FY 2004

Progress Report for Recycling End-of-Life Vehicles of the Future

Prepared for:
Automotive Lightweighting Materials

U.S. Department of Energy
Energy Efficiency and Renewable Energy
FreedomCAR and Vehicle Technologies

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RECYCLING

A. Recycling Assessments and Planning

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Contract No.: W-31-109-Eng-38

Objectives

- Ensure that any real or perceived recycling barriers that might preclude the use of advanced lightweighting automotive materials are removed.
- Enable the optimum recycling of all automotive materials, current and future, thereby obviating the need for legislative recycle mandates.
- Assess the critical needs for cost-effective recycling of automotive materials and components.
- Establish research priorities to enable cost-effective recycling of advanced automotive technology materials and components.
- Communicate a collaborative industry/government approach to automotive materials recycle issues.
- Coordinate research with other agencies and stakeholders in the United States, Europe, and Asia.

Approach

- Consult with automotive manufacturers and recycling industries, the U.S. Council on Automotive Research (USCAR) and its affiliates, national laboratories, universities, and other relevant organizations to assess critical recycling needs/barriers.

- Develop a recycling research plan that will serve as a "working document" to guide the U.S. Department of Energy (DOE) in establishing priority goals, with an initial emphasis on lightweight body and chassis materials.
- Establish an outreach/communication function to enable cooperation and leveraging of resources with all stakeholders and with the international community.
- Assist DOE in establishing advanced recycling research and development (R&D) initiatives and provide technical oversight to ensure that priority objectives/goals are accomplished.

Accomplishments

- Prepared *A Roadmap for Recycling End-of-Life Vehicles of the Future*.
- Prepared a draft 5-year research plan based on the recommendations and priorities identified in the Roadmap and based on an initial planning meeting with the management council of the Vehicle Recycling Partnership (VRP) of USCAR.
- Negotiated a Cooperative Research and Development Agreement (CRADA) with the VRP, the American Plastics Council (APC) and Argonne National Laboratory (ANL), as partners; effort under the CRADA was initiated in August 2003.
- Held a CRADA announcement event at Argonne on December 2, 2004; the event was attended by representatives of the press, industry, and government.
- Presented a co-authored DOE, USCAR, and APC keynote paper entitled "Market Driven Recycling in North America" at the 2004 International Car Recycling Workshop in May.
- Held a meeting with the CRADA partners and representatives of the Institute of Scrap Recycling Industries (ISRI) in August; the CRADA team was invited to make a presentation to ISRI's Shredder Committee meeting upcoming in Dallas.

Future Direction

- Continue development and management of the research plan with the CRADA partners.
- Continue ongoing efforts toward the milestones and objectives of the CRADA statement-of-work.
- Develop a joint "US ELV CRADA" Team presentation kit and brochure and establish a US ELV CRADA Team Web site to publicize the approach and work of the partners.
- Continue outreach efforts to broaden the basis for cooperation among stakeholders.
- Continue ongoing project efforts to assist DOE in preparation of planning documents, priority recycling R&D needs, proposal reviews, and related tasks.
- Update the ELV Roadmap.

Summary

The objective of this project is to establish priorities and develop cost-effective recycling technologies and strategies in support of the U.S. Department of Energy (DOE) FreedomCAR Vehicle Technology (FCVT) long-term objectives and goals. 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 vehicle are not precluded from use due to a perception that those materials are not recyclable, and (3) continue to enable market-driven vehicle recycling.

Today, cars that reach the end of their useful service life in the United States are profitably processed for materials and parts recovery by an existing recycling infrastructure. That infrastructure includes automotive dismantlers who recover useable parts for repair and reuse; automotive remanufacturers who remanufacture a full range of

components, including starters, alternators, and engines to replace defective parts; and ultimately the scrap processor who recovers raw materials such as iron, steel, aluminum, and copper from the remaining auto "hulk" after components have been recovered for recycling.

Today, more than 75% of the materials from obsolete cars is profitably recoverable for recycling.

The recyclability of end-of-life vehicles (ELVs) is presently limited by the lack of commercially proven technical capabilities to cost-effectively separate, identify, and sort materials and components and by the lack of profitable postuse markets. During the next 20 years, both the number and complexity of ELVs are expected to increase, posing significant challenges to the existing recycling infrastructure. The automobile of the future will use significantly greater amounts of lightweighting materials (e.g., ultra-light steels, aluminum, plastics, and composites) and more sophisticated/complex components.

Roadmap Recommendations

A roadmap was developed with input from key stakeholders to guide DOE's recycle research. The key recommendations from the roadmap follow:

- Come together as a unified recycling community to cost-share the development of required new technology.
- Incorporate reuse, remanufacturing, and recycling into the design phase for cars whenever possible.
- Recycle as early in the recycling stream as possible, while relying on the market to optimize the value and amount recycled at each step.
- Maintain a flexible recycling process that can adapt to diverse model lines fabricated with different techniques and materials from various suppliers.
- Develop automated ways to recover bulk materials.
- Emphasize R&D on postshred material identification, sorting, and product recovery.
- Focus R&D efforts on materials not recycled today by sorters (e.g., postshred glass, rubber, fluids, textiles, plastics).
- Develop uses for recovered materials (whether in the same or different applications) and testing specifications.
- Encourage investment in the infrastructure needed to achieve the recyclability goal. Build on the existing infrastructure.
- Develop a means to prevent the entry of polychlorinated biphenyls and other hazardous materials into the recycling stream and promote acceptable limits in shredder residues.
- Consider the recycling requirements of new technologies entering fleets as early as possible.

The 5-Year R&D Plan

Based on the roadmap and continuing discussions with key stakeholders, a 5-year research plan has been prepared. The plan includes the following three focus areas:

Area 1. Baseline Technology Assessment and Infrastructure Analysis

The focus of the work under this activity will be to develop the tools and document the information necessary to make effective decisions relative to technology needs to facilitate sustainable future vehicle recycling and to make effective decisions regarding allocation of R&D resources.

Area 2. Materials Recovery Technology Development and Demonstration

Research to be conducted in this area will initially focus on addressing technology needs for postshred materials recovery, including mechanical recycling and conversion to fuels and chemicals. Projects that enhance preshred recovery, including disassembly for materials recovery and direct reuse and remanufacturing of components, will also be considered. In the long term, components such as fuel cells, advanced batteries, and hydrogen reformers are more likely to enter the recycle stream through preshred recovery for remanufacturing, repair, and materials recovery. Research will be undertaken to determine the technology needs to ensure the recyclability of these very advanced automotive components.

Area 3. Recovered Materials Performance and Market Evaluation

Understanding and enhancing recovered materials performance is an essential ingredient to a successful recycling program. This is especially true in automotive systems when the materials and components that are recovered have been in use for an average of from 10 to 15 years. This area will include projects to quantify the relative performance of recovered materials vis-à-vis new or virgin materials; research on compatibilization of recovered polymers to improve performance properties; development of technologies to upgrade the recovered materials, such as separation of fibers from polymeric substrates; and development of applications for other recovered materials, such as rubber and glass.

CRADA Projects

A collaborative research and development agreement (CRADA) among Argonne, the Vehicle Recycling Partnership of U.S. Council for Automotive Research (USCAR), and the American Plastics Council (APC) has been structured to provide a core team of expertise and the resources to enable the optimum recycling of all automotive materials.

The CRADA team's R&D agenda focuses on the following key objectives:

- Develop and demonstrate sustainable technologies and processes for ELV recycling.
- Demonstrate the feasibility of resource recovery from shredder residue, including materials recovery for reuse in automotive and other applications, chemical conversion of residue to fuels and chemicals, and energy recovery.
- Develop viable strategies for the control and minimization, or elimination of substances of concern.
- Benchmark recycling technology and provide date to stakeholders.
- Stimulate markets for reprocessed materials to support economic collection, processing, and transportation.
- Transfer technology to commercial practice.

This project provides for the overall management of the CRADA team activities and for communication and advocacy with other organizations. The other major projects that have been initiated under the CRADA follow:

- Baseline Assessment of Recycling Systems and Technology
- Postshred Materials Recovery Technology Development and Demonstration
- Development of Technology for Removal of PCBs and Other Substances of Concern from Shredder Residue
- Compatibilization/Compounding Evaluation of Recovered Polymers

The objectives and progress on these projects are discussed in their respective sections of this report. Effort under the CRADA was initiated in the fourth quarter of FY 2003.

Outreach Efforts

While the CRADA team provides a core of expertise, cooperation with other organizations is key to achieving the overall program objectives. In the United States, a market-driven recycle infrastructure is in place. The team is actively pursuing cooperation with the organizations and companies that are a part of that infrastructure. Cooperation with other stakeholders is also essential.

Papers outlining the industry/government collaboration have been presented at international conferences. A joint DOE, USCAR, and APC paper on "Market Driven Recycling in North America" was presented as the keynote paper at the recent 2004 International Car Recycle Congress in Washington, D.C. A paper entitled "Sustainable End-of-Life Vehicle Recycling: R&D Collaboration between Industry and the U.S. DOE" appeared in the August 2004 issue of the JOM.

An initial meeting with representatives of the Institute of Scrap Recycling Industries (ISRI) was held in August to brief ISRI on the CRADA objectives and projects and to elicit ISRI participation. Representatives of the CRADA team will make a presentation to the ISRI Shredder Committee meeting upcoming in October 2004 to develop a relationship with this organization.

To further communicate the U.S. approach to ELV recycling, a one-page CRADA summary has been developed, a CRADA brochure is under development, and a U.S. ELV CRADA Team Web site is being developed.

Publications

Market Driven Automotive Recycling in North America, Duranceau, C., presented at the Institute of Scrap Recycling Industries Shredder Meeting, Dallas, TX (Oct. 30, 2004).

Sustainable End-of-Life Vehicle Recycling: R&D Collaboration between Industry and the U.S. DOE, Daniels, E.J., Carpenter, J.A. Jr., Duranceau, C., Fisher, M., Wheeler, C., and Winslow, G., JOM, The Mineral, Metals & Materials Society, vol 56, no 8, pp 28-32 (Aug. 2004).

Market Driven Automotive Recycling in North America, Duranceau, C., USCAR, Carpenter, J., U.S. DOE, Fisher, M., American Plastics Council, keynote at the 2004 International Car Recycling Workshop, May 19, 2004, Washington D.C.

Automotive Materials Recycling: A Status Report of U.S. DOE and Industry Collaboration, Daniels, E. J., Ecomaterials and Ecoprocesses, Proc. of the International Symposium on Ecomaterials and Ecoprocesses, August 24-27, 2003, Vancouver, BC, Canada, pp 389-402.

Effects of Transportation on the Ecosystem, Carpenter, J.A., Jr., Ecomaterials and Ecoprocesses, Proc. of the International Symposium on Ecomaterials and Ecoprocesses, August 24-27, 2003, Vancouver, BC, Canada, pp 13-22.

Automotive Technology: Looking Forward, Sullivan, R., D. Hamilton and J.A. Carpenter, Jr., Ecomaterials and Ecoprocesses, Proc. of the International Symposium on Ecomaterials and Ecoprocesses, August 24-27, 2003, Vancouver, BC, Canada, pp 49-67.

A Roadmap for Recycling End-of-Life Vehicles of the Future, prepared by Energetics for U.S. Department of Energy, Office of Advanced Automotive Technologies, (May 2001).

B. Baseline Assessment of Recycling Systems and Technology

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Recyclability Studies P.I., Roy Muir, USCAR, VRP

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Contract No.: W-31-109-Eng-38

Objective

- Establish the baseline or state-of-the-art for automotive materials recovery/recycling technology.

Approach

- Review the state-of-the-art of worldwide automotive materials recovery/recycling technologies.
- Develop technology profiles of emerging automotive materials recycle technology.
- Review international, federal and state regulatory information regarding vehicle recyclability, substances of concern, and recycle laws and mandates.
- Conduct life-cycle studies to quantify the environmental burdens associated with various end-of-life recycling technologies.
- Conduct reference case end-of-life recyclability studies.

Accomplishments

- Conducted a literature search that identified technologies that are being classified as mechanical, thermo-chemical conversion and energy recovery, and technology profiles are being developed.
- Characterized the existing U.S. recycling infrastructure and derived estimates of automotive recycle rates from the literature.

- Initiated a review of global regulatory requirements regarding end-of-life vehicle recycling; the review includes not only recycle mandates but also proposed and existing requirements regarding handling of substances of concern.
- Initiated life-cycle studies of selected alternative recycle technologies; the initial studies will provide a comparison of alternative mechanical recycle technologies relative to technologies proposed for the thermo-chemical conversion of shredder residue to fuels.
- Conducted reference recyclability calculations for reference cases and three lightweight alternatives: lightweight steel, composite, and aluminum.

Future Direction

- Prepare database of recycle technologies.
- Conduct CRADA-led visits to evaluate state-of-the-art material and energy recovery technologies, as appropriate in Japan and Europe.
- Continue life-cycle comparisons.
- Plan additional recyclability evaluations using the current study as a starting point for assessing recyclability of vehicles of the future.

Summary

The objectives of this project are to benchmark the automotive materials recycling industry and to compile information in an accessible format regarding the status of existing and emerging recycling technology and research.

The focus of the work under this activity will be to develop the tools and document the information necessary to make effective decisions relative to technology needs to facilitate sustainable future vehicle recycling and also to make effective decisions regarding allocation of R&D resources.

The state-of-the-art of worldwide automotive materials recovery/recycling technologies and associated resource recovery infrastructures will be reviewed to identify technology gaps and needs and to identify differences in automotive recycling strategies between the United States, Europe, and Japan. Technologies that will be included in this review include, but are not limited to, postshred materials recovery technologies, preshred materials recovery technologies, materials identification technologies, automated dismantling technologies, bumper recycle processes, fuel tank recycle technology, and thermochemical conversion technology.

Life-cycle analyses of alternative recycle technologies will be conducted to identify differences of technologies such as mechanical recycling vis-à-vis thermochemical recycling relative to energy and environmental benefits.

Regulations at the international, federal, and state level will be reviewed to identify the impact that proposed and existing regulations may have regarding recycling of automotive materials.

Reference case recyclability calculations will be undertaken to quantify the expected recyclability of alternative vehicle designs.

Infrastructure

The North American recycle infrastructure has been characterized (Figure 1). Material flows within the existing infrastructure are being quantified.

Technology Profiles

The recent literature has been reviewed, and summaries and profiles of available and emerging recycle technologies are being compiled into a database.

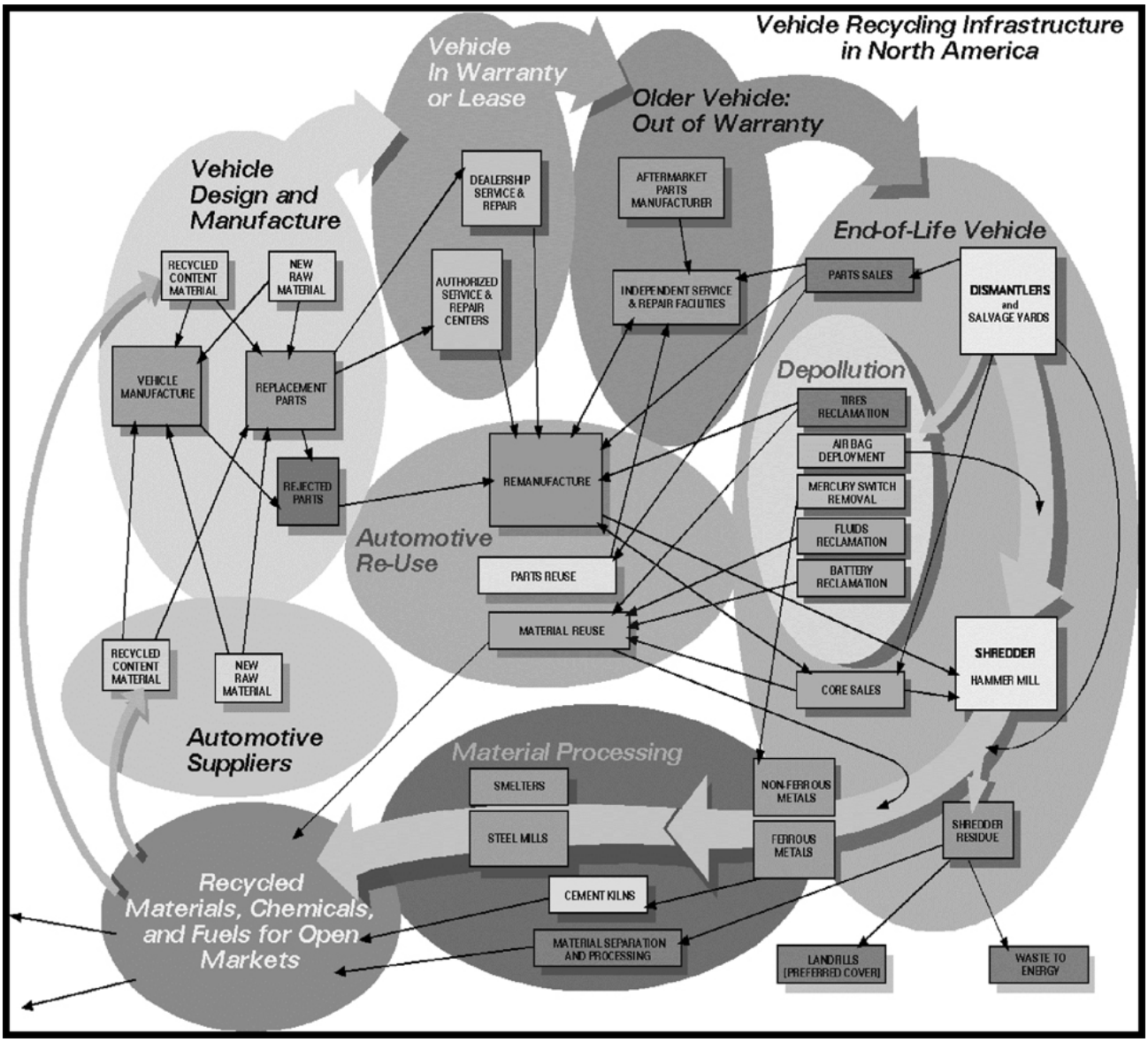

Figure 1. Representation of the North American recycle infrastructure.

A bibliography of abstracts of papers that discuss automotive recycling issues has been compiled. The bibliography is organized in the following sections:

- Recycle infrastructure
- Design for recycle
- Legal and regulatory issues
- Life-cycle analysis
- Research programs
- Substances of concern
- Disassembly technologies and case studies
- Reuse of automotive parts and subassemblies
- Remanufacturing
- Mechanical separation technology
- Thermochemical conversion technology
- Energy recovery technology
- Other technology
- Advanced materials recycle technology
- Case studies of materials recycled for auto applications

The bibliography was compiled from the following primary sources:

1. Society of Automotive Engineers (International) World Congresses from 1997 to 2004
2. Environmental Sustainability Conference and Exhibition, 2001
3. Society of Plastics Engineers
   - Automotive Research Consortium ’98 Conference
   - Automotive Research Consortium’99 Conference
   - GPEC 2002 Conference
   - GPEC 2003 Conference
4. Other conference proceedings
   - International Automobile Recycling Congress 2002
   - TMS Fourth International Symposium of Recycling of Metals and Engineered Materials, 2000
   - Ecomaterials and Ecoprocesses, The Conference of Metallurgists, COM 2003

Conference proceedings from the International Automobile Recycling 2001, 2003, and 2004 conferences have been ordered as have been the ARC 2000 proceedings for inclusion of relevant papers into the bibliography. At present, the bibliography includes 110 citations (Table 1).

Table 1. Citations included in the recycle bibliography (as of September 2004)

Bibliography section	Number of citations
Recycle infrastructure	4
Design for recycle	1
Legal and regulatory issues	16
Life-cycle analysis	5
Research programs	7
Substances of concern	2
Disassembly technologies and case studies	6
Reuse of automotive parts and subassemblies	1
Remanufacturing	0
Mechanical separation technology	13
Thermochemical conversion technology	5
Energy recovery technology	7
Other technology	17
Advanced materials recycle technology	7
Case studies of materials recycled for auto applications	18
Total citations	110

Regulatory Situation

The European Union has issued End-of-Life Vehicle Recycle Directives. The enforcement of these directives is, however, the responsibility of each member state. The status of the member states’ position relative to the directives and the policies for implementing the directives are under review. While the United States has not developed a federal policy or mandate, regulations at the federal and state level can impact the technology needs for recycling automotive materials. For example, U.S. Environmental Protection Agency (EPA) regulations regarding polychlorinated biphenyl (PCB) disposal limits the concentration of PCB on recycled materials to below 2 ppm. State regulations regarding mercury and polybrominated diphenyl ethers (PBDEs) can also impede materials recycling. A review of the regulatory arena is ongoing to identify the impacts of regulations relative to technology options for recycling.

Life-Cycle Studies

The objective of this project is to use life-cycle analysis to assess the environmental impacts of various mechanical separation technologies and alternative end-of-life recycling technologies used with automotive shredder residue. This information will then be used to create a flexible, computerized, life-cycle inventory model, which is process specific and yet can be modified to include additional recycling technologies and various material inputs. Life cycle involves assessing all of the upstream burdens associated with the production of the materials and energies used in the process, including the transport of all materials to the facility.

The Vehicle Recycling Partnership (VRP) contracted PE Europe GmbH, a company that is experienced in conducting life-cycle assessments and in model development using their own GaBi (Ganzheitliche Bilanzerung) software, to assess Salyp NV’s mechanical separation process and create a flexible end-of-life module based on this scenario.

Salyp NV's separation process, the first technology examined as part of this project, combined equipment developed by Argonne National Laboratory and others to create a facility that currently separates shredder residue into discrete fractions of metals, foam, mixed plastics, fiber-rich, and dust streams.

Because a life-cycle inventory requires the collection of primary data on each process, including all energy, water, and material inputs plus data on emissions to air and water, wastes, and products produced, these data were collected for the Salyp separation process and then input into the GaBi software to create a flexible model of the process. Table 2 shows the percentages used for the creation of the model, and Figure 2 shows the mass flow of the material as depicted in the GaBi software.

Table 2. Average shredder residue composition: basis used for LCA modeling

Material	ASR (%)
Plastic	34.0
Ferrous metals	33.4
Sand, dirt	15.7
Unknown	4.0
Glass	3.4
Wood	2.8
PU foam	2.8
Nonferrous metals	2.2
Copper	1.1
Stainless steel	0.6

Three different scenarios for handling the various materials recovered from the separation

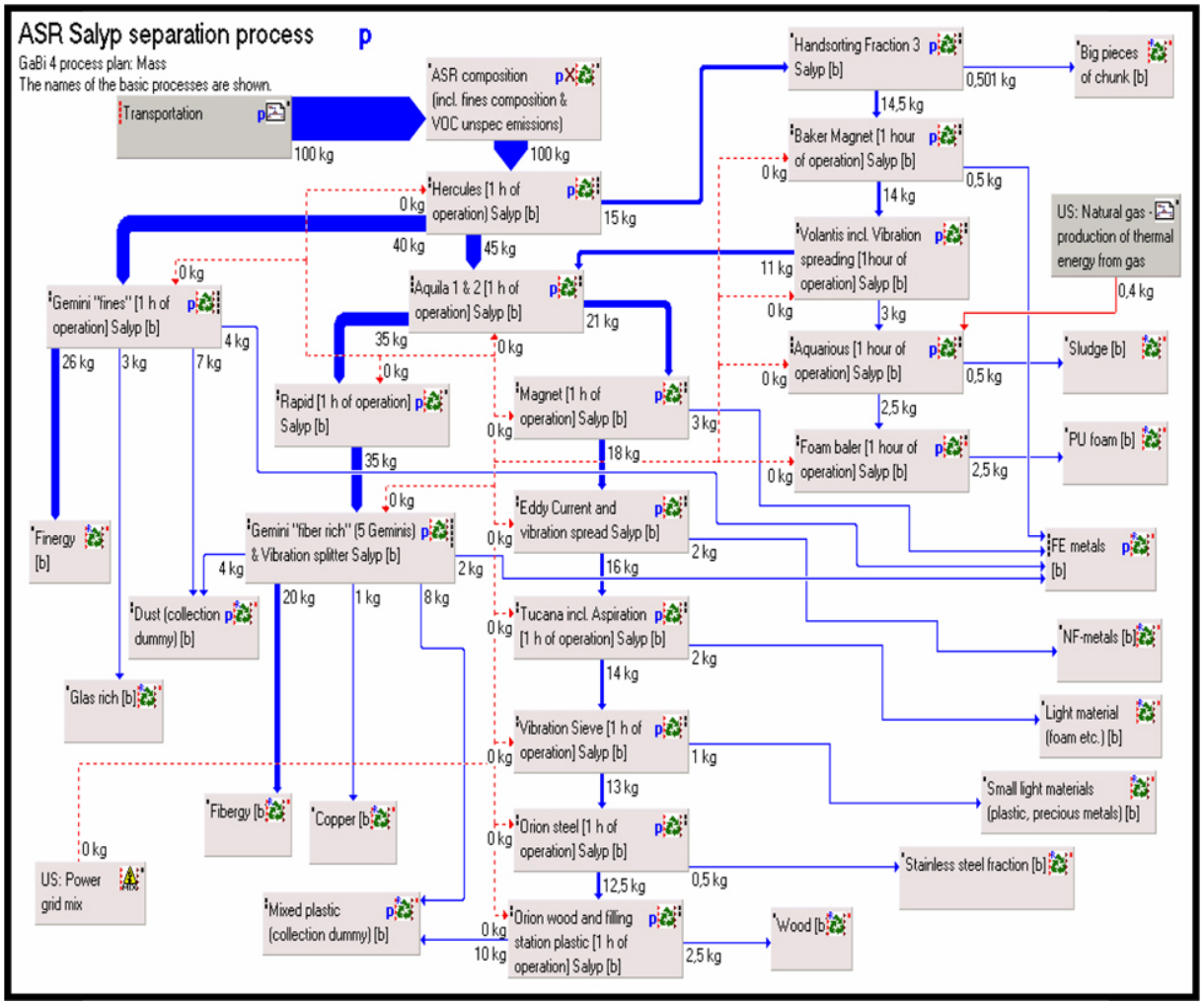

Figure 2. Life-cycle analysis mass flow representation of Salyp separation process.

process were determined along with their market values. These included waste treatment such as material recovery, energy recovery, turning specific material fractions into oil for cement kilns, as well as material substitution using mixed plastics to replace products such as wood pallets and polypropylene (PP) pellets. GaBi allows for the analysis of the various scenarios in a range of impact categories, including primary energy demand, photochemical ozone creation potential, and CO_2 emissions. All of these scenarios can be changed within the GaBi software to account for different or new types of treatments that arise in the future, which could lead to different impacts on the environment.

The model allows the user to run simulations on shredder residue separation within different boundary conditions. The following boundary conditions can be modified: (1) shredder residue composition, (2) location of the facility, (3) type and distance of transportation, (4) market values for the separated fractions, (5) new potential applications for separated fractions, and (6) utilization ratio of the facility.

Additional life-cycle studies are underway to compare mechanical separation to other thermal/chemical conversion technologies. When completed, the goal is to have a comprehensive end-of-life model that will allow us to rapidly and accurately assess the potential environmental impact of various material/design changes in our future vehicles.

Recyclability Studies

Recyclability studies are being conducted to examine the effect of using automotive lightweighting material on recyclability. A Toyota Prius hybrid was selected for a reference case. This vehicle is a second-generation hybrid with a gas/electric powertrain. Evaluating the recyclability of this vehicle and its new technology will be a step in identifying changes that will impact end-of-life recycling of vehicles of the future.

In collaboration with Johnson Controls, Inc. (JCI), the VRP dismantled the vehicle according to VRP procedures to single material components and entered data for each part into a database. A material list that identified the breakdown of materials into separate classifications such as ferrous and nonferrous metals, as well as composite materials and plastics was prepared. The materials breakdown is summarized in Table 3 and shown in Figure 3. In comparison, the materials composition of a production Ford Taurus is summarized in Table 4 and Figure 4.

Table 3. 2004 Toyota Prius materials breakdown

Materials	Mass (kg)	Percent
Ferrous metals	776.94	60.55
Nonferrous metals	229.99	17.92
Plastics	154.85	12.07
Elastomers	39.66	3.09
Inorganic material	34.71	2.71
Other	28.21	2.20
Organic materials	18.84	1.47
Vehicle mass (less fluids)	1283.1	100.00

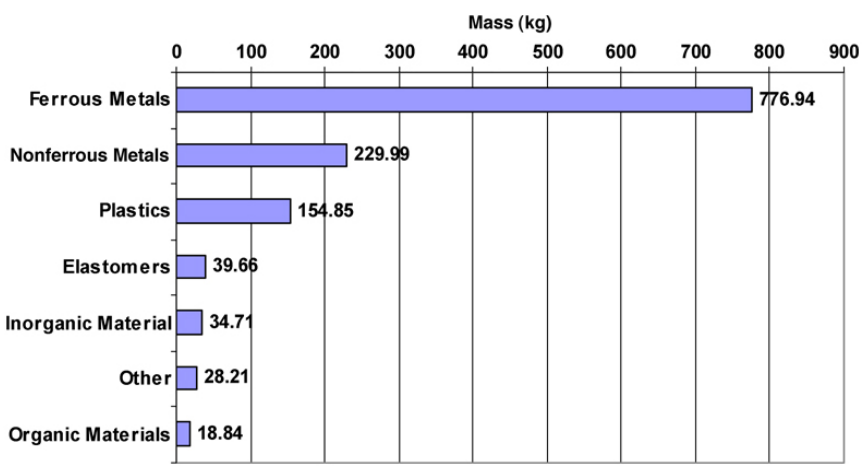

Figure 3. 2004 Toyota Prius materials breakdown.

Table 4. 2004 Ford Taurus materials breakdown

Materials	Mass (kg)	Percent
Ferrous metals	1008.28	70.37
Plastics	154.41	10.78
Nonferrous metals	141.43	9.87
Elastomers	68.71	4.80
Inorganic material	40.91	2.86
Other	17.45	1.22
Organic materials	1.66	0.12
Vehicle mass (less fluids)	1432.86	100.00

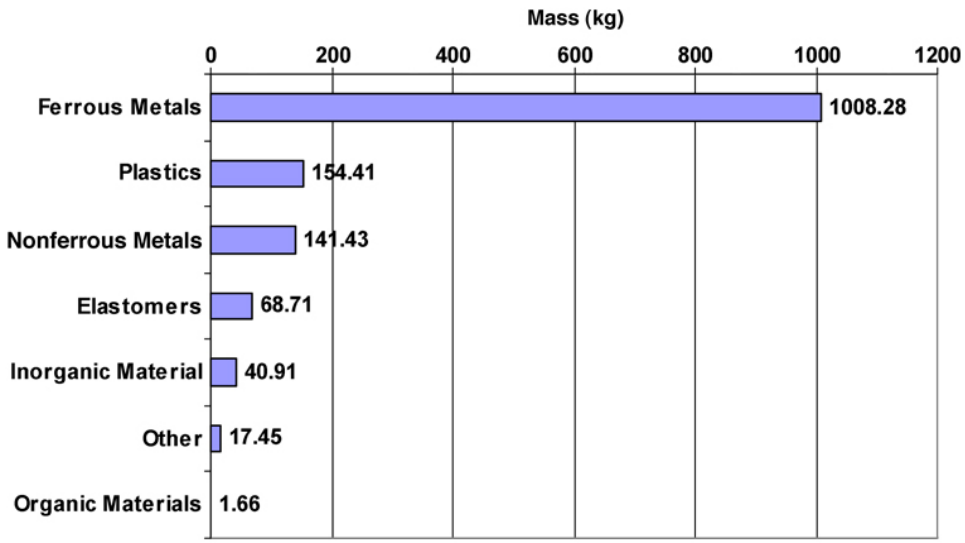

Figure 4. 2004 Ford Taurus materials breakdown.

Three different recyclability calculations were made (Table 5). The Federal Trade Commission (FTC) recyclability number is the percentage by weight of the material that is currently being recycled, and it includes metals, fluids less fuel, and batteries. The European guidelines include FTC materials plus fuel at 90% of a full tank, plastics that could be recycled, and up to 10% by weight energy recovery. Note that Europe requires 95% recyclability for new vehicles. The feasible-to-recycle number includes the FTC materials plus plastics that can be recycled. Changes to the current infrastructure would be required to increase recycling beyond the current FTC percentage.

Table 5. Reference case recyclability: 2004 Toyota Prius

Federal Trade Commission	80.86%
European	97.61%
Feasible to recycle	85.58%
Ref. 2000 Ford Taurus	80.50%
Federal Trade Commission	

To establish an indication of the impact of lightweight materials on the reference case recyclability calculations, the production Toyota Prius is compared to a proposed aluminum-intensive lightweight vehicle and a proposed composite lightweight vehicle based on the 2004 Toyota Prius. The production 2004 Toyota Prius hybrid vehicle body was steel with aluminum hood and decklid. The suspension was of steel except for an aluminum steering knuckle on the front suspension. This was used as the base for this study.

The aluminum alternative is for a 2004 Toyota Prius with an aluminum body and magnesium

engine cradle and rear axle substituted for the production parts. In addition, seat frames, body brackets, and the instrument panel cross car beam have been changed from steel to aluminum. As a result the weight has been reduced by approximately 630 lb or 21%. Because the weight reduction is entirely in the currently recycled portion of the vehicle, the recyclability is adversely affected and is reduced from 80.86% to 76.10%. No changes were made to the currently nonrecycled portion of the vehicle. Aluminum replaced steel at 50% by weight of the original steel.

The composite alternative is for a 2004 Toyota Prius with a carbon fiber body with 40% carbon fiber and 60% thermoset polyurethane/urea resin by volume, 49.72% carbon and 50.28% thermoset polyurethane/urea resin by weight, and magnesium engine cradle and rear axle substituted for the production parts. In addition, seat frames, body brackets, and the instrument panel cross car beam have been changed from steel to composite. As a result the weight has been reduced by approximately 711 lb or 24%. Because the weight reduction is entirely in the currently recycled portion of the vehicle, the recyclability is adversely affected and is reduced from 80.86% to 57.20% if none of the composite is recycled or 74% if all of the composite material is recycled. No changes were made to the currently nonrecycled portion of the vehicle. The composite material replaced steel at 40% by weight of the original steel.

There are reductions in all three recyclability calculations for lightweighted vehicles, even though there is no change to the rest of the vehicle (Table 6). Where the aluminum and composite material is being recycled, the same amount of material would be landfilled in each of the three scenarios. The only difference is that the recycled portion of the lightweighted vehicles would be lighter. While the recyclability would be less, there would be no difference in landfill, and the lighter vehicles would use less fuel during their life. As can be seen, lightweighting presents challenges in the European market. Note that these calculations do not take into account downweighting of related components that would accompany any lightweight vehicle, such as powertrains, brakes, tires, etc. Because the downweighted components are high in metallic content, downweighting will further reduce recyclability and make it difficult to meet the European 95% requirement.

Table 6. 2004 Toyota Prius recyclability, reference case vs aluminum and composite body materials

	As produced (%)	Aluminum body (%)	Composite body (%)
FTC	80.9	76.1	74.0[a]
European	97.6	96.0	94.5[a]
Feasible to recycle	88.3	85.6	83.9[a]

[a]If the composite material were not recycled, then the numbers would be FTC—57.2%, European—78.2%, and Feasible to Recycle—67.1%. Recycling of the composite material would require significant changes in the current recycling infrastructure. In addition, a market for the recycled carbon fibers would need to be developed. Current technology for recycling carbon fibers results in a 20% loss in fiber length and properties, which would limit their reuse in the original applications.

In conjunction with this study, additional evaluations are planned using these data as a starting point for assessing recyclability of cars of the future. The impact of vehicle lightweighting and material selection on recyclability will be evaluated. In addition, powertrain changes including hybrid and fuel cell alternatives will be compared to current vehicles. An assessment of various alternatives on recycling and the effect on the current recycling infrastructure will be produced. No downsizing of other components was included in this study. Future studies will reflect downweighting of powertrains, brakes, tires, and other components in recyclability calculations. Items requiring further study resulting from these assessments will support future projects to determine the feasibility of various alternative vehicle configurations and material selection choices.

Publications

Modular Life Cycle Model – Basis for Analyzing the Environmental Performance of Different Vehcile End-of-Life Options, Binder, M., Simon, N., Duranceau, C., Wheeler, C., Winslow, G., Proc. of the 5th International Automobile Recycling Congress, Amsterdam (Mar. 9-11, 2005).

Modular Life Cycle Model of Vehicle End-of-Life Phase- Basis for Analysis of Environmental Performance, Binder, M., Wheeler, C., Simon, N., Duranceau, C., Winslow, G., presented at the 2005 Annual SAE Conference.

United States National Life Cycle Inventory Database Project, A Status Report, Sullivan, J., Wheeler, C., and Simon, N., presented at the 2005 Annual SAE Conference.

C. Postshred Materials Recovery Technology Development and Demonstration

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The Association of Plastics Manufacturers of Europe provided cost-sharing for the Salyp NV process evaluation.
Changing World Technologies is cost-sharing on the evaluation of their thermal depolymerization process.
The Polyurethanes Recycle and Recovery Council (PURCC) is also participating and cost-sharing on the evaluation of the Troy Polymers, Inc., polyurethane glycolysis process.

Contractor: Argonne National Laboratory
Contract No.: W-31-109-Eng-38

Objective

- Develop and demonstrate technology for the cost-effective recovery of materials from postshred residues.

Approach

- Characterize shredder residues from a number of sources to determine composition variability.
- Conduct bench-scale and large-scale process/technology tests to benchmark technology.
- Build and operate a shredder residue separation pilot plant to produce samples of recovered materials for market evaluation.
- Conduct costs and performance analysis of alternative technologies to establish the business case for the technologies and to identify technology gaps.

Accomplishments

- Completed characterization of five shredder residues; two European and three United States.
- Completed large-scale tests of Salyp's "thermoplastics sorting" technology using residue from two European and one U.S. location as feed materials.

- Completed construction in the first quarter of FY 2004 of a large-scale pilot separation facility at Argonne National Laboratory; shakedown of the facility occurred during the second and third quarter, production campaigns have been started.
- Completed bench-scale testing of Changing World Technologies (CWT) thermal depolymerization process; test runs have been initiated using 3000 lb of bulk shredder residue.
- Started bench-scale testing of a glycolysis process for conversion of polyurethane foam to polyol initiators.
- Developed an Excel-based process cost model that incorporates two primary modules for recovery of automotive plastics: the first module includes the unit operations required for recovering a plastics concentrate from shredder residues, and the second module includes the unit operations required to recover selected plastics from the mixed plastics concentrates.

Future Direction

- Continue characterization of shredder residue.
- Complete CWT thermal depolymerization tests; evaluate process economics; define path forward.
- Complete Polyventure/TPI glycolysis bench-scale tests; evaluate process performance; define path forward.
- Complete Argonne froth flotation campaigns, evaluate process performance and economics; define path forward.
- Update process cost analysis model.
- Review/critique technology developments with representatives of the automotive shredding industry.

Summary

The objective of this project is to develop and demonstrate technology for the cost-effective recovery of materials from postshred residues.

A wide range of materials recovery technologies is at various stages of development. Certain of those technologies specific to recovery of materials from postshred materials streams will be evaluated and demonstrated to fully understand the commercial viability of those processes.

The objective of this project is to determine the performance (e.g., yield, purity, efficiency, and cost) of these emerging technologies such that an optimized and integrated process for recovering these materials from shredder residue can be developed.

Research conducted in this project will provide data essential to establishing a business case for sustained recycling of automotive materials from postshred residue.

Research has been completed on the Salyp N.V. physical separation/thermosorting process. Research is ongoing on the Argonne physical separation/froth flotation process, the Changing World Technologies (CWT) thermal depolymerization process, and The Polyventure/Troy Polymers process for glycolysis of polyurethane foam.

Characterization of Shredder Residue

To facilitate the development of technology for recovery of materials and resources from shredder residue, characterization of shredder residue from different sources has been conducted by MBA Polymers. Small (2-kg) samples of shredder residue from five sources have been characterized to date: two European and three American. Samples of shredder residue from other sources will be analyzed as appropriate throughout the course of the project.

In general, while there are some differences in the composition of the shredder residue from each source, the differences do not yet appear to be significant in terms of the design constraints of recovery technology. The bulk composition of the residue samples is compared in Table 1. The composition of the plastics fraction for each sample is compared in Table 2.

Table 1. Bulk composition of European and U.S. shredder residue (*Basis*: small sample, ~1 kg, analysis)

Materials	Europe 1	Europe 2	U.S. 1	U.S. 2	U.S. 3
Fines (<1/8 in.)	18.0	4.9	37.5	32.8	5.3
Residual metals	3.0	6.4	9.3	7.1	15.5
Foam	36.8	31.6	21.3	26.6	26.9
Wood	0.4	3.2	7.2	4.0	1.9
Rubber	17.3	22.5	4.9	9.3	27.7
Stone, fiber, other	10.1	0.0	7.4	8.9	5.5
Plastics	14.4	31.4	12.4	11.3	17.2

Table 2. Composition of the plastics fraction of European and U.S. shredder residue (*Basis*: small sample, ~1 kg, analysis)

Plastic	Europe 1	Europe 2	U.S. 1	U.S. 2	U.S. 3
Polypropylene	41.4	31.9	26.3	41.0	33.3
Polyethylene	3.7	17.3	6.6	7.0	5.3
High-impact PS	4.9	3.3	25.9	15.2	28.1
ABS	8.8	11.5	17.1	22.2	11.8
PA	11.8	2.1	2.9	3.7	10.7
PVC	0.7	10.4	0.0	0.0	1.9
Rigid urethane	18.9	13.4	4.1	0.5	4.1
PC/PBT	6.6	4.2	1.9	2.7	4.4
Other	3.2	5.9	15.2	7.6	5.7

Argonne Pilot Plant

Construction of the pilot plant at Argonne was completed in the first quarter of FY 2004. The facility will be used to

1. conduct optimization/integration studies,
2. provide a production capability to produce large samples of recovered materials for market evaluation,
3. demonstrate the effectiveness of alternative separation technologies and systems, and
4. serve as a user/demonstration facility to conduct separation tests for residue from specific sources.

The pilot plant consists of two major unit operations. The first is a mechanical separation facility; the second is a wet-density/froth-flotation separation facility.

The mechanical separation facility is shown schematically in Figure 1. An overview of the facility is shown in Figure 2. The mechanical separation facility processes the raw shredder residue to yield a "plastics concentrate." The raw shredder residue is separated into the following fractions:

- oversize tramp material,
- fines (–5/16 in.),
- oversize [polyurethane foam (PUF), fiber, etc.],
- nonferrous,
- ferrous,
- small fluff and other light materials,
- other reject, and
- middling/plastics concentrate.

The "middling" fraction is further processed for size reduction in a small shredder to produce the plastics concentrate.

The wet density/froth-flotation facility is shown schematically in Figure 3. An overview of this pilot plant is shown in Figure 4. It includes six continuous stages for separation and recovery of targeted materials from the plastics concentrates derived from shredder residue.

The first stage cleans the plastics concentrate and also recovers the lighter olefins for further processing. The second stage drops out heavy

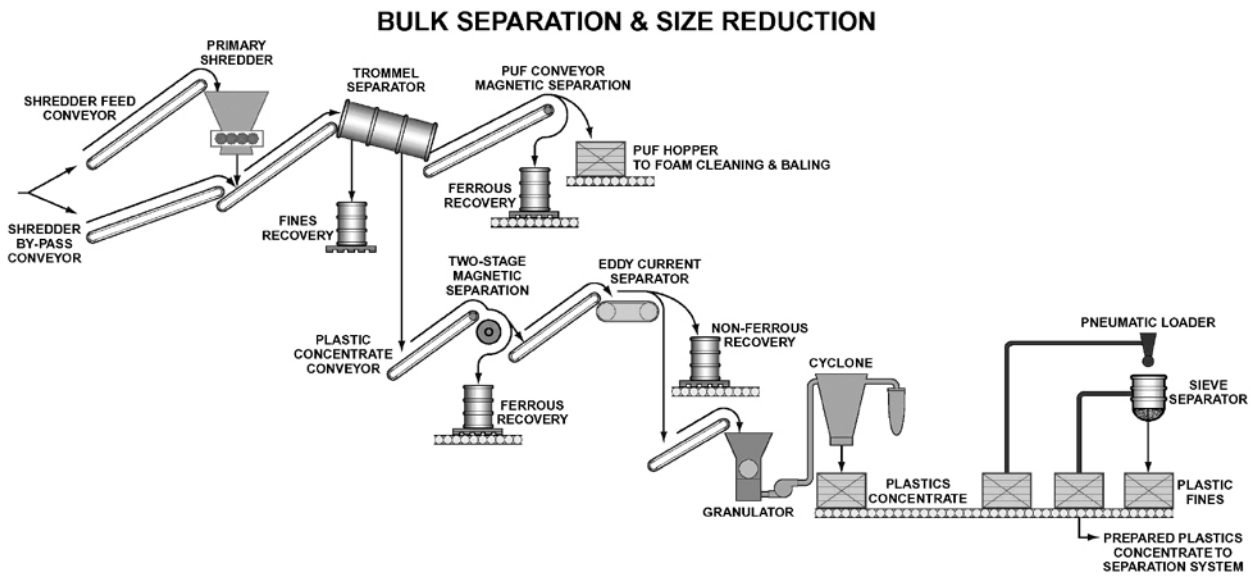

Figure 1. Schematic of the Argonne Pilot Mechanical Separation System for processing raw shredder residue.

Figure 2. Overview of the Argonne Bulk Separation Pilot Plant.

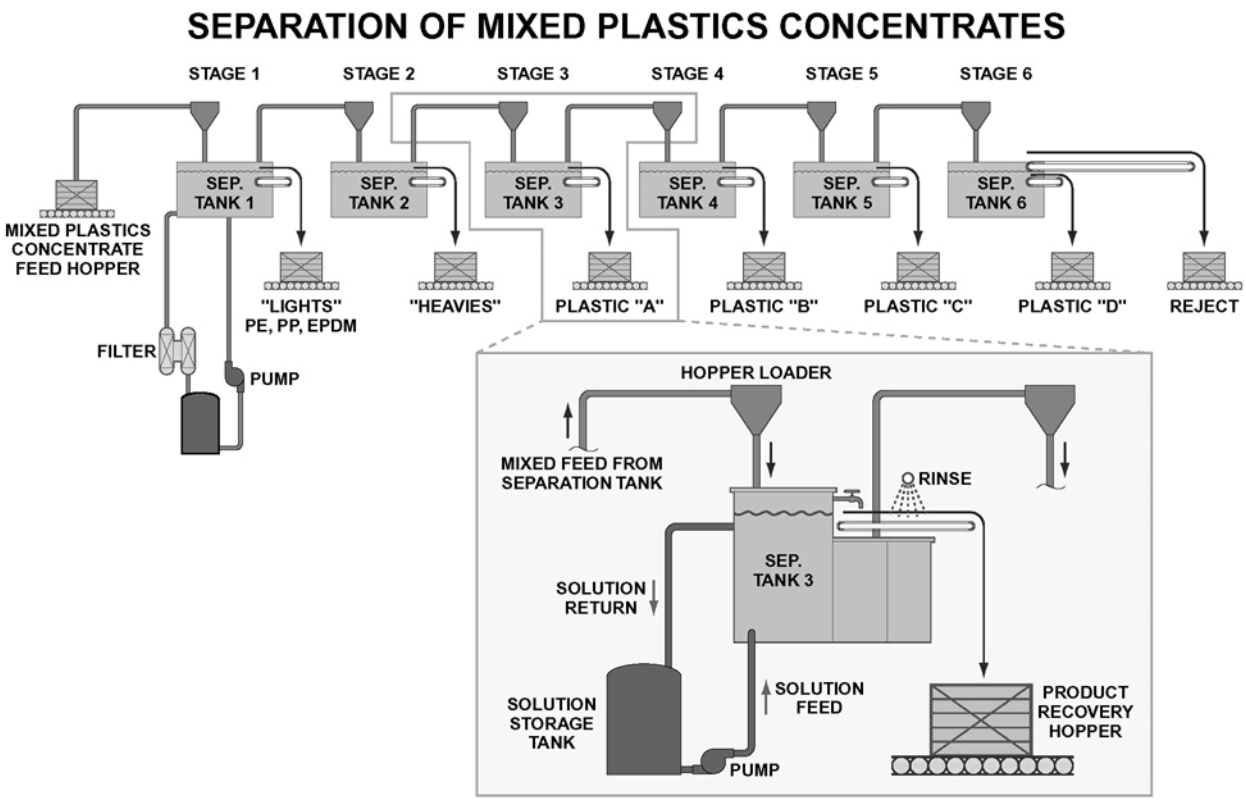

Figure 3. Schematic of the Argonne Pilot Wet Separation System for recovery of plastics from shredder residue.

Figure 4. Overview of the Argonne Froth-Flotation Pilot Plant.

materials, including any residual metals that remain in the concentrate.

The following four stages will process the balance of the concentrate for recovery of the following targeted materials:

- acrilonitrile-batadiene-styrene (ABS),
- high-impact polystyrene (HIPS),
- nylon, and
- polyvinyl chloride (PVC).

Depending on recovery rates and yield, other polymer cuts may be explored to define the overall best strategy for separation and recovery of the materials from the concentrates.

Shakedown of the wet density/froth-flotation facility was conducted during the second quarter of FY 2004. Shakedown was conducted using about 4000 lb of postconsumer electronics and appliance mixed plastics because the composition of these materials is much less variable than the composition of plastics concentrate from shredder residue. The composition of a feed material for the shakedown trials is shown in Figure 5. The shakedown tests were conducted using four of the six froth-flotation stages targeting recovery of the ABS and HIPS from the feed material. In these trials, approximately 75% of the feed material HIPS was recovered in a single fraction at a purity of 97% (Figure 6). The ABS yield was lower at about 55%; however, the purity of the ABS was 98%. Physical properties of the recovered materials were consistent with a range of "virgin" or primary grades of HIPS and ABS,

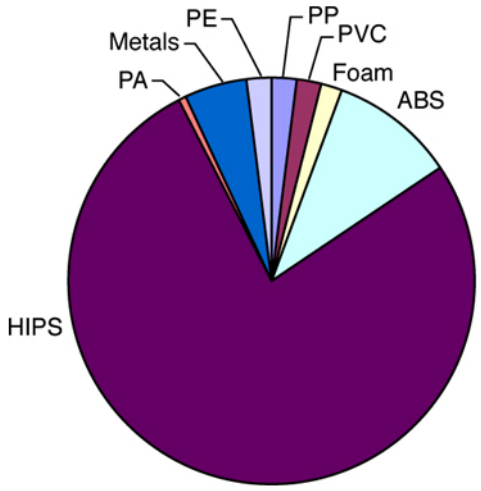

Figure 5. Composition of postconsumer mixed plastics used in Argonne Froth-Flotation Pilot Plant shakedown trials.

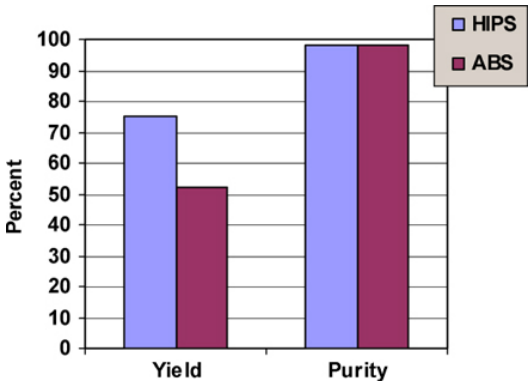

Figure 6. Percentage of HIPS and ABS recovered (yield) and purity of the recovered HIPS and ABS.

respectively. (See Compatibilization/Compounding Evaluation of Recovered Polymers annual report, see 6.E)

Following shakedown of the froth-flotation system, shakedown and debottlenecking of the bulk separation pilot plant was undertaken during the third quarter of FY 2004.

During the fourth quarter, campaigns were undertaken that resulted in the physical/bulk separation of about 60,000 lb of shredder residue (6 campaigns). The average yield of plastics concentrate from these campaigns was about 17% (Figure 7). The composition of the recovered plastics concentrate is, of course, much more complex than the plastics fraction from just appliance or electronics scrap (Figure 8).

The initial froth-flotation campaigns run with the shredder residue plastics concentrate showed that the process could recover a concentrated

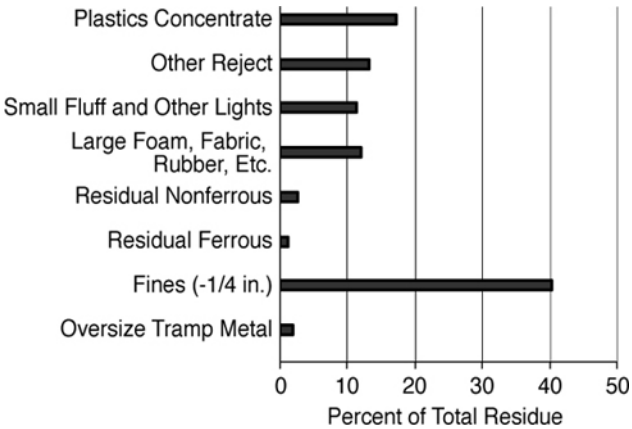

Figure 7. Bulk composition of shredder residue processed in Argonne's Bulk Separation Pilot Plant. (*Basis*: 60,000 lb, six campaigns.)

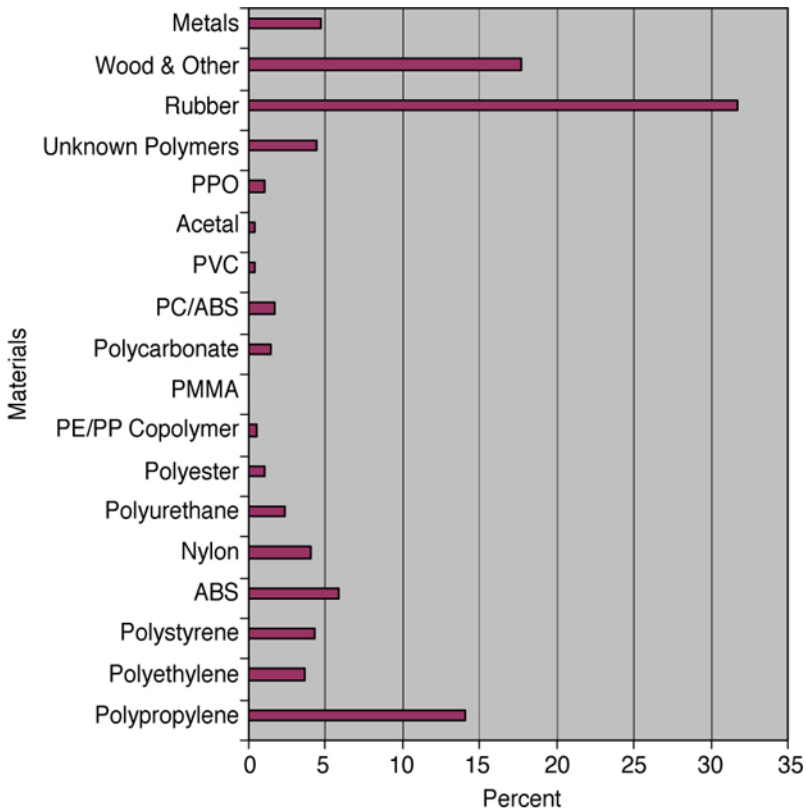

Figure 8. Average composition of the plastics concentrate fraction recovered from shredder residue. (*Basis*: 60,000 lb, six campaigns.)

polyolefin's fraction and a concentrated ABS fraction, but that these materials contained a significant amount of residual wood and rubber. The effectiveness of the froth-flotation process is dependent on the ability to isolate these materials from the balance of the plastics concentrate. The technical feasibility of conventional separation equipment such as gravity tables, mineral jigs, and hydrocyclones in isolating the wood and rubber from the plastics concentrate will be evaluated as the research on mechanical separation continues. Alternative operating conditions for the froth-flotation system are also being evaluated.

Salyp Thermo-Plastics Sorting Technology

Salyp N.V., a Belgium company has developed and integrated a full recycling line using different sorting technologies, which processes and recycles various material fractions from shredder residue. The key objective of the project was to determine the feasibility of a mechanically automated, near industrial recovery of various mixed engineering plastics into individual plastic streams.

Salyp processed three different shredder residues totaling 100 metric tons that included one U.S. shredder and two European shredders. Each shredder selected sent approximately 33 metric tons of shredder residue to Salyp for processing.

Results from this study indicated that Salyp was able to separate different material streams that included

- metals,
- fibers,
- foam (using Argonne's technology),
- fines, and
- plastic concentrates.

The economics of shredder residue separation were determined, and the following costs were defined.

- Investment cost for machinery and equipment to process 40,000 tons of shredder residue per year is estimated at $3.6M.
- Cost for separation of a mixed plastic stream is estimated at 13¢/lb.

Salyp's near-industrial sorting line was able to recover a mixed plastics fraction. However, sorting the mixed plastic fraction into individual plastic streams could not be accomplished.

Changing World Technologies

Changing World Technologies, Inc. (CWT) has developed a two-stage thermal conversion process that converts organic material into fuels, gases, and solids. CWT's first commercial facility based on this technology was commissioned in April 2003 and converts 200 tons/d of turkey offal into fuels and fertilizers. This installation is a joint venture partnership with ConAgra and CWT. The thermal conversion process should be able to process the organic materials in shredder residue.

CWT's research and development center is located at the Philadelphia Naval Yard where they have a 7-ton/d pilot plant (Figure 9).

The CRADA team funded a study on a limited basis to CWT titled "Protocol Testing Shredder Residue Project." This study focused on a select sampling of two different types of shredder residue. Results from this initial study indicated that the CWT process was able to convert the shredder residue samples to three product fractions: an oil, a gas, and a carbon char. The resultant oil product characteristics are summarized in Table 3.

Based on the results of this initial project testing, CWT has offered to process 3,000 lb of shredder residue to further confirm the technical and economic feasibility of this process.

At the completion of this study, CWT will prepare a final report for the CRADA team; it will include a Performance Cost Analysis that defines converting plastics from shredder residue into fuels and chemicals. Additionally, the output products will also be made available to the CRADA project members for further analysis and testing.

If the results look promising, the CRADA team will investigate further funding opportunities that will aid in the launch of a scale-up study.

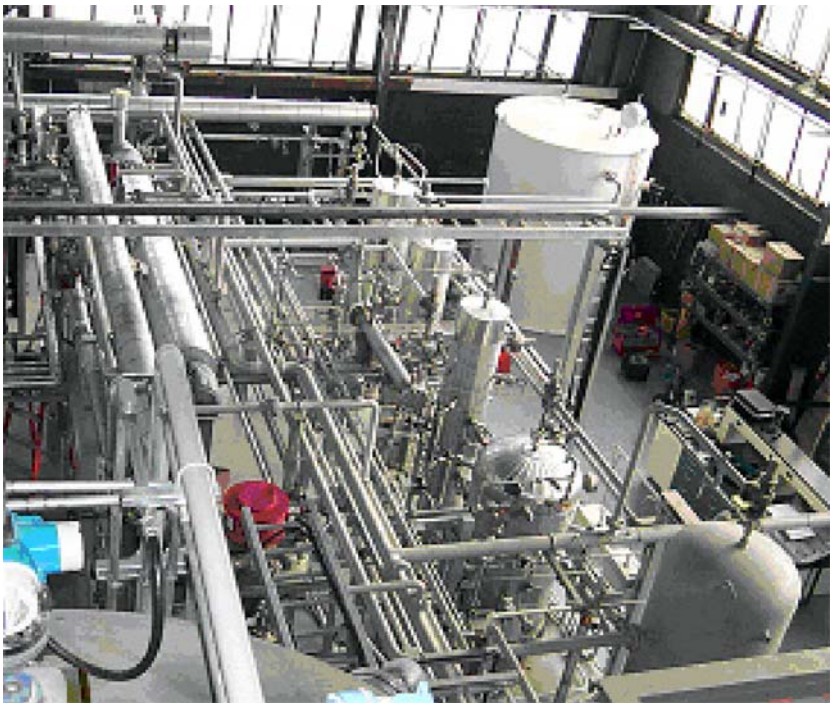

Figure 9. Overview of the CWT Thermal Conversion Pilot Plant.

Table 3. CWT oil characteristics from shredder residue feedstock

Method	Test	SR bucket 1	SR bucket 2
D-287	API@60°F	37.6	40.7
D-93	Flash point, °F	<72	<72
D-86	Distillation, °F		
	IBP	200	119
	10%	320	234
	50%	460	451
	90%	668	652
	FBP	712	691
D-4294	Sulfur, wt %	0.125	0.124
D-97	Pour point	–38°F/–39°C	–38°F/–39°C
D-482	Ash, wt %	0.004	0.003
	Carbon, %	86.38	85.30
	Hydrogen, %	13.47	14.54
	Nitrogen, %	<0.1	<0.1
D-240	Heat content		
	Btu/lb	19,094	18,622
	Btu/gal	133,046	127,409

Troy Polymers Process for Glycolysis of PUFs

Troy Polymers, Inc. (TPI) has developed a patented glycolysis process (assigned to TPI and Polyventure, Inc.) for the conversion of mixed PUFs into polyol initiators (Figure 10). The process concept can recycle foam collected at shredders and convert the recovered PUF into polyol initiators, which can then be utilized to produce new urethane products (Figure 11).

Working with the Polyurethane Recycle and Recovery Council (PURRC), bench-tests to establish proof-of-concept were undertaken. The tests demonstrated the technical feasibility of the process in converting mixed clean PUFs from shredder residue to polyol initiators at a yield of about 88% (Table 4). Dirty foam was converted to polyol initiators at a yield of about 72%. However, the product from the dirty foam required more extensive filtration because of the solid residue contained within the foam.

Preliminary characterization of the products was also performed. The OH number, which is an indicator of molecular size (412 for the polyol initiator derived from clean foam and 570 for the polyol initiator derived from dirty foam), proves that the foam has been broken into smaller molecules. Commercially produced initiators can have OH numbers from about 100 to 1000 mg KOH/g. The OH numbers from the bench-test indicate that propoxylation of these intermediate products to produce polyols with OH numbers between 42 and 56 mg KOH/g, as commonly used in industry, is feasible. Obviously other characteristics of the polyols such as acid number, water content, color,

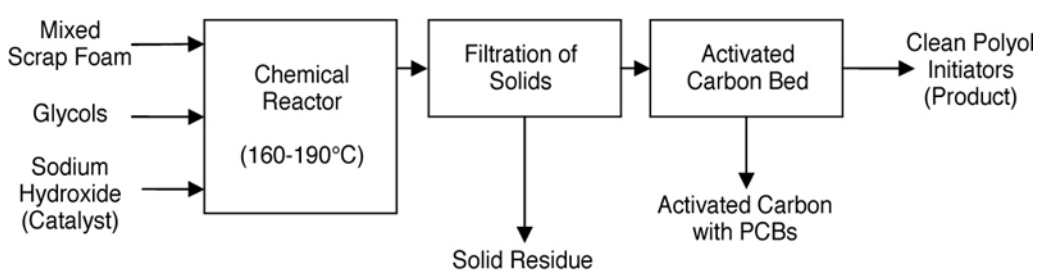

Figure 10. Glycolysis process conceptual process flow sheet.

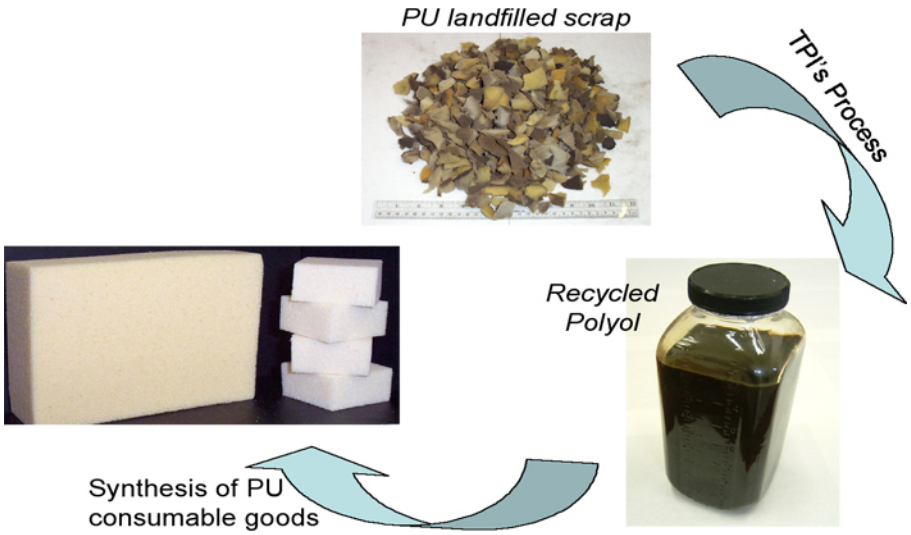

Figure 11. Glycolysis process concept.

Table 4. Glycolysis reaction input materials and product yield

Designation	Clean PUF	Dirty PUF
Starting Materials		
Diethylene glycol, g	1200	1200
NaOH, g	12.0	12.0
Foam scrap, g	1800	1800
Product yield		
Weight of products after glycolysis, g	2750	2762
Percent of recovered materials, %	91	92
Liquid fraction in products after filtration, %	96	79
Solid fraction (reside) in products after filtration, %	4	21
Yield of liquefied fraction, g	2640	2182
Yield of liquefied fraction (mass of liquid product)/ (mass of total input materials)*100	88	72
OH number (mgKOH/g)	412	570
Viscosity (cPs)		
• @23°C	350	500
• @50°C	200	300
• @77°C	100	—

pH, content of terminal unsaturation, acid and alkalinity content, amount of peroxide and carbonyl groups, amount of antioxidant and residual solvent, will have to be determined and controlled. The viscosity values of the polyol initiator products are also typical of the initiators used by industry. The greater viscosity of the product recovered from dirty foam indicates that further filtration of the product may be necessary.

As a result of this initial phase study, the CRADA team has agreed to fund a larger study at TPI. The study will include processing approximately 1,000 lb of dirty foam and produce about 50–100 gal of polyol for market evaluation. The polyurethane industry producers BASF, Bayer, and Dow have agreed to evaluate the polyol initiator product and identify potential applications.

Publications

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Chemical Recycling of Mixed Polyurethane Foam Stream Recovered from Shredder Residue into Polyurethane Polyols, Sendijarevic, V., Sendajarevic, I., Winslow, G., Duranceau, C., Simon, N.,

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Recycling Automotive Shredder Residue and Plastics Using the CWT Thermal Process, Winslow, G.R., T. Adams, Proc. of the 10th Annual Global Plastics Environmental Conference (GPEC), Detroit, MI, February 18, 2004.

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Cost Effective Recovery of Thermoplastics From Mixed Scrap, Jody, B. J., J. A. Pomykala, Jr. and E. J. Daniels, Materials Technology, Volume 18 Number 1, March 2003, pp 18-24.

Separation and Recovery of Thermoplastics From Mixed-Scrap Plastics, Pomykala, J. A. Jr., B. J. Jody, E. J. Daniels, and J. Greminger, Proc. of the 9th Annual Global Plastics Environmental Conference (GPEC), Detroit, MI, February 26-27, 2003, pp 7-16.

D. Development of Technology for Removal of PCBs and Other Substances of Concern (SOCs) from Shredder Residue

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The Polyurethane Recycle and Recovery Council (PURCC) is also participating and cost-sharing in this project.
PURCC Project Lead: Steve Niemic

Contractor: Argonne National Laboratory
Contract No.: W-31-109-Eng-38

Objective

- Develop viable strategies and technology for the control and minimization or elimination of polychlorinated biphenyls (PCBs) and other substances of concern (SOCs) from recycled automotive materials.

Approach

- Identify efficient and environmentally acceptable process solutions for removal of contaminants, including PCBs from materials recovered from shredder residue.
- Conduct large-scale washing/cleaning tests using plastics from shredder residue in commercially available equipment.
- Identify necessary modifications to existing equipment to improve its performance and/or economics.
- Examine variances in analytical procedures/test results for PCB analysis.

Accomplishments

- Completed bench-scale screening of 11 surfactants and 3 organic solvents for removal of PCBs and other contaminants from polymers derived from shredder residues and specified preferred surfactant/cleaning solutions.
- Reviewed and identified commercially available washing equipment that can be adapted to a commercial-scale recycle process.
- Conducted trials of selected equipment; performed analyses of samples of cleaned product.
- Conducted laboratory tests to develop an understanding of the variability inherent in the analytical procedures for PCB analysis.

Future Direction

- Complete the large-scale cleaning tests using commercially available equipment and systems.
- Identify necessary modifications to existing equipment for most efficient and economical operation.
- Prepare a cost analysis of modified systems.
- Complete laboratory tests to quantify variability in PCB analytical procedures.

Summary

The objective of this project is to develop techniques and/or technology to identify and/or cost-effectively remove polychlorinated biphenyls (PCBs) and other substances of concern (SOCs) from recycled automotive materials.

SOCs can impact the recyclability of automotive materials in a number of ways. Certainly, their presence in either recycled materials and/or materials source stream impact the overall costs of recovering recyclable materials. In some cases, their presence at parts-per-million levels, such as PCBs, can prevent the reuse of the recovered materials such as polymers and polyurethane foams.

The strategy that is required for control of the SOCs may vary regionally. For example, requirements are different in Europe, North America, and Asia for various SOCs. Strategies for control of SOCs can also depend on the technology that is being proposed for recycling the automotive material.

The presence of SOCs in current vehicles and/or in other durable goods that are presently recycled with end-of-life vehicles is likely to impact the materials recycle stream for the foreseeable future. Consequently, control of certain SOCs will require technology that will effectively remove the SOCs from recovered materials consistent with current regulatory requirements and consistent with the market requirement for the recovered material.

The initial focus of the work in this project is on the development of options and technology for removal of PCBs from potentially recyclable materials recovered from shredder residue. PCBs, at parts-per-million levels, are routinely found in shredder residue. The source of the PCBs is not completely understood but historically has been associated with liquid PCB-containing capacitors and transformers that inadvertently escape the scrap inspections and control process at the shredders.

Bench-scale screening of commercially available surfactants and large-scale testing of commercially available equipment for cleaning of recovered materials has been conducted.

Laboratory experiments have also been performed to develop an understanding of the variability in PCB analytical procedures.

Bench-Scale Screening of Commercially Available Surfactants for Removal of PCBs

Working with Argonne, Troy Polymers, Inc. (TPI) completed the bench-scale screening of 11 surfactants and 3 organic solvents for removal of PCBs and other contaminants from polymers derived from shredder residue. Multiple samples of mixed plastics and polyurethane foam that were

recovered from shredder residue were used in the study.

The surfactant TRITON RW 50 was found to be the most efficient surfactant among the ones tried. PCB concentrations in the plastics and foam samples that were washed with this surfactant were reduced to below 2 ppm (Table 1).

The three organic solvents were also effective but were precluded from further consideration due to environmental considerations and cost.

Evaluation and Testing of Commercially Available Equipment

Technologies that can potentially be adapted for cleaning/washing of plastics from shredder residue fall into three major categories:

1. conventional methods that include mechanical transport of material through a cleaning solution through an agitation and/or scrubbing process by rotating drums and/or auger systems,
2. ultrasonic systems with and without agitation, and
3. centrifugal systems.

TPI undertook a review of the commercially available equipment, including the following:

- GraPar Corporation, Warren, Michigan. The company's expertise is in the design and manufacturing of aqueous cleaning equipment and systems.
- Almco, Inc., Industrial Finishing Systems, Albert Lea, Minnesota. The company's expertise is in the design and manufacturing of aqueous washers, dryers and liquid filtration systems).
- CarolMac Corporation, Greenville, North Carolina. The company markets centrifuge washers built by SeKoN, Bergamo, Italy.
- RANSOHOFF, Cincinnati, Ohio. The company's expertise is in the design and manufacturing of agitating ultrasonic washers.
- RG Hanson Co., Inc., Bloomington, Indiana. This is a testing lab for developing cleaning specifications and selecting cleaning equipment.
- JTW International, Inc., Lawrenceville, Georgia. The company's expertise is in the design and manufacturing of size reduction, separation, cleaning, and preparation of post-consumer plastic scrap.
- Greco Brothers Incorporated, Providence, Rhode Island. The company's expertise is in the design and manufacturing of aqueous ultrasonic cleaning systems.
- MTA Technical Cleaning, Reseda, California. The company's expertise is in the design and manufacturing of aqueous and ultrasonic parts cleaning equipment.
- Sanborn Technologies, Walpole, Massachusetts. The company's expertise is in the design and manufacturing of separation, ultra-filtration and nano-filtration and in fluid management and disposal issues.
- SeKoN, Italy. The company's expertise is in the design and manufacturing of aqueous washing using centrifugation equipment.

Table 1. Concentration of PCBs in plastics and foam before and after washing, bench-scale tests for surfactant selection

Designation	PCBs before washing (ppm)	
Plastics	2.8 ± 1.4	
Foam	27.2	
Surfactant or solvent used	PCBs in plastics after washing (ppm)	PCBs in foam after washing (ppm)
Triton DF-12	<1	2.4
Triton RW-100	<1	2.7
Tergitol TMN-6	<1	4.1
Bio-Terge Pas-8S	3.2	6.0
Triton RW-50	<0.08	2.0
Triton RW-75	—	4.7
No surfactant used	—	6.2

Preliminary large-scale cleaning/washing experiments were conducted using plastics from shredder residue in the following equipment to identify the limitations of various types of existing equipment: ALMCO rotary drum washer, equipped with a dryer, and SeKoN centrifuge equipment. The tests were carried out on approximately 100 lb of plastic chips each. The particle sizes were between 0.2 and 0.5 in. In each of these large tests, the washed material was "visually" clean as far as dirt and oils are concerned. However, the results for the PCB analyses indicated that the tests were not successful in meeting targets for residual concentrations under the test conditions (residence times, surfactant loading). Analysis of residual heavy metals is not yet complete.

Evaluation and testing of the commercially available equipment, to date, suggests that existing equipment may require modification to efficiently and economically clean plastics that are recovered from shredder residue.

Modifications that are suggested are intended to address two issues: (1) the dirt and oil are not evenly distributed on the plastics; (2) plastics are generally hydrophobic in nature and therefore have the tendency to re-adsorb oils and other organics. Key modifications involve (1) ensuring that the washed material does not come in contact with the liberated oil and dirt that is floating on or dispersed in the wash tank, as the washed material is removed from the tank; (2) ensuring that adequate agitation is provided so that the heavier plastics that will tend to sink stay afloat to achieve adequate mixing and contact between the plastics and the washing solution in the tank; (3) ensuring rapid and adequate removal of the oils and dirt from the wash solution to minimize or eliminate readsorption on the plastics; and (4) rinsing of the washed plastics as they exit the wash tank.

Based on these considerations, GraPar Corp. built a pilot-scale test stand. Controlled tests are planned in the GraPar machine at TPI to further delineate the issues (e.g., surfactant loading, residence times, etc.) with regard to effective cleaning of recovered materials so that more effective evaluations of commercially available equipment can be undertaken.

Evaluation of the Variability of PCB Analytical Procedures

In the large-scale washing tests, there was a significant degree of apparent inconsistency in the analytical results of residual PCB concentrations on the washed materials. Evaluation of these results suggested that this variability may be due to a number of factors including

1. sample size,
2. plastics particle size,
3. PCBs extraction procedure,
4. analytical procedures, and
5. interference from other compounds.

To begin an investigation of the effect of these factors, a series of controlled laboratory experiments were conducted at TPI, to investigate sample size, extraction procedures, plastics particle size, and analytical procedures.

In these experiments, samples of plastics were sent for direct PCB analysis to three different laboratories. Split samples of about 300 g each were extracted in hexane at TPI, and the resultant extract was analyzed for PCB concentrations. Typically, analysis of materials for PCBs is done using samples of only few grams of material.

The split samples were extracted with hexane nine times each in exactly the same manner. Three equivalent sets of these samples were then analyzed by three different laboratories using standard PCB analysis techniques. Preliminary results follow:

1. The three laboratories produced fairly consistent results for each set of samples.
2. Direct analysis of the samples, from the three labs showed that the PCBs concentration in the granulated plastics was about 5 ppm, while the concentrations reported for the ungranulated samples were about 10 ppm. Because the granulated samples have larger surface area per unit mass than the other samples, a more efficient extraction of PCBs from the plastics would be expected in the case of the granulated chips. These apparently inconsistent results are an indication of the variability that can be encountered with direct analysis of the plastics.

3. Calculation of the PCBs concentration in the 300-g samples based on hexane extractions showed concentrations of PCBs in the granulated samples to be comparable to the ungranulated samples. These results indicate that the PCB contamination is a surface contamination and that the PCBs have not been absorbed below the surface of the plastics.

Two of the laboratories identified Aroclor 1242 as the only PCB present, while the third laboratory identified Aroclors 1232 and 1254 as the only two present, and all three labs reported about same overall PCB concentrations. Each of these Aroclors consists of a multiple of congeners, and assignment of the PCB to a particular Aroclor is based on the measured distributions of specific congeners present as interpreted by the analysts. This is an indication of the complexity of the PCB analysis in these samples.

Analyses of samples using GC-ECD (gas chromatography-electron capture detector) and GC-MS (gas chromatography-mass spectroscopy) methods were conducted to compare these techniques. Results from the two methods are in good agreement, even though the GC-MS method seems to consistently predict slightly higher values.

Based on the results of these experiments, the cooperative research and development agreement (CRADA) team is planning a seminar to discuss PCBs analysis with expert chemical analysts to determine whether further work is needed or recommended with regard to analytical procedures.

Publications

Screening Study to Evaluate Shredder Residue Materials, Sendijarevec, V., N. Simon, C. Duranceau, G. Winslow, R. Williams, C. Wheeler, S. Niemiec, D. Schomer, SAE Paper No. 2004-01-0468, presented at the Annual SAE Congress, March 8, 2004.

E. Compatibilization/Compounding Evaluation of Recovered Polymers

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Contractor: Argonne National Laboratory
Contract No.: W-31-109-Eng-38

Objective

- Evaluate the market opportunity of polymers recovered from shredder residue.
- Identify limitations to the re-use of the materials as recovered and determine the need for postprocessing technology to upgrade the recovered materials to meet the requirements of the market.

Approach

- Specify standard protocols for material testing, content characterization, and performance properties.

Accomplishments

- Established a test protocol for material testing, content characterization and physical properties testing of polymeric materials.
- Issued a contract to Midland Compounding to evaluate the properties of polymers that are recovered as part of the technology demonstrations that are being conducted under the project "Postshred Materials Recovery Technology Development and Demonstration."
- Initiated physical properties testing of recovered samples.

Future Direction

- Continue physical properties testing of recovered polymers.
- Evaluate the market potential for clean mixed plastics streams recovered from shredder residue.
- Establish a database of properties of recovered polymers vis-à-vis general purpose virgin polymers.
- Identify candidate automotive applications for recovered polymers.
- Conduct mold trials using recovered polymers.

Summary

The objectives of this project are (1) to characterize the properties of potentially recyclable automotive materials and (2) to confirm the technical and economic feasibility of using those materials in value-added applications.

The project will initially focus on establishing the properties of polymeric materials that are recovered as part of the Post-Shred Materials Recovery Technology Development and Demonstration project.

Regardless of the effectiveness of any automotive materials recovery technology, the materials that will be recovered will be on average 10 to 15 years old. In this project, the performance properties of recovered polymers will be compared vis-à-vis new or virgin materials to establish a database of the properties of recovered automotive polymers. At present, there are few data concerning the physical properties of polymers recovered from postconsumer durable goods. Absent such data, it is unlikely that sustainable applications for recycled materials will be either identified or developed.

Blending and compounding tests will be done, as required, to achieve desired performance properties of the recovered materials for target applications. Mold trials may also be conducted to confirm the technical and economic feasibility of using recycled polymers in specific applications.

Physical properties testing is conducted by Midland Compounding, Inc. Midland will also run composition testing for comparison with compositional analysis done on recovered materials by Argonne.

Three other companies, Collins and Aikman Corporation, Enviro-Plas Corporation, and Mayco Plastics, Inc., have agreed to evaluate, compound, and run mold trials using recovered materials subject to the physical properties of the recovered materials.

Polymer Physical Properties and Materials Composition Analysis

Typically, 10-lb samples of recovered materials are utilized to define physical properties and to characterize the composition of the material.

To quantify physical properties, the sample is extruded on a single-screw extruder, melt screened through a 40-mesh screen, molded into American Society for Testing and Materials (ASTM) test bars and plaques, and tested. The molded parts and a random selection of regrind chips from each sample are evaluated for material identification on a Bruker P/ID 28 IR machine.

Physical properties that are measured for each sample include the following:

— melt flow rate,
— Izod impact,
— flexural modulus,
— tensile strength at yield,
— tensile strength at rupture,
— elongation at rupture,
— deflection temperature,
— Gardner impact, and
— specific gravity.

Physical properties of the high-impact polystyrene (HIPS) and the acrilonitrile-butadienestyrene (ABS) materials recovered during the shakedown tests of the Argonne froth-flotation process are summarized in Table 1. The shakedown trials were conducted using postconsumer shredded electronics and appliances scrap, not plastics from a typical automotive shredding

Table 1. Physical properties of HIPS and ABS recovered during Argonne froth-flotation shakedown trials

Properties	HIPS 1	HIPS 2	ABS
Melt flow rate, g/10 min, 200°C, 5 kg	5.4	5.5	5.2
Izod impact, ft-lb/in., 73°F	1.6	1.6	1.6
Flex modulus 1% secant, psi	248,662	262,939	341,543
Tensile strength at yield, psi	3,068	3,091	5,242
Tensile strength at rupture, psi	3,082	3,137	5,035
Elongation at rupture, %	38	41	33
Deflection temperature under load, 264 psi, °F	147	153	165
Gardner impact, 73°F, in.-lb	12	20	4
Specific granty, g/cm^3	1.05	1.05	1.08

operation. (See the Annual Report, "Postshred Materials Recovery Technology Development and Demonstration, see 6.C.)

A comparison of the physical properties of the recovered HIPS to various primary or "virgin" grades of HIPS indicates that the properties of the recovered postconsumer material are within the ranges of the "virgin" grades (Table 2).

Polymer Physical Properties Database

A physical properties database is being compiled to provide comparison of the physical properties of the recovered polymers vis-à-vis general purpose virgin polymers. The Vehicle Recycling Partnership had previously compiled physical properties data on selected polymers that were recovered during the U.S. Field Trials. These materials were recovered by disassembly. These data will also be included in the database to provide a comparison between the physical properties of materials recovered by disassembly relative to materials that are recovered from postshred operations.

General purpose physical properties have been compiled from the literature for the following plastics:

- ABS,
- nylon (6 cast, 6/6 extruded, 30% glass filled),
- PPO (unfilled, 30% glass filled),
- polycarbonate,
- polyethylene (LDPE, HDPE, UHMW),
- polypropylene,
- polystyrene (general purpose, high impact), and
- polyvinyl chloride (PVC).

Other polymer specifications may be added to the database as appropriate.

Table 2. Comparison of "recycled" and "virgin" grades of HIPS

Properties	HIPS 1	HIPS (natural)	Dow 484 HIPS (natural)
Generic material description	As received	Range	Typical HIPS
MFR, g/10 min, 200°C, 5 kg	5.7	2–14	2.8
Izod impact, ft-lb/in., 73°F	1.8	1–4	2.1
Flex modulus, 1% secant, psi	275,927	240,000–430,000	277,000
Tensile strength at yield, psi	2,660	2200–4500	2,800
Tensile strength at rupture, psi	3,033	2100–4500	3,500
Elongation at rupture, %	48	25–70	52
DTUL, 264 psi, °F	178	157–199	165
Gardner impact, 73°F, in.-lb	14	10–330	160
SG, g/cm^3	1.053	1.04	1.04