrelationships of all steps in the recycling process from a financial perspective which will promote the development of an infrastructure capable of handling the volume and complexity of future fleets is a high priority. The net environmental impact of recycling verses vehicle life cycle energy use and environmental impact will have to be determined. Analysis of this data is needed to better understand the environmental and economic tradeoffs. Processing of large enough samples of shredder residue from different sources is necessary to generate such data.

Lower the Risk of Technology Development and Purchase

This is considered a high priority item. The recycling industry will need to make major investments in technology to significantly improve recyclability. The market value of recovered components and material, especially from the SR, is currently not high enough to create the necessary market pull. While the recycling community would like market forces to determine the value of recycled materials as much as possible, both demonstrations and tax incentives are needed to encourage investment to reduce the risks associated with R&D and technology purchases. Demonstrations will show the feasibility of new technology such as achieving a competitive recycled-material delivered price. Currently, a state-of-the-art facility that shows the capabilities of an ongoing recycling operation does not exist. Tax incentives will encourage innovative technology development and investment. Demonstrations and tax incentives will enable the significant level of investment needed to build the required U.S. recycling infrastructure. It is important here to continue to track new technology and R&D progress in the United States, and overseas.

Automobile manufacturers design new vehicles with available materials that meet the required specifications at the lowest cost. With technology advancements, plastic components and systems can be investigated to meet the specifications and be recovered in bulk and from the SR.

Component and Material Design for Recycling

This is a medium priority. Recycling issues should be elevated in the design process so that material selection and component designs should take in consideration ease of recycling such as ease of bulk recovery.

Pre-Shred Recovery

This is considered a medium priority. Dismantling is labor-intensive so improving its efficiency will help make some material and component recovery more economical. New technologies that are anticipated to be in end-of-life vehicles after 2010 may require unique recycling technologies in order to recover valuable materials and/or avoid rendering the post-shred residue hazardous. In addition, increasing the value and scope of reused and remanufactured parts and components will foster pre-shred recovery.

This effort should include development of low-cost dismantling processes to improve material and component recovery using an industrial engineering approach especially for new challenging systems (e.g., fuel cells, powder metals, nano materials).

This effort should also develop and validate reuse and remanufacture techniques including rapid automatic recognition of parts of value.

Post-Shred Material Identification and Sorting

This is considered a top priority because recycling materials from shredder residue is a must to increasing recyclability and meeting regulations such as those proposed in Europe and Japan. Eventually, almost everything in a vehicle will reach its end-of-life and be shredded or otherwise processed as scrap. The capability to quickly separate, identify, and sort materials into fractions that have economic value–including the removal of contaminants or substances of concern– is absolutely necessary to significantly improved recyclability. Over 90% of the metallics in ELVs are easily removed using magnetic and eddy current separation. Non-metallic materials such as plastics, rubber, glass, and organics are difficult to separate. Plastics require additional separation to be of value because of polymer incompatibility. Currently, there is no commercially proven way to separate all of the polymers that are or will be used in cars. Therefore, it is a top priority to develop technology to separate and recover materials, particularly polymers and residual metals, from shredder residue. This effort should focus on:

- Development of processes to sort post-shred non-metallic and commingled metallic material at high speed
- Continue R&D on rapid identification and sorting of polymers, especially mixed polymers
- Development of methods
- Identify best practices and best uses for mechanical recycling pre-sort or pre-treat streams (bulk separation), e.g., use fines, do not mix classified ASR fractions
- Work with shredders to facilitate scale-up and demonstrate the technology

Increase End-Use Value of Recovered Materials

This is considered a high priority. Even though limited markets for mixed plastics streams exist their market value is generally low (under $0.05 per pound), increasing their value by sorting and purification will create the market pull necessary to prevent disposal through incineration or land filling. Profitable applications for rubber, glass, and other materials are needed. If polymer compatibilizers were available, they could simplify and reduce the cost of polymer separation processes in some cases. The ability to separate higher value materials, such as composites, could lead to a reuse market that could create economic incentives for the entire sort stream.

Removal of Substances of Concern from Recovered materials

– Unless substances of concern, particularly PCBs, can be effectively and economically removed from materials recovered from shredder residue the recovered materials can not be introduced into commerce. Therefore, it is a high priority to develop and demonstrate technology to clean the recovered materials so that they meet governing regulations. Work done so far indicates that commercially available cleaning processes can not reduce the concentration of PCBs on polymers recovered from shredder residue to below 2 PPM, which is the recommended EPA limit. Therefore, technology should be developed and demonstrated to resolve this issue. It is also important to initiate a proactive dialog with policymakers in EPA about technology entering the market. A starting point should be the state-level EPA(s) with a stake in recycling or state/region.

Identification of new lightweighting materials and characterization of their impact on recycling

New materials, including carbon fiber composites and light steel are already in use in some vehicles and their use is likely to increase in the near future. Other lightweight materials as well as materials that will be part of future vehicle designs such as hybrids and fuel cells will also eventually reach their end-of-life and will require recycling. It is difficult, if not impossible, in some cases, to predict what the future materials will be and what their impact on recycling they will have. Compare to the other priorities this is considered as a medium priority at this time. Attention should be given to materials that are already under evaluation, testing or consideration by the vehicle manufacturers or their suppliers. These include, but not limited to:

- Metals: magnesium, titanium, aluminum and different alloys. If these are used to replace steel they will reduce the wt% of the vehicle that will be recycled as metals and increase the wt% that will end up as shredder residue.
- Chemicals: catalysts for pollution control or for deploying air bags, fire retardants. These could cause some parts of the waste stream to become hazardous. Some of these may be in the form of noble metals (such as platinum in the fuel cells) which will be valuable if recovered.
- Composites: carbon fiber composites, glass fiber composites. If these are used to replace metals they will increase the wt% that will end up as shredder residue.
- New polymers. Even when present in small percentages these could challenge the separation process and may adversely impact the quality of

other recovered materials because of incompatibilities. It is important to foster more involvement of plastics manufacturers in characterizing these materials.

- Nano particles and materials utilizing nano particles

Exhibit 4. Priority Needs for End-of-Life Vehicle Recycling

Proactive Industry-Wide Action (Time Frame- Ongoing)

Develop and maintain a web-based system to make information available to the recycling industry and stakeholders. Post information such as CRADA plans, and achievements, available technology, contact information, pre-competitive information, papers, abstracts, advocate information, etc.

Continue to track new technology and R&D progress in the United States, and overseas.

Foster more involvement of plastic manufacturers in evaluating separation technologies and resulting materials

Initiate a proactive dialog with policymakers about ELV, and improve the format and effectiveness of communications

Initiate a proactive official dialog with EPA about technology entering the market, e.g., allowing the use of new PCBs removal technology

- Start with state-level EPA(s) with a stake in recycling or state/region; identify how scrap is defined
- Agree on the terminology needed for clear communication

- Develop generally accepted definitions for the recycling industry

Continue to develop an industry-wide partnership to work with other consumer goods industries to build synergies and improve material recycling (SR includes these goods too)

- Reach out to other comparable organizations with recycling challenges (appliance, electronic, etc.). Listen and learn from them, and let them know that "our stuff gets mixed with your stuff"
- Identify how auto issues and their issues impact each other
- Identify what they are doing and planning to do in the future
- Identify what recovery innovation they have that we can use
- Develop best practices benchmarks with similar industries, and identify what we can do next (and what we both can do differently)
- Develop and present process model changes to help with recycling (e.g., soldering)
- Create an on-going dialog; if they are moving away from a material, identify the implications for the recycling stream

Raise awareness of how the insurance repair industry impacts recycling, e.g., Canada dictates what is pulled from automobiles and what is left

Industry-Wide Analysis (Time Frame- Ongoing)

Continue developing a baseline assessment of existing and emerging automobile recycling systems to understand the state-of-the-art and identify what is needed

Demonstrate the entire recycle stream (including inorganics) to show the complexity and process optimization challenges to policy makers, auto companies, recyclers, shredders, etc.

Develop a model of the net environmental impact of automobile recycling, including the trade-off between life cycle energy use and increased recyclability. Use the lifecycle model to evaluate specific technology options

Develop a database of technology and materials recycling. Develop a "process hypothesis" to determine what to study more closely and what not to study [if use the technology, then...]

Validate existing and emerging technologies to verify claims (yield, cost, environmental saving, etc)

Develop and propose a process to screen and validate recycling technology based on economics, feasibility, environmental impact, applicability to future ELVs, phase of impact, and other criteria; identify R&D needs based on technology assessments, gaps, future recycling needs, and priorities. Disseminate information to decision makers. This will require an ongoing, two-way dialog with regulators and the recycling community

Assess fluid collection of the vehicle process industry (dismantlers, shredders, etc.)

Exhibit 4. Priority Needs for End-of-Life Vehicle Recycling, *continued*

Lower the Risk of Technology Deployment and Purchase (ongoing)

- Continue R&D to bring technology to scale in order to facilitate technology transfer and the lower the risk of implementation
- Leverage cooperative deployment and promotion
- Study/model local permitting and compliance requirements that impact implementation (threshold of stream, concentrates, and undesirables)
- Develop scenarios and business cases of value and advantages of technology (even ones we don't see); ask: What combinations of talent/businesses could take it to the next step? (scrap becomes feedstock material)
- Conduct feedstock analysis to identify reliable and complementary streams of material; ask: Where are "supplies," material and alternate material?
- Identify options for dispositions of residuals to decrease liabilities from hazards
- Obtain reliable market data to support recycling, identify sources and price indexes and post on website

Component and Material Design (ongoing)

- Design recyclable plastic parts and systems for ease of bulk recovery
- Analyze emerging materials such as nano materials to understand how to recycle (consider health and other characteristics)
- Determine how recycling may affect performance

Pre-Shred Recovery

- Develop dismantling methods for new challenging systems (e.g., fuel cells, powder metals) and focus on new areas of concern
  - Develop a low-cost dismantling process to improve material and component recovery using an industrial engineering approach
- Incorporate de-pollution preparation steps (i.e., removing tires will increase the value of rubber)
- Develop and validate reuse and remanufacture techniques including rapid recognition of parts of value

Exhibit 4. Priority Needs for End-of-Life Vehicle Recycling, *continued*

Post-Shred Material Identification and Sorting (by 12/07)

Develop the ability to sort post-shred non-metallic and commingled metallic material at high speed (e.g., plastic, rubber, glass, and organics)

Continue R&D on rapid identification and sorting of polymers, especially mixed polymers

Develop methods for removing PCBs and other toxic materials from materials recovered from shredder residue
- How we do it will depend on what we plan to do with it next, e.g., recover plastic for resale

Develop technology to concentrate the organic stream

Identify where PCBs are coming from

Evaluate glycolysis on polyesters and other plastics

Identify best practices and best uses for mechanical recycling pre-sort or pre-treat streams (bulk separation), e.g., use fines, do not mix classified ASR fractions
- SR can be mixed or in separate piles; pre-sorted or pretreated materials to facilitate recycling, e.g., one pile may be better suited for a use than others
- Work with shredders to facilitate scale-up and demonstrate the technology

Increase End-Use Value Of Recovered Materials

Continue R&D on polymer compatiblizers to ease separation requirements
Determine properties of recovered materials

Develop methods to separate fiber from resins for reuse (e.g., metal matrix composites, carbon-reinforced composites, glass-reinforced composites, rubber)

Develop general-purpose products from recycled materials and find applications to create an economic pull for recycling (e.g., sewage treatment, railroad ties, glass, and rubber)
- Develop a separation process and post-use applications for glass to create value (its in fines with sands)
- Develop a separation process and applications for rubber (e.g., tires, window strip, hoses); monitor to see that existing infrastructure does not duplicate R&D; need to know added value before identifying applications
- Determine feasibility of concentrating fines and concentrating metals to become smelter feed
- Process ASR as a fuel for cement kilns
- Remove contaminants in value stream

KEY

Edit ed R&D Needs from 5/25/01 Roadmap

New R&D Needs

Priority ranking TBD

VI. Next Steps for Implementing Roadmap Priorities

This roadmap sets forth the priority needs and direction for how the recycling community will improve vehicle recyclability over the next 20 years. Through active, engaged partnerships with industry, stakeholders, and Congress, significant near-term and long-term impacts on recyclability can be achieved.

A key priority of the 2000 Roadmap was the formation of an industry-wide alliance to synergistically focus efforts improving recyclability. The 2003 U.S. ELV CRADA coordinates a diverse range of activities among the stakeholders in pursuit of the priorities. Projects are funded on a project-by-project basis, and financial and technical contributions come from relevant stakeholders, including the recycling industry, equipment manufacturers, automobile industry, material suppliers, trade associations, and government research programs.

Stakeholders include:

- *Recycling Industry – Transporters, Dismantlers, Reuse/Remanufacturers, Shredders/sorters*
- *Equipment Manufacturers*
- *Automobile Companies*
- *Material and Component Suppliers*
- *Trade Associations*
- *Government Research Programs*
- *National Laboratories*
- *Universities*
- *Independent Research Institutes*

The DOE Office of Energy Efficiency and Renewable Energy (EERE) recognizes the recycling challenges that exist with vehicles now and in the future. EERE is pursuing activities to support the development of recycling capabilities for advanced automotive technologies. Continued government leadership from EERE is essential to achieving significant improvements in recyclability. Specifically, the recycling community would like EERE to assist with the following:

- Continue to support the U.S. ELV CRADA Team's research, development, and demonstration activities
- Assist with the formation of an automobile recycling alliance to provide clear communication to stakeholders and bolster ELV recycling
- Use the priorities in this roadmap to guide EERE program activities
- Co-fund R&D projects at national laboratories and universities. Priority areas include lowering the risk of technology development and purchase, demonstrating the entire recycle stream, and post-shred material identification and sorting
- Assess progress periodically so this effort is kept up-to-date as new materials and technologies are incorporated in new fleets
- Encourage participation of all stakeholders

The Importance of Government Involvement

Almost all of the 5 million tons of nonmetallic components in ELV are entering the waste stream today, requiring landfill space. Cost-effective markets do not exist for this material. Government involvement is needed to reduce the social and environmental impacts from this waste.

New ELV material streams will require new recycling technology and economies. Market drivers to encourage the R&D that is needed do not currently exist. The needed R&D will require long-term timeframes and high-risk efforts that the industry is reluctant to pursue alone. Without government assistance new technology purchases in the scale needed to improve recyclability nation-wide could not happen fast enough to significantly improve recyclability by 2020.

Different steps in the recycling process have different economies, issues, and priorities. For example, from a shredder's perspective, design is not a factor except for what and how much materials end up in the shredder residue. Government can serve as a catalyst to bring together the diverse perspectives across the recycling and automobile industries, while allowing these industries to lead the effort to ensure optimal decisions. Neither the recycling industries nor the automobile industry should be expected to independently fund and/or undertake all of the needed research.

Independent, unbiased source of data is needed to help the recycling and automobile industries come together and to provide credible data to Congress and the Environmental Protection Agency. Government involvement can assure credible data and help keep partnerships pre-competitive. Regulatory barriers to inhibiting environmentally sound and economically sustainable recycling may need to be addressed.

Automobile companies are international, and they need to reach economies-of-scale and design for all markets. As these companies face competitive pressures, technological solutions may come from overseas where landfill costs are higher and markets for recovered products are more competitive. Government involvement can ensure optimal decisions for recycling in the United States and promote the understanding of how other countries have different markets and different needs.

APPENDIX

A. Background

In 2000, the Department of Energy's Office of Advanced Automobile Technologies (OAAT) and Argonne National Laboratory (ANL) sponsored a workshop which brought together 24 experts representing OEMs, material suppliers, recyclers, and researchers. They reached consensus on the goals, challenges, and critical needs for improving automobile recyclability. The output from the workshop was incorporated into the document, *A Roadmap for Recycling End-of-Life Vehicles of the Future*.

The roadmap has been used to guide activities among the ELV recycling community. To help implement the Roadmap, the U.S. Department of Energy (DOE) signed a five-year, multi-million dollar, cost-shared Cooperative Research and Development Agreement (CRADA) among industry and government leaders in 2003. The U.S. ELV CRADA Team has been actively engaged in a broad range of research, development, and demonstration activities to advance technology for the sustainable recycling of materials used in automotive vehicles today and in the future.

The U.S. ELV CRADA Team

- The Vehicle Recycling Partnership of the United States Council for Automotive Research (USCAR) – a partnership of DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation
- The American Plastics Council (APC)
- Argonne National Laboratory

In continued support of these efforts, the Department of Energy's FreedomCAR and Vehicle Technologies Program and Argonne National Laboratory (ANL) sponsored a workshop on September 14, 2005, at ANL in Argonne, Illinois, to update the 2000 Roadmap. This event brought together 22 experts representing OEMs, material suppliers, recyclers, and researchers. Participants reached consensus on the goals, challenges, and critical needs for improving automobile recyclability. Information from the 2000 Roadmap and the output from the workshop were analyzed and incorporated into this document.

B. Contributors to the 2006 Roadmap

We extend our gratitude to the workshop participants who volunteered their time and contributed their expertise. They are listed below. The content of this Roadmap reflects a diverse set of perspectives to illuminate promising directions for recycling End-of-Life vehicles. The thoughtful comments received from the reviewers of this report were instrumental in sharpening and improving the final *Recycling End-of-Life Vehicles of the Future: A Roadmap Update*. The Energy Systems Division of Argonne National Laboratory sponsored the workshop and the Roadmap under the direction of Edward J. Daniels. This Roadmap was prepared by Melissa Eichner and Katie Jereza of Energetics Incorporated in Columbia, Maryland.

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C. Definitions

Terms and Acronyms Used in this Roadmap

AA—Aluminum Association. A trade association for U.S. producers of primary aluminum, recyclers, and semi-fabricated aluminum products.

ANL—Argonne National Laboratory. A laboratory of the Department of Energy located in Argonne, IL.

APC—American Plastics Council. A national trade association representing major plastic resin producers and distributors.

APME—Association of Plastic Manufacturers in Europe. A trade association representing over 40 companies representing over 90% of Western Europe's polymer production capacity.

APRA—Automotive Parts Rebuilders Association. An association with over 2000 member companies that rebuild automotive-related "hard" parts, such as starters, alternatives, clutches, transmissions, brakes, and drive shafts.

ARA—Automotive Recyclers' Association. A trade association that represents about 12,000 auto dismantlers, the companies that typically recycle cars for used parts.

Chemical Recycling. In this document, chemical recycling implies a change of the chemical structure of the material in such a way that the resulting chemicals can be used as a raw material to produce the original material again or used for other purposes.

ELV—End-of-Life Vehicles. Motor vehicles that have reached the end of their useful service life.

Hulk. The obsolete ~~car~~ vehicle after reusable parts or components have been removed from it by an auto dismantler for reuse. The hulk is typically flattened for shipment to an auto shredder who shreds the hulk and recovers recyclable materials, predominantly iron, steel, aluminum and other metals.

ISRI—Institute of Scrap Recycling Industries. A trade association that represents scrap material recyclers including about 200 shredder operators who recover recyclable metals and materials from obsolete cars, home appliances and other metal containing scrap.

Recycling. In this document, recycling is defined as any cost-effective use of parts, components or materials from an obsolete car that would otherwise be landfilled, including parts re-use and remanufacturing, materials recovered or reused in an original application or for use in any other viable application, and materials recovery for thermochemicial conversion to fuels and/or chemicals.

Recyclability. The process of dismantling and/or separation of products or parts or materials with the goal of return (i.e., to use as a functional part or as a raw material, including chemical and/or energy feedstock, for manufacture or utilization in another product).

SR—Shredder Residue. The reject material that is landfilled after processing by shredding of scrap (such as hulks from obsolete cars and appliances) for recovery of metals. Typically, shredders process a variety of feed materials to recover materials for recycling, including home appliances, demolition scrap, and industrial scrap in addition to obsolete cars and auto hulks.

SRI—Steel Recycling Institute. A division of the American Iron & Steel Institute that educates the solid waste management industry, government, businesses and ultimately the consumer about the economic and environmental benefits of recycling steel. Through its regional offices, SRI works to ensure the continuing advancement of the steel recycling infrastructure.

VRP—Vehicle Recycling Partnership. An organization formed by General Motors, Ford, and DaimlerChrysler to promote and conduct non-competitive research to enhance the recycling of obsolete automobiles. Since its inception in 1991, the VRP has been conducting research in collaboration with organizations such as the AA, APC, ARA, ISRI, and the federal government through ANL since its inception.