

**FY 2005**

**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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## 6. RECYCLING

### A. Recycling Assessments and Planning

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### **Objectives**

- Eliminate any real or perceived recycling barriers that might preclude the use of advanced automotive materials.
- 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 materials and components.
- Communicate a collaborative industry/government approach to issues related to the recycling of automotive materials.
- 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 lightweighting body and chassis materials.

- Establish an outreach/communication function to enable cooperation amongst, and leveraging of resources with, all stakeholders and 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**

- On September 14, 2005, held a workshop to update the Roadmap for Recycling End-of-Life Vehicles of the Future, which was issued in May of 2001. The updated Roadmap will be issued in the third quarter of FY 2006.
- On September 13, 2005, held a two-year program review that was attended by experts in the field, in addition to the CRADA partners.
- Developed a joint “U.S. ELV (end-of-life vehicle) CRADA” Team presentation kit and brochure.
- Established liaison with the Institute of Scrap Recycling Industries (ISRI) and held several meetings with the CRADA partners and representatives of ISRI in FY 2004 and FY 2005.
- Held a CRADA announcement event at Argonne on December 2, 2004 — the event was attended by representatives of the press, industry, and government.
- Negotiated a CRADA with the Vehicle Recycling Partnership (VRP) and the American Plastics Council (APC) and Argonne National Laboratory (ANL), as partners; effort under the CRADA was initiated in August 2003.
- Prepared a five-year research plan based on (1) the recommendations and priorities identified in the Roadmap and (2) an initial planning meeting with the management council of the VRP of USCAR.

### **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.
- 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 as necessary.

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### **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’s) FreedomCAR Vehicle Technology (FCVT) Program’s 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 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.

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, which recover useable parts for repair and reuse; automotive remanufacturers, which remanufacture a full range of components, including starters, alternators, and engines to replace defective parts; and ultimately the scrap processor, which 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 are profitably recoverable for recycling.

The recyclability of the remaining 25% of the end-of-life vehicles (ELVs) is limited at present by the lack of (1) commercially proven technologies to identify and cost-effectively separate materials and components and (2) profitable post-use 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 lightweight materials (e.g., ultra-light steels, aluminum, plastics, and composites) and more sophisticated/complex components.

### **Roadmap Recommendations**

A workshop to update the original roadmap, which was published in 2001, was held on September 14, 2005, at Argonne. Representatives from DOE, key stakeholders, and other experts attended the meeting (Exhibit 1). The updated roadmap will be published during the third quarter of FY 2006. The workshop evaluated the original Roadmap and its recommendations. The following were identified as some of the factors that can affect the recyclability of future shredder residue:

- Vehicles containing new materials of construction for lightweighting (composites, light weight steel, aluminum alloys, and magnesium);
- Catalysts for better environmental control; and
- Vehicles powered by fuel cells, electric batteries, hydrogen, and hybrids.

The key recommendations from the original roadmap, which was developed with input from key stakeholders to guide DOE's recycle research, were:

- Come together as a unified recycling community to cost-share in 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 post-shred material identification, sorting, and product recovery.
- Focus R&D efforts on materials not recycled today by sorters (e.g., post-shred 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 Five-Year R&D Plan**

On the basis of the roadmap and continuing discussions with key stakeholders, a five-year research plan was prepared. The plan includes three focus areas, as discussed below.

#### **Area 1. Baseline Technology Assessment and Infrastructure Analysis**

The focus of the work under this activity is 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 the 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 post-shred materials recovery, including mechanical recycling and conversion to fuels and chemicals. Projects that enhance pre-shred recovery — including disassembly for materials recovery and direct reuse and remanufacturing of components — will also be considered. In the long term, such

components as fuel cells, advanced batteries, and onboard hydrogen reformers are more likely to enter the recycle stream through pre-shred 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 10–15 years. Area 3 includes 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 the elimination of substances of concern.
- Benchmark recycling technology and provide data to stakeholders.

- Stimulate markets for reprocessed materials to support economic collection, processing, and transportation.
- Transfer technology to commercial practice.

This project (Recycling Assessments and Planning) 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 include the following:

- Baseline Assessment of Recycling Systems and Technology.
- Post-Shred 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 recycling infrastructure is in place. The CRADA 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 2004 International Car Recycle Congress in Washington, D.C.

Several meetings with representatives of the Institute of Scrap Recycling Industries (ISRI) were held to brief ISRI on the CRADA objectives and projects and to elicit ISRI participation.

To further communicate the U.S. approach to ELV recycling, a one-page CRADA summary and a CRADA brochure have been prepared.

As previously mentioned, a review of the projects and ongoing efforts of the CRADA team was held September 13, 2005 and a workshop was also held on September 14, 2005, to review and update the ELV Roadmap. The updated roadmap will be issued during the third quarter of FY 2006.

### **Publications**

*Market Driven Automotive Recycling in North America*, Duranceau, C. M., 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.M.; Fisher, M.M.; Wheeler, C.S.; and Winslow, G.R., JOM, The Mineral, Metals & Materials Society, vol. 56, no. 8, pp. 28–32 (Aug. 2004).

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

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

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

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

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

### **Keywords**

Recycling, automotive materials, plastics, metals, lightweighting materials, end-of-life vehicles

**Exhibit 1.** List of Roadmap Workshop Attendees

<b>Organization</b>	<b>Represented By</b>
American Plastics Council	Trip Allen
Consultant	Richard Paul
American Plastics Council	Mike Fisher
Argonne	Ed Daniels
Argonne	Bassam Jody
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Argonne	Jeff Spangenberg
Bayer Material Sciences	Don Schomer
DaimlerChrysler	James Frusti
DaimlerChrysler	James Ryan
DaimlerChrysler	Nakia Simon
DaimlerChrysler	Gerry Winslow
Energetics	Melissa Eichner
Energetics	Catherine Jereza
Ford	Claudia Duranceau
Georgia Tech	Bert Bras
Gesing Consultants	Adam Gesing
GM	Steve Cadle
GM	Candace Wheeler
ISRI	Dave Wagger
PURRC	Stephen Niemiec
Rochester Institute of Technology	Nabil Nasr
Steel Recycling Institute	Bill Heenan
Troy Polymers	Ibrahim Sendijarevic
Troy Polymers	Vahid Sendijarevic
Univ. of Windsor	Edwin Tam
USCAR	Susan Bairsley
USCAR	Stacey Keast
USCAR	Mike Martin
USCAR	Virginia Smith
USDOE	Joseph Carpenter

## B. Baseline Assessment of Recycling Systems and Technology

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*Contractor: Argonne National Laboratory*

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

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### **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 recycling technologies.
- 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**

- Prepared a draft article that reviewed the state-of-the-art in recycling of vehicles and automotive materials.
- Conducted a literature search that identified mechanical, thermo-chemical conversion, and energy recovery technologies.
- Conducted life-cycle studies of selected alternative recycle technologies, including mechanical recycling and thermo-chemical conversion of shredder residue to fuels.
- Characterized the existing U.S. recycling infrastructure and derived estimates of automotive recycling rates from the literature.

- Conducted recyclability calculations for reference cases and three lightweight alternatives: lightweight steel, composite materials, and aluminum.

### **Future Direction**

- Update the database of recycling technologies as new technologies emerge, a process that will include visits, as appropriate, to evaluate state-of-the-art material and energy recovery technologies in Japan and Europe.
- Continue life-cycle analysis and comparisons.
- Plan additional recyclability evaluations by using the current study as a starting point for assessing the recyclability of cars 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 is (1) to develop the tools and document the information necessary to make effective decisions relative to technology needs to facilitate sustainable future vehicle recycling and (2) 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 has been reviewed to identify technology gaps and needs and to identify differences in automotive recycling strategies among the North America, Europe, and Asia. Technologies that are included in this review include, but are not limited to, post-shred materials recovery technologies, pre-shred materials recovery technologies, materials identification technologies, automated dismantling technologies, technologies for the recycling of specific components of vehicles (such as bumpers and fuel tanks), and thermochemical conversion technologies.

Life-cycle analyses of alternative recycle technologies have also been conducted to identify differences between technologies, such as mechanical recycling vis-à-vis thermochemical recycling, relative to energy and environmental benefits.

Regulations at the international, federal, and state levels are examined to identify the impact that proposed and existing regulations may have regarding recycling of automotive materials.

Reference case recyclability calculations are made to quantify the expected recyclability of alternative vehicle designs.

### **Infrastructure**

The North American recycling infrastructure has been characterized (Figure 1).

### **Technology Profiles**

The recent literature has been reviewed, and summaries and profiles of available and emerging recycle technologies have been compiled into a draft working document and will be updated annually as new information becomes available.

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

- Recycling infrastructure,
- Design for recycling,
- 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, and
- Case studies of materials recycled for auto applications.

The bibliography was compiled from an extensive literature search, which included the following 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:
  - ARC '98 Conference
  - ARC '99 Conference
  - ARC '00 Conference
  - GPEC 2002 Conference
  - GPEC 2003 Conference
4. Other conference proceedings:
  - International Automobile Recycling Congress 2001, 2002, 2003, 2004
  - TMS Fourth International Symposium of Recycling of Metals and Engineered Materials, 2000
  - Ecomaterials and Ecoprocesses, The Conference of Metallurgists, COM 2003

At present, the bibliography includes 196 citations (Table 1). References will be added to the bibliography as available.

### **Recycling Technologies: State of the Art**

A draft document describing the state of the art in recycling technologies for end-of-life vehicles, post-shred residue, and automotive materials has been prepared. Because post-shred residue contains residue from shredded white goods and other obsolete items (in addition to vehicles), these were also discussed in the document. The table of contents of this document is shown in Table 2.

### **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. Although 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) limits the concentration of PCB on recycled materials to below the detectable limit (i.e., 2 ppm). State regulations regarding mercury and polybrominated diphenyl ethers (PBDEs) can also impede materials recycling.

**Table 1.** Citations included in the recycling bibliography (as of September 2005).

Bibliography Section	Number of Citations
Recycling infrastructure	18
Design for recycling	4
Legal and regulatory issues	24
Life-cycle analysis	9
Research programs	10
Substances of concern	5
Disassembly technologies and case studies	9
Reuse of automotive parts and subassemblies	1
Remanufacturing	0
Mechanical separation technology	21
Thermochemical conversion technology	12
Energy recovery technology	16
Other technology	36
Advanced materials recycle technology	7
Case studies of materials recycled for auto applications	24
Total citations	196

**Table 2.** Draft state-of-the-art assessment table of contents.

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1.0. Introduction and Background
2.0. The Process of Recycling Automobiles
– Dismantling for Direct Resale
– Shredding
3.0 The Process for Recycling White Goods
– Refurbishing of Units for Resale
– De-Pollution of the Units
– Shredding
4.0. Shredder Residue
– Composition
– Recycling of Materials from Shredder Residue
5.0. Technologies for Concentrating Recyclables from Shredder Residue
– Mechanical Separation Systems
– Gravity Separators
– Electrostatic Separators
6.0. Technologies for Separating and Recovering Products from Shredder Residue
– Argonne's Separation and Recovery of Flexible Polyurethane Foam
– Separation and Recovery of Plastics from Shredder Residue
• Argonne's Froth Flotation Process
• The RPI Process
• The Salyp Process
• The VW/SiCon Process
• The Galloo Process
• The MBA Process
• The Toyota Process
7.0. Thermochemical Processes for Recycling Shredder Residue
• CWT Hydrolysis Process
• TPI Glycolysis Process
• Other
8.0. Energy Recovery from Shredder Residue
9.0. Substances of Concern
– Polychlorinated Biphenyls (PCBs)
– Heavy Metals
– Flame Retardants
10.0 Recycling of Advanced Vehicles
– Recycling of Fuel Cell vehicles
– Recycling of Electric and Hybrid Vehicles
– Recycling of Aluminum and Magnesium from New Generation vehicles
– Recycling of Composites
11.0 Recycling of Other Vehicle Materials
– Catalytic Converters
– Tires
– Carpet
– Fluids
– Fuel Tanks

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## Life-Cycle Studies

The objective is to use life-cycle analysis to assess the environmental impacts of various mechanical separation technologies and alternative end-of-life recycling technologies. 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.

PE Europe GmbH, a company that is experienced in conducting life-cycle assessments and in model development using its own GaBi (Ganzheitliche Bilanzierung) software, was contracted to perform these analyses. Two analyses have been done: one for Salyp NV's mechanical separation process and another for Changing World Technologies' (CWT's) thermal conversion process. PE Europe has also developed a flexible end-of-life model, and the model was used to compare the two different approaches to recycling shredder residue. 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.

Salyp's separation process combined equipment developed by Argonne National Laboratory and several others to create a facility that separates shredder residue into discrete fractions of metals, foam, mixed plastics, and fiber-rich and fines streams. On the other hand, the CWT process converts organic materials into hydrocarbon fuels and other potential products.

Primary data were collected for both the Salyp and the CWT processes, including all energy, water, and material inputs, plus data on emissions to air and water, wastes, and products produced. Both sets of data were entered into the GaBi software to create a flexible model of the process.

Figure 2 illustrates the flow streams for the Salyp case.

In the case of the Salyp separation process, three different scenarios for handling the various materials recovered from shredder residue were determined. These scenarios included using specific material fractions as fuel for cement kilns (energy recovery), as well as using mixed plastics to replace such products as wood pallets and polypropylene (PP) pellets (material substitution). The various scenarios were assessed by using a variety of impact categories, including primary energy demand and CO<sub>2</sub> emissions. In the case of primary energy demand, all scenarios showed a net credit in total energy use. For the three scenarios studied, substituting recovered PP/PE in a new PP application had the greatest benefit. However, if the mixed plastic stream was used to replace wood (e.g., decking material, park benches, wood pallets, etc.), the benefits to primary energy demand were less than if the recovered materials were simply used for energy recovery. In terms of CO<sub>2</sub> emissions, the PP application again showed the greatest benefit. Substituting PP for wood applications was next with a lower benefit, while the energy recovery scenario showed a negative impact on CO<sub>2</sub>.

In the case of the CWT process, two basic scenarios were assessed. They involved using the light hydrocarbon oil generated by the process for fuel oil used in power plants to generate electricity and substituting light hydrocarbon oil for diesel oil (both with and without an added hot-oil processing step). While the oil product generated is more refined than an actual crude oil, it would require additional steps before it could be considered a true diesel oil. Therefore, reality is probably located somewhere between scenarios 1 and 2. In this study, the impact on primary energy demand resulted in a benefit in all cases. The benefits in the diesel substitution case were slightly greater than in the fuel oil case. In the case of CO<sub>2</sub> emissions, all scenarios again showed an overall benefit. However, the diesel substitution case had a greater benefit than the fuel oil substitution case.

A comparison of these two technologies is under way. Although early results show that the thermal conversion process has an overall advantage over the mechanical separation process, these results are heavily dependent on the assumed use of the end products in the life-cycle

assessment, as well as on key assumptions on contamination and metals recovery. These factors are being addressed.

### **Recyclability Studies**

Recyclability studies are being conducted to examine the effect of using automotive lightweighting material on recyclability. A Toyota Prius hybrid was selected as 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. In comparison, the materials composition of a production Ford Taurus is summarized in Table 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)	1,283.1	100.00

**Table 4.** 2004 Ford Taurus materials breakdown.

Materials	Mass (kg)	Percent
Ferrous metals	1,008.28	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)	1,432.86	100.00

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 feasibility-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.

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

**Table 5.** Reference case recyclability: 2004 Toyota Prius.

Calculation Method	Recyclability (%)
Federal Trade Commission	80.86
European	97.61
Feasibility of recycling	85.58
Ref. 2000 Ford Taurus	80.50

The aluminum alternative is for a 2004 Toyota Prius with an aluminum body and a magnesium engine cradle and a 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 that consists of (1) 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 (2) a 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 wt% of the original steel.

There are reductions in all three recyclability calculations for lightweighted vehicles, even though the rest of the vehicle is not changed (Table 6). Where the aluminum and composite material is being recycled, the same amount of material would be disposed of in landfills in each of the three scenarios. The only difference is that the recycled portion of the lightweighted vehicles would be lighter. Although the recyclability would be less, there would be no difference in the amount of material disposed of in landfills, 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 the downsizing of related components that would

accompany any lightweight vehicle, such as powertrains, brakes, and tires. Because the downsized components are high in metallic content, downsizing will further reduce recyclability and make it difficult to meet the European 95% requirement.

In conjunction with this study, additional evaluations are planned by using these data as a starting point for assessing the recyclability of cars of the future. The impact of vehicle lightweighting and material selection on recyclability will be evaluated. In addition, the impact of powertrain changes in future vehicles (including hybrid and fuel cell alternatives) on recyclability will be determined in comparison to powertrains in 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 the downsizing 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 choices of materials.

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

Calculation Method	As Produced (%)	Aluminum Body (%)	Composite Body (%)
FTC	80.9	76.1	74.0 <sup>a</sup>
Europe	97.6	96.0	94.5 <sup>a</sup>
an Feasibility of recycling	88.3	85.6	83.9 <sup>a</sup>

<sup>a</sup>If the composite material were not recycled, then the numbers would be FTC, 57.2%; European, 78.2%; and feasibility of recycling, 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 properties and would limit their reuse to short fiber applications.

These results demonstrate the need for technology to recycle new automotive material if recycling mandates are to be met and to ensure that lightweighting materials are not excluded because of the inability to recycle them.

## **Publications**

*Modular Life Cycle Model — Basis for Analyzing the Environmental Performance of Different Vehicle End-of-Life Options*, Binder, M.; Simon, N. L.; Duranceau, C. M.; Wheeler, C. S.; Winslow, G. R., Proc. of the 5<sup>th</sup> 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*, Wheeler, C. S.; Simon, N. L.; Duranceau, C. M.; Winslow, G. R.; Binder, M., SAE Paper 2005-01-0847.

*United States National Life Cycle Inventory Database Project, A Status Report*, Sullivan, J. L.; Wheeler, C. S.; and Simon, N. L., SAE Paper 2005-01-0852.

## **Keywords**

Recycling, recycling technology, life-cycle analysis, recyclability, automotive materials, end-of-life vehicles

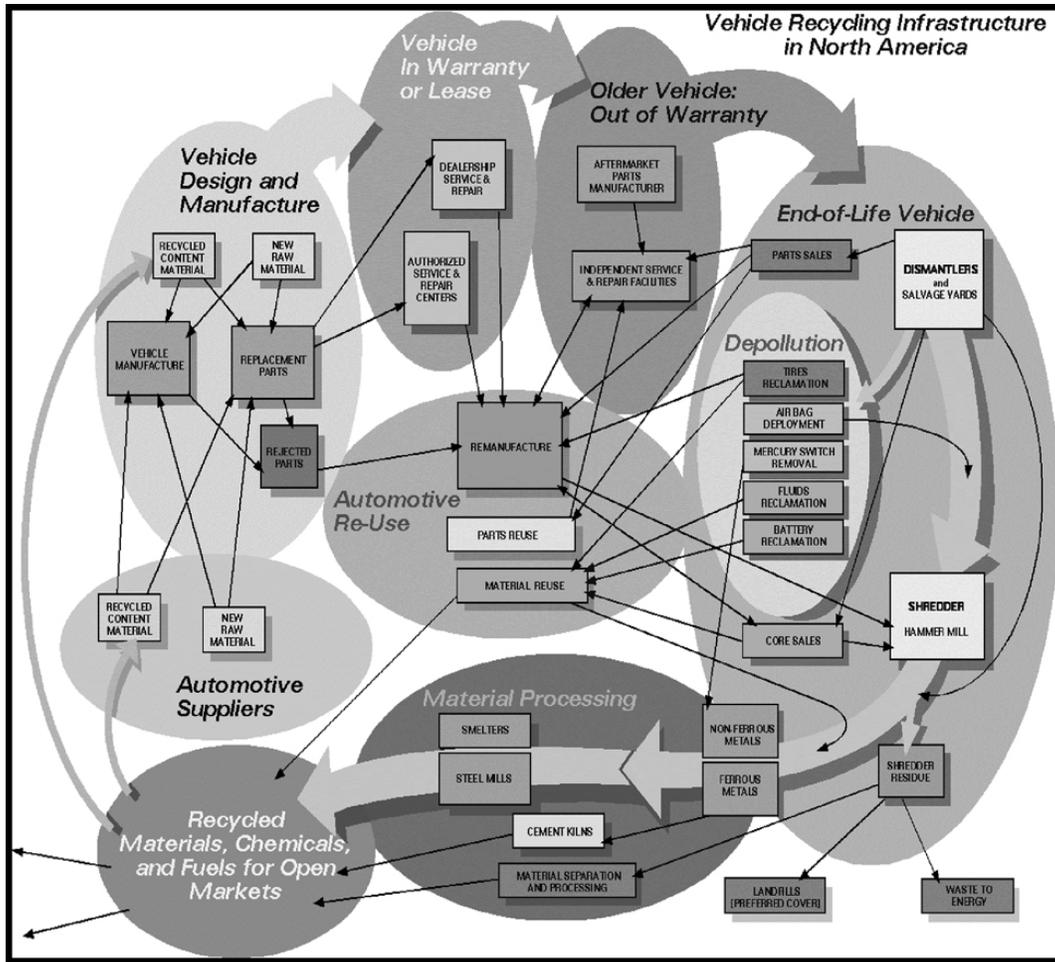


Figure 1. Representation of the North American recycle infrastructure.



## C. Post-Shred Materials Recovery Technology Development

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*Changing World Technologies is cost-sharing on the evaluation of its 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 technology for the cost-effective recovery of materials from post-shred residues.

### **Approach**

- Characterize shredder residue 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 pilot plant for the separation of shredder residue to produce recovered materials for market evaluation and to provide "control" samples of materials for testing of alternative technologies, as appropriate.
- Conduct cost and performance analysis of alternative technologies to establish the business case for the technologies and to identify technology gaps.

### **Accomplishments**

#### *Mechanical Separation of Shredder Residue*

- Processed over 160,000 lb of shredder residue in Argonne's mechanical separation pilot plant. Over 50,000 lb of plastics concentrate were produced. Construction of the plant was completed in the first quarter of FY 2004, and shakedown of the facility occurred during the second and third quarters.

- Increased, through process improvements, yield of polymer concentrate from as low as 40% to 95%.
- Performed mass balance on the process and characterized the shredder residue and the polymer concentrate. Ten shredder residues, including two European and eight United States, were characterized.
- *Froth Flotation Process for Recovering Plastics*
  - Completed construction and shakedown of a six-stage froth flotation plastics separation plant in the first quarter of FY 2005 and started froth flotation separation trials.
  - Recovered over 3,500 lb of polyolefins (polypropylene [PP] and polyethylene [PE]) product.
  - Completed a series of tests to define density distributions and settling velocities of polymers and other materials present in the polymer concentrate.
  - Upgraded process to isolate unexpected high content of wood and rubber in the plastics concentrate.
- *Thermal/Chemical Conversion Processes*
  - Completed bench-scale and pilot-scale batch testing of Changing World Technologies' (CWT's) thermal depolymerization process for converting shredder residue to fuels.
  - Conducted testing in a five-gallon reactor of Troy Polymer, Inc.'s (TPI's), glycolysis process for conversion of urethane foam to polyol initiators. Over 1,200 lb of foam were used, and over 100 gal of polyol initiators were produced.
- *Other Accomplishments*
  - Completed large-scale tests of Salyp's "thermoplastics sorting" technology by using residue from two European locations and one U.S. location as feed materials.
  - Developed an Excel-based process cost model that incorporates two primary modules for the 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 Argonne froth flotation campaigns and evaluate process performance and economics; define path forward.
- Complete CWT thermal depolymerization process evaluation; define path forward.
- Complete Polyventure/TPI glycolysis process evaluation; define path forward.
- Test and evaluate the Volkswagon/Sicon (VW/Sicon) technology for separating plastics from shredder residue.
- 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 technology for the cost-effective recovery of materials from post-shred residues. Research will

provide data essential to establishing a business case for sustainable recycling of automotive materials from post-shred residue. A wide range of materials recovery technologies is at various stages of development worldwide. Technologies

specific to the recovery of materials from post-shred material streams are being evaluated and demonstrated to determine their commercial viability. The performance (e.g., yield, purity,

- Large variations in non-plastic materials (e.g., fines, residual metals, rubber and wood) and
- Less-significant variation in the

**Table 1.** Variability of yield of polymer concentrate from a given source over a six-month period

Run #	Polymer Concentrate (wt%)	Run #	Polymer Concentrate (wt%)
2	41	6	45
3	26	7	37
4	36	8	43
5	39	9	45
		Average	40

efficiency, and cost) of these emerging technologies will be determined to enable the development of an integrated process for recovering materials from shredder residue.

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

### **Characterization of Shredder Residue**

To facilitate the development of technology for the recovery of materials and resources from shredder residue, MBA Polymers characterized five shredder residues (two European and three American) by using 2-kg samples. The analysis showed significant variations in these samples. For example, the fines in these fractions ranged between 5% and 38%, and foam in the samples ranged between 21% and 37%, which is about four to seven times what is expected for polyurethane foam. These differences are due to a large extent to the small size of the samples used and demonstrate the difficulty in sampling the heterogeneous shredder residue. After processing over 80 tons of shredder residues from five different U.S. shredders in Argonne's mechanical separation plant, which is described in the next section, we observed (Figure 1):

composition of the polymer fraction.

In addition, the polymer concentrate separated from different shredder residues showed, for the most part, little variation (Figure 2), and the weight percent (wt%) of the polymer concentrate recovered from a given source over a six-month period was reasonably consistent (Table 1).

### **Argonne Pilot Plant**

Argonne's pilot plant consists of two major facilities. The first is a mechanical (physical) separation facility; the second is a wet-density/froth-flotation separation facility. The pilot plant was used to:

1. Recover materials from shredder residue,
2. Conduct process improvement/integration studies,
3. Provide a capability to produce large samples of recovered materials for market evaluation,
4. Define the effectiveness of alternative separation technologies and systems, and
5. Serve as a user/demonstration facility to conduct separation tests for residue from specific sources.

The mechanical separation facility is shown in Figure 3. The mechanical separation facility processes the raw shredder residue to yield a polymer concentrate and other fractions, as shown in Figure 1.

The wet density/froth-flotation facility is shown in Figure 4. It includes six continuous

stages for the separation and recovery of targeted materials from the polymer concentrate derived from shredder residue. Its design capacity is 1,000 lb of mixed plastics per hour.

#### Mechanical Separation Pilot-Plant

Initially, six campaigns totaling 60,000 lb of shredder residue were undertaken to debug and shake down the mechanical separation pilot-plant. The average yield of polymer concentrate recovered from these campaigns was only about 17% of the total weight of the shredder residue. This yield was significantly lower than anticipated. Analysis of the various separated streams showed that the recovery of the polymers from shredder residue in the polymer concentrate fraction was also low (40–70%) for the different source materials. As a result, a loss analysis was undertaken. The analysis included sampling and quantification of residual polymers in each of the fractions that are generated in the bulk processing of shredder residue to recover the polymer concentrate. On the basis of this loss analysis, minor process modifications were made, and some of the fractions were reprocessed. As a result, the yield of plastics concentrate more than doubled.

Loss analyses were also conducted on the various non-polymer concentrate fractions after the modifications were made. These analyses indicated that the recovery of polymers targeted for recovery in the polymer concentrate was about 95% of those polymers available in the shredder residue. Although the yield of the polymers targeted for recovery in the polymer concentrate was about 95%, the polymer concentrate also included an unexpectedly high and varying concentration of wood and rubber (Figure 2). The wood content was about 1–4% by weight. In Figure 2, the wood is included in the “non-polymers.”

Trials were conducted by using commercially available air aspirators, classifiers, air-gravity tables, and mineral jigs to remove wood and rubber from the polymer concentrate. Using this equipment did not yield satisfactory results.

#### Froth Flotation Pilot Plant

A shakedown of the wet density/froth-flotation facility was conducted during the second quarter of FY 2005 by using about 4,000 lb of

post-consumer electronics and appliance mixed plastics. These materials were used because their composition is much less variable than the composition of plastics concentrate from shredder residue. The shakedown tests were conducted to target the recovery of acrylo-nitrile-butadiene-styrene (ABS) and polystyrene (PS). Trials were also conducted by using colored plastics supplied through the American Plastics Council. These trials confirmed the effectiveness of the basic system.

The initial trials of the froth flotation system on shredder residue plastics were complicated by the unexpected high rubber and wood content of the polymer concentrate. Bench-scale tests were conducted to define the specific gravity and settling velocities of the wood and rubber relative to other species in the polymer concentrate. Several plastics, wood, and rubber species were found in every specific gravity range. Several plastics, wood, and rubber species were also found to have overlapping settling velocities. The data indicated that neither specific gravity nor settling velocity differences were large enough to affect the separation of wood and rubber from the plastics.

Trials using various process solution conditions were also conducted. These trials ultimately yielded a set of conditions to remove almost 100% of the wood and to concentrate the rubber into two separate fractions with a nominal loss (less than 5%) of the polymers (such as the polypropylene [PP] and polyethylene [PE]) that are being targeted for recovery. The resultant process conditions have been incorporated into the Argonne froth flotation process. More than 3,500 lb of a PP/PE fraction that is over 95% PP/PE have been consistently produced. Its wood content is less than 0.2%. The recovered PP/PE has properties similar to those of some commercially available PP materials. The recovered PP/PE product constituted about 5%–6% of the starting shredder residue weight.

An 80% rubber concentrate was also recovered. A 50-lb sample of the rubber concentrate was submitted for testing by using the “TireCycle” process used for recycling rubber materials. It was determined that the presence of the plastics in the rubber concentrate is likely to improve the properties of the recycled rubber

when used to make construction products (such as roofing shingles).

A 75% ABS concentrate has been recovered. The ABS concentrate contained incompatible materials, including filled PP. Trials are ongoing to improve the composition of the ABS concentrate and to recover other polymers from the polymer concentrate.

### **Changing World Technologies**

Changing World Technologies, Inc. (CWT), has developed a thermal conversion process that converts organic material into high hydrocarbon oil. The process was tested for processing shredder residue. The process was able to convert the shredder residue samples into three product fractions: an oil, a gas, and a carbon char. A pilot-scale test apparatus was designed and built by CWT to simulate commercial-scale handling and depolymerization/dissolving of a mixed automotive waste stream (90% shredder residue/10% post-consumer tires). Tests were conducted to confirm the technical and economic feasibility of this process.

In the process, a 1/16-in. mesh vibrating screen was used to separate the fines (mostly inorganic matter), which constituted about 36% of the total shredder residue sample weight. The shredder residue was supplied by Argonne. About 700 lb of the remaining fines-free material was processed along with 80 lb of shredded tires and 1,700 lb of used motor oil. Samples of the various products were sent out for analysis to determine the fate of the inert solids and contaminants (i.e., heavy metals, polychlorinated biphenyls [PCBs], and chlorine).

Thermal cracking tests of this CWT hydrocarbon fuel were performed in bench-scale Parr reactors to simulate the production of transportation fuels. The products generated were hydrocarbon oil, a fuel-gas, and a solid carbon product. The distribution of oils/gas/carbon fractions was determined to be 84%, 10%, and 6%, respectively. A fractional distillation of the oil was also performed. This process generated gasoline, diesel, and heavy hydrocarbon oils (Figure 5). The distribution was gasoline (12%), middle-distillate (38%), diesel (32%), heavy-oil (15%), and gas (3%).

### **Troy Polymers Process for Glycolysis of PUFs**

Troy Polymers, Inc. (TPI), has developed a patented process for the conversion of mixed polyurethane foams (PUF), such as that present in shredder residue, into polyol initiators (Figure 6), which can then be utilized to produce urethane products. PUFs first undergo glycolysis, followed by filtration and removal of PCBs and other substances of concern from the liquid glycolized product. In a second stage, the glycolized products are propoxylated by using propylene oxide to produce polyols.

In FY 2004, bench-scale testing was undertaken to establish proof-of-concept. The results demonstrated the technical feasibility of the process for converting mixed, clean PUF from shredder residue to polyol initiators at a yield of about 88%. The yield for dirty foam was about 72%. The product from dirty foam required extensive filtration to remove the solid residue. The results also indicated that commercially available activated carbons were able to reduce the concentration of PCBs to below 1 ppm.

In FY2005, the process was scaled up in a 5-gal reactor. Scale-up included testing of the filtration of solid impurities and removal of PCBs and other substances of concern from the polyol initiator. Over 1,200 lb of foam separated from shredder residue have been processed, and over 100 gal of polyol initiator have been produced. The effects of temperature, glycol-to-foam ratio, and catalyst types on the reaction yields have been evaluated. Results indicate that diethylene glycol (DEG) gives a higher yield and allows reaction at lower temperature than dipropylene glycol (DPG). Potassium hydroxide (KOH) was preferred over sodium hydroxide (NaOH) as a catalyst. By using optimized reaction conditions with DEG and KOH catalyst, >90% reaction yields were consistently achieved.

Various filtration methods were also evaluated for the removal of unreacted solids from the polyol initiator. A nylon bag filter was installed in a recirculation loop with the 5-gal reactor to remove solids larger than 200  $\mu\text{m}$ . Although bag filtration worked well on a 5-gal scale, for a production-scale process, continuous filtration systems will most likely be required.

Treatment with activated carbon was also capable of removing PCBs from the polyol initiator to nondetectable levels (<2 ppm). The PCBs are removed more readily from the polyol initiators produced from DEG than DPG. The removal of PCBs via activated carbons from polyol initiator was demonstrated by using Aquasorb 1500 activated carbon. Twenty gallons of the polyol initiator, which had an equivalent weight of 163, was also submitted for propoxylation to Pelron Corporation in Illinois, where two lots were produced. In one lot, the equivalent weight of polyol was 354, and in the other lot, it was 173. That two different equivalent weights were produced proves that polyols with different equivalent weights can be produced from the recycled polyol initiators.

The recycled polyols produced from shredder residue foam were also tested in preparing rigid PUFs. The recycled polyols exhibited several advantages over the virgin commercial polyols. They were more reactive than the virgin polyols in that they required fewer or no catalysts. Furthermore, the foams based on the recycled polyols had much better flame resistance than the foams based on the virgin polyol.

Initial economic analysis of the process to produce polyol initiator and polyols via propoxylation indicated that the glycolysis process is economical.

## **Publications**

*Recycling Shredder Residue Containing Plastics and Foam Using a Thermal Conversion Process*, Winslow, G.R.; Appel, B.S.; Adams, T.; Simon, N.I.; Duranceau, C.M.; Wheeler, C.S.; and Sendijarevic, V., SAE Paper #2005-01-0848.

*Chemical Recycling of Mixed Polyurethane Foam Recovered from Shredder Residue into Polyurethane Polyols*, Sendijarevic, V.; Sendijarevic, I.; Winslow, G.R.; Duranceau, C.M.; Simon, N.I.; and Wheeler, C.S., SAE paper # 2005-01-0850.

*Sustainable End-of-Life Vehicle Recycling: R&D Collaboration between Industry and the U.S. DOE, Journal of Metals*, Daniels, E.J.; Carpenter, J.A., Jr.; Duranceau, C.; Fischer, M.; Wheeler, C.; and Winslow, G., Vol. 56, No. 8, August 2004.

*Advanced Separation of Plastics from Shredder Residue — Mechanical Separation, Salyp Process Technology*, Winslow, G.R.; Simon, N.L.; Duranceau, C.M.; Williams, R.; Fisher, M.M.; Kistenmacher, A.; and VanHerpe, I., SAE paper # 2004-01-0469.

*Screening Study to Evaluate Shredder Residue Materials*, Winslow, G.R.; Wheeler, C.S.; Williams, R.L.; Duranceau, C.M.; Simon, N.L.; and Schomer, D.R., SAE paper # 2004-01-0468.

## **Keywords**

Recycling, recycling technology, froth flotation, mechanical separation, thermal conversion, thermal depolymerization, glycolysis, end-of-life vehicles

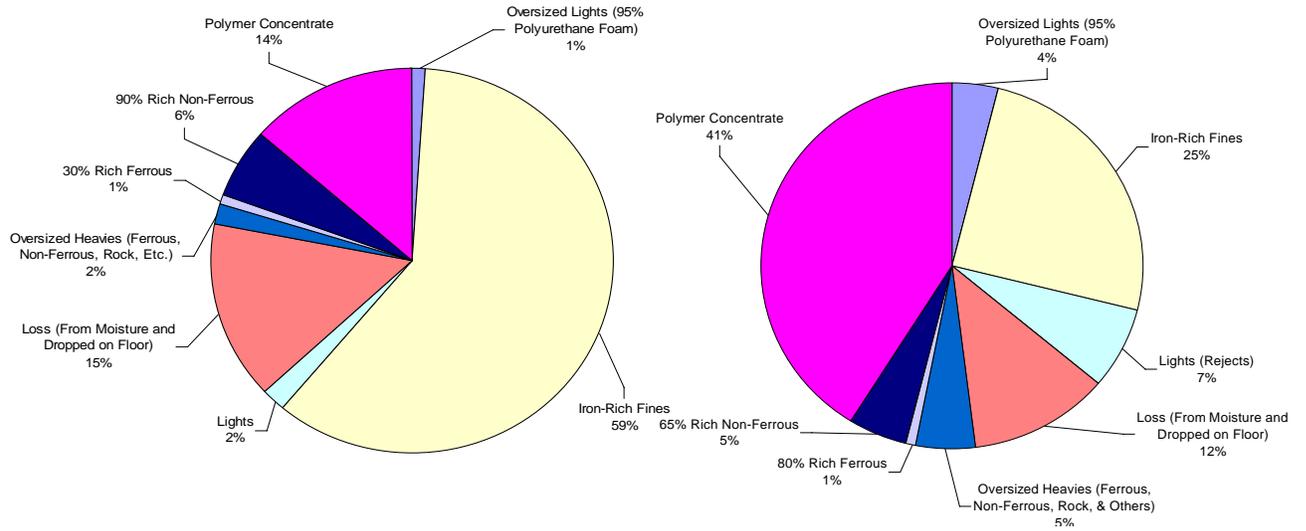


Figure 1. Comparison of shredder residue composition from two shredders.

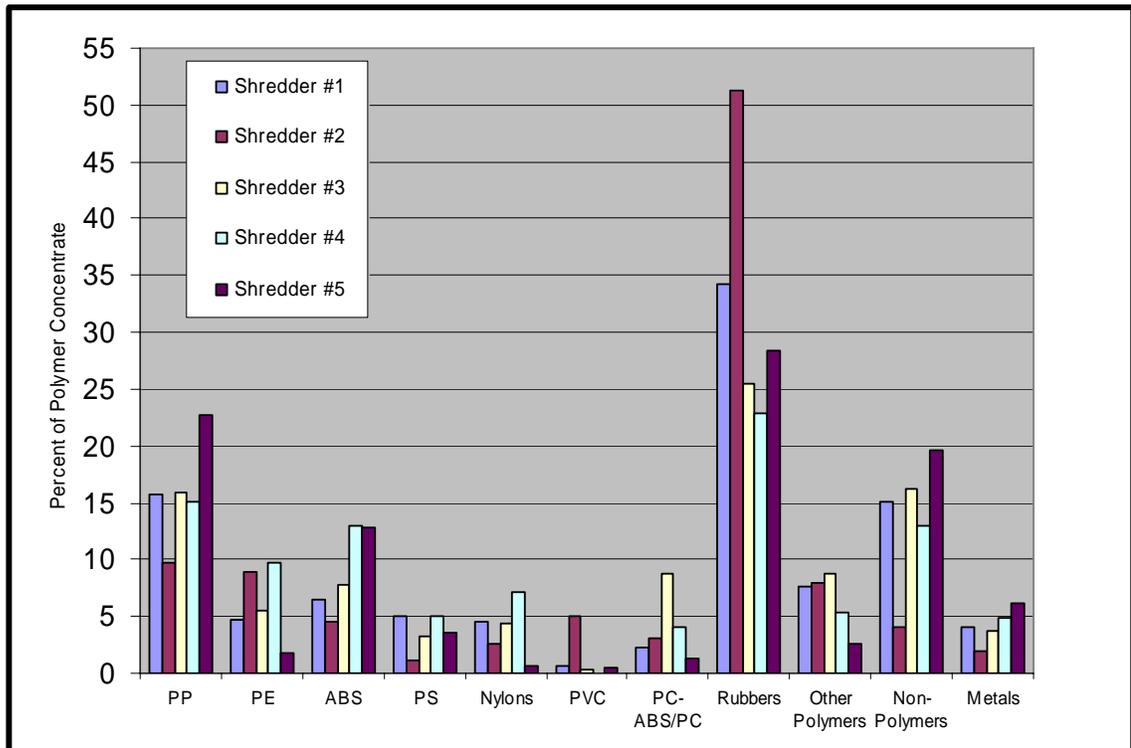


Figure 2. Similarity in composition of polymer concentrate from different shredders.

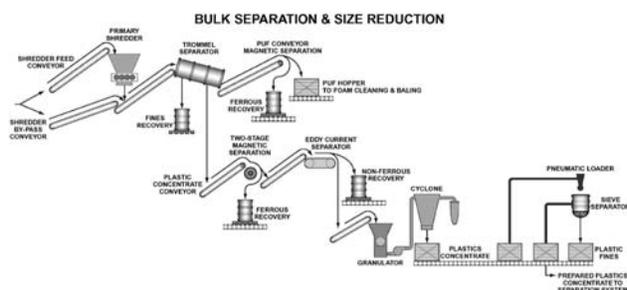


Figure 3. Argonne pilot mechanical separation system for processing raw shredder residue.

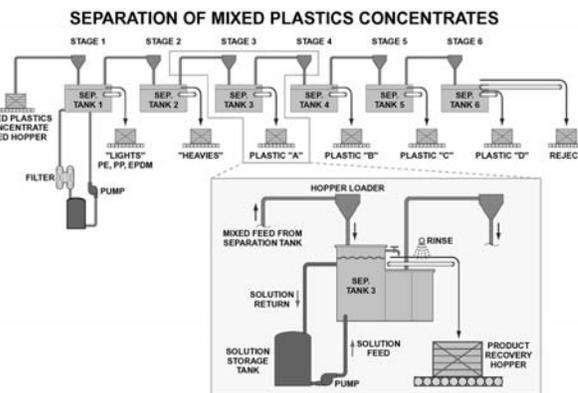


Figure 4. Argonne pilot wet separation system for recovery of plastics from shredder residue.



Figure 5. Left to right: gasoline, middle distillate, diesel, and heavy fuel oil reduced by the CWT process..

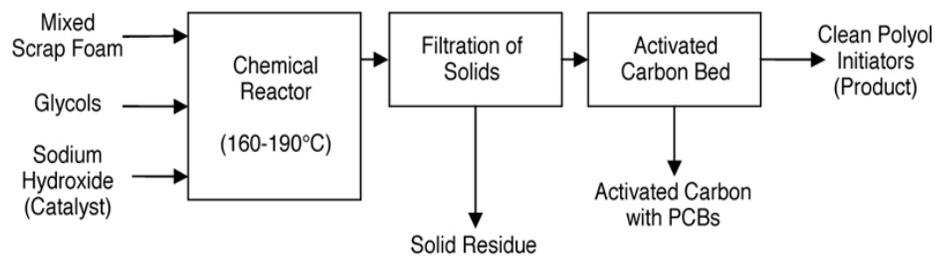


Figure 6. TPI's glycolysis process conceptual process flow sheet.

## **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*

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*Contractor: Argonne National Laboratory*

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

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### **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.
- Define variances in analytical procedures/test results for PCB analysis.

## Accomplishments

- Conducted washing/cleaning tests of plastics recovered from shredder residue in:
  - Proprietary solvent-based solutions and in CO<sub>2</sub> and
  - Equipment using aqueous solutions with surfactants.
- Conducted laboratory tests to develop an understanding of the variability inherent in the analytical procedures for PCB analysis.
- Completed bench-scale screening of 11 surfactants and three organic solvents for removal of PCBs and other contaminants from polymers derived from shredder residues and specified preferred surfactant/cleaning solutions.
- Conducted a seminar with experts to further identify issues with regard to variability in analytical results for PCBs.
- Investigated impact on the analytical results of sample size, extraction solvent, and number of extractions used.

## Future Direction

- Conduct additional testing on PCBs removal methods, including steam stripping.
- Integrate washing/cleaning system with the process for polymers recovery from shredder residue and identify necessary modification to facilitate the integration.
- Conduct a cost analysis of modified systems.

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## 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 in the case of PCBs, can prevent the reuse of the recovered materials, such as polymers and polyurethane foams.

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

The presence of SOC's 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, the control of certain SOC's will require technology that will effectively remove the SOC's 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 the 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 it has been associated with liquid PCB-containing capacitors and transformers that inadvertently escape the scrap inspections and control process at the shredders.

## Evaluation and Testing of Solvent-Based Washing Systems

Three companies with equipment and/or proprietary washing solvents and solutions that could potentially be used for non-aqueous removal of PCBs from plastics recovered from shredder residue were identified by Troy Polymers, Inc. (TPI):

- Environmental Technology Unlimited (Wilmington, North Carolina);
- Cool Clean Technologies, Inc. (Burnsville, Minnesota); and
- ITec Environmental Group, Inc. (Oakdale, California).

Each company was supplied with a sample of plastics with the assigned (determined) concentration of PCBs of 11 ppm. Samples were washed at the three companies, and the washed samples were evaluated for PCB levels.

Environmental Technology Unlimited uses a proprietary METHEX solvent-based system and aqueous-based systems. Environmental Technology Unlimited performed six treatments of shredder residue plastics, and five out of the six washed samples reduced the PCBs concentration to below 2 ppm. The METHEX solvent-based system was superior to the aqueous system.

Cool Clean Technologies technology used CO<sub>2</sub> only. The washing failed to remove the PCBs.

ITec Environmental Group reduced PCB levels in the plastics from 11 ppm to 2.8 ppm via solvent washing; no CO<sub>2</sub> treatment, which normally follows the basic process, was used.

On the basis of these results, it appears that Environmental Technology Unlimited and ITec Environmental Group have the technology that could remove PCBs to below 2 ppm. However, at this time, only ITec has the full-scale equipment ready to be integrated with a plastics recycling process.

### **Evaluation and Testing of Commercially Available Aqueous-Based Washing Systems**

Before testing the solvent-based systems, large-scale cleaning/washing tests were conducted using plastics from shredder residue by means of aqueous solutions and a surfactant previously identified earlier as the most promising from among many tested. The objective was to identify the limitations of the various types of existing washing equipment. Testing was done by using an 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 particles were between 0.2 and 0.5 in. in size. Under a CRADA contract, GraPar Corporation built, for

Troy Polymers, Inc. (TPI), and tested a specially designed machine that has a design capacity of about 300 lb/hour of plastics. TPI conducted further testing on this machine in its facilities.

In each of these large tests, the washed material was “visually” clean in terms of dirt and oils. However, PCBs analyses were highly variable and indicated that in some cases, the PCBs concentration had increased after washing. As a result, it was determined that the PCBs analysis procedures should be reexamined, as is discussed in the next section.

The results suggest that existing aqueous-based equipment, as is, is not likely to reduce the concentration of PCBs to acceptable levels. Modifications are necessary to wash small chips (1/8 to 1/2 in.) of plastics — such as what will be recovered from shredder residue — efficiently and economically.

### **Evaluation of the Variability of PCB Sampling and Analytical Procedures**

The large variability in the analytical results raised questions about the analytical sampling and analyses procedures. Therefore, laboratory experiments were performed to develop an understanding of the variability in PCB analytical procedures and explain the variability in the results.

The variability may be due to a number of factors, including sample size, plastics particle size, PCBs extraction procedure, analytical procedures, and/or interference from other compounds. A one-day seminar was held and attended by analytical experts from the United States and overseas to develop recommendations for improved sampling and analysis techniques specific to plastics chips recovered from shredder residue.

To investigate the possible interference of phthalates in the PCBs analysis, a sample of plastics chips derived from shredder residue was thoroughly mixed and then divided into four parts. The first part was analyzed by using Gas Chromatography and an Electron Capture Detector (GC-ECD) and by using Gas Chromatography/Mass Spectroscopy (GC/MS). The other three parts were spiked with different quantities of phthalates, as shown in Table 1, and the spiked samples were analyzed by using the same two methods. The results show no apparent interference of the phthalates in the PCBs analysis.

**Table 1.** Effect of phthalates on PCBs analysis

Weight-Percent of Phthalates added	PCBs Concentration (ppm) by GC/ECD	PCBs Concentrations (ppm) by GC/MS
0	4.6+/-0.3	7.9+/-1.0
0.5	4.7+/-0.3	7.4+/-0.2
1.0	5.1+/-0.6	7.0+/-0.4
2.5	4.8+/-0.3	7.4+/-0.3

To investigate the effects of plastics particle size on extraction efficiency of PCBs, a series of laboratory experiments were conducted at TPI on 300-g samples of plastics with two different particle sizes (one made of chips about 0.2 in. in size and the other was granulated to about 0.04 to 0.08 in. in size). Typically in PCBs analyses, extractions are done on a few grams of material, even though the dirt, oil, and the PCBs are not evenly distributed on the shredder residue plastics.

Samples of the plastics before and after washing were analyzed directly by three different laboratories by using standard PCBs analytical procedures. Extracts from nine sonications of 300-g samples were also analyzed for PCBs by three laboratories. The results show that (Tables 2–5):

1. The three labs are fairly consistent for each set of samples.
2. Direct analysis of the samples from the three labs showed that the concentration of PCBs in the granulated plastics was about 5 ppm, and for the un-granulated, it was 10 ppm. Obviously, the granulated samples have larger surface area per unit mass than the other samples. Therefore, more efficient extraction of PCBs from the plastics would be expected in the case of the granulated chips. Because this was not the case, the results indicate that the particle size does not affect the PCB results. Further, the results indicate that the PCBs are on the surface of the plastics and not absorbed in the plastics. After extraction, the samples all had less

than 2 ppm of PCBs, except for one sample that showed 2.8 ppm.

3. Calculation of the concentration of PCBs in the original samples based on the determined PCBs in the hexane extracts (prepared via 9 sonications of 300-g samples) showed that the concentrations of PCBs in the granulated samples were comparable with those of the un-granulated samples. These results further indicate that the PCBs are predominantly on the surface of the plastics and not absorbed in the plastics, otherwise the granulated samples would have shown higher concentrations.

In addition, 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. Each of these Aroclors consists of multiple congeners.

TPI also conducted an analysis of various plastics samples by using GC-ECD and GC-MS methods. The results are compared in Table 6. Results from the two methods are in reasonable agreement, even though the GC-MS method seems to consistently predict higher values.

### Evaluation of Soxhlet Method for PCBs Extraction

Successful commercialization of technology for recovering polymers and other materials from shredder residue depends on a reliable and inexpensive technique to analyze samples for PCBs in the recovered polymers in the field. The U.S. EPA and European protocols for PCBs analysis were reviewed and experiments were conducted to gain a good understanding of the requirements for reliable on-site analysis. A Soxhlet-based method appears to be appropriate for testing because of its simplicity and because it is among the methods specified in both the U.S. EPA protocols and in the European protocols (Table 7). Experiments to define the operating conditions for the Soxhlet method were conducted. The results are discussed below.

### Selection of a Solvent

Two solvents were tested: hexane and toluene. Three 120-g samples were extracted with hexane for 8 h, and another three 120-g samples were extracted with hexane for 24 hours. Similarly, three 120-g samples were extracted with toluene for 8 h, and another three 120-g samples were extracted with toluene for 24 hours. All extractions were carried out while maintaining the siphoning time at 8–10-min intervals. This procedure resulted in 24 samples of extracts and 12 samples of extracted plastics that were analyzed. The results are summarized in Table 8. The results indicate that hexane is a better solvent because it resulted in less PCBs remaining in the extracted plastics.

### Determination of Extraction Time

In addition to the experiments discussed above, three additional 120-g samples were extracted with hexane for 4 hours each. This procedure resulted in six samples of extracts and three samples of extracted plastics that were analyzed. The results are given in Table 8 and indicate that a Soxhlet extraction time of 4 hours is adequate because it reduced the PCBs concentration in the extracted plastics to below the detectable limits in two of the three samples and reduced it in the third to 1 ppm, even though these samples apparently had more PCBs initially, as evidenced by the higher level of PCBs in the solvent.

### Determination of Adequate Sample Size

In addition to the six 120-gram samples extracted for 24 hours discussed above, six additional 60-gram samples and six additional 30-g samples were processed and sampled in the same manner as before (24-hour extraction time and same siphoning intervals) by using hexane. The results are summarized in Table 9. The results indicate that a sample size of 30 g appears to be adequate.

Sample preparation was also investigated. The results indicated that a well-mixed plastics sample of at least one pound should be granulated to a size of

1 mm and mixed before sampling and analysis is done.

### Comparison of the U.S. EPA and the European Quantification Methods

Four of the extracts from the 120-g samples that were extracted with hexane for 24 hours and two of the 120-g samples that were extracted with hexane for 8 hours were also quantified by using the European method. The results were essentially identical within analytical errors (Table 10).

These results lead to the following conclusions:

1. A conventional Soxhlet extractor using hexane is effective for PCBs extraction from plastics.
2. A total extraction time of 4 hours with siphoning intervals of 8–10 min is adequate for complete extraction of the PCBs.
3. The EPA and the European quantification methodologies yield very close results.
4. This method is simple enough to be adopted for field applications.

### Publications

*Overview of Washing Systems for Commercial Cleaning of Plastics Separated from Automotive Shredder Residue*, Sendijarevic, I.; Sendijarevic, V.; Winslow, G.R.; Duranceau, C.M.; Simon, N.L.; Niemiec, S. F.; and Wheeler, C.S., SAE Paper No. 2005-01-0851.

*Screening Study to Evaluate Shredder Residue Materials*, Sendijarevec, V.; Simon, N.; Duranceau, C.; Winslow, G.; Williams, R.; Wheeler, C.; Niemiec, S.; and Schomer, D., SAE Paper No. 2004-01-0468.

### Keywords

PCBs, polychlorinated biphenyls, plastics, recycling, automotive materials, shredder residue.

**Table 2.** Concentration of PCBs (ppm) in plastics before and after extraction with hexane (granulated and ungranulated) — analysis by standard PCBs analysis procedures

	Aroclor 1232	Aroclor 1242	Aroclor 1254	Total
Designation	ppm	ppm	ppm	ppm
Laboratory #1				
Ungranulated before extraction	10.34 +/- 1.53	N/D	1.27 +/- 0.29	11.6 +/- 1.51
Ungranulated after extraction	1.06 +/- 0.32	N/D	0.07 +/- 0.01	1.13 +/- 0.32
Granulated before extraction	4.54 +/- 0.84	N/D	0.06 +/- 0.16	5.14 +/- 0.98
Granulated after extraction	0.54 +/- 0.33	N/D	0.07 +/- 0.01	0.60 +/- 0.34
Laboratory #2				
Ungranulated before extraction	N/D	8.69 +/- 1.02	N/D	8.69 +/- 1.02
Ungranulated after extraction	N/D	2.8 +/- 0.98	N/D	2.8 +/- 0.98
Granulated before extraction	N/D	5.31 +/- 2.04	N/D	5.31 +/- 2.04
Granulated after extraction	N/D	0.75 +/- 0.18	N/D	0.75 +/- 0.18
Laboratory #3				
Ungranulated before extraction	N/D	9.93 +/- 4.67	N/D	9.93 +/- 4.67
Ungranulated after extraction	N/D	1.57 +/- 0.17	N/D	1.57 +/- 0.17
Granulated before extraction	N/D	3.07 +/- 0.26	N/D	3.07 +/- 0.26
Granulated after extraction	N/D	0.68 +/- 0.27	N/D	0.68 +/- 0.27

**Table 3.** Concentration of PCBs in the ungranulated samples, as calculated from the analysis of the hexane solution extracts

	Aroclor 1232	Aroclor 1242	Aroclor 1254	Total
Designation	ppm	ppm	ppm	ppm
Laboratory #1				
Extract 1	8.67 +/- 0.87	N/D	1.02 +/- 0.29	9.69 +/- 0.99
Extract 2	4.59 +/- 1.52	N/D	0.28 +/- 0.05	4.86 +/- 1.49
Extract 3	0.51 +/- 0.09	N/D	0.14 +/- 0.01	0.65 +/- 0.10
<b>Total</b>	<b>13.76 +/- 2.47</b>	<b>N/D</b>	<b>1.43 +/- 0.34</b>	<b>15.19 +/- 2.57</b>
Laboratory #2				
Extract 1	N/D	7.62 +/- 0.58	N/D	7.62 +/- 0.58
Extract 2	N/D	1.44 +/- 0.04	N/D	1.44 +/- 0.04
Extract 3	N/D	0.62 +/- 0.04	N/D	0.62 +/- 0.04
<b>Total</b>	<b>N/D</b>	<b>9.67 +/- 0.65</b>	<b>N/D</b>	<b>9.67 +/- 0.65</b>
Laboratory #3				
Extract 1	N/D	6.56 +/- 0.67	N/D	6.56 +/- 0.67
Extract 2	N/D	1.52 +/- 0.23	N/D	1.52 +/- 0.23
Extract 3	N/D	0.64 +/- 0.03	N/D	0.64 +/- 0.03
<b>Total</b>	<b>N/D</b>	<b>8.71 +/- 0.92</b>	<b>N/D</b>	<b>8.71 +/- 0.92</b>

**Table 4.** Concentration of PCBs in the granulated samples, as calculated from the analysis of the hexane solution extracts

	Aroclor 1232	Aroclor 1242	Aroclor 1254	Total
Designation	ppm	ppm	ppm	ppm
Laboratory #1				
Extract 1	18.62 +/- 8.99	N/D	2.20 +/- 0.61	20.81 +/- 9.59
Extract 2	2.30 +/- 2.56	N/D	0.25 +/- 0.06	4.86 +/- 1.49
Extract 3	0.62 +/- 0.14	N/D	0.11 +/- 0.01	0.65 +/- 0.10
<b>Total</b>	<b>21.52 +/- 11.69</b>	<b>N/D</b>	<b>2.55 +/- 0.67</b>	<b>24.07 +/- 12.25</b>
Laboratory #2				
Extract 1	N/D	7.24 +/- 0.34	N/D	7.24 +/- 0.34
Extract 2	N/D	1.01 +/- 0.03	N/D	1.01 +/- 0.03
Extract 3	N/D	0.42 +/- 0.03	N/D	0.42 +/- 0.03
<b>Total</b>	<b>N/D</b>	<b>8.67 +/- 0.40</b>	<b>N/D</b>	<b>8.67 +/- 0.40</b>
Laboratory #3				
Extract 1	N/D	6.29 +/- 1.98	N/D	6.29 +/- 1.98
Extract 2	N/D	1.10 +/- 0.06	N/D	1.10 +/- 0.06
Extract 3	N/D	0.48 +/- 0.03	N/D	0.48 +/- 0.03
<b>Total</b>	<b>N/D</b>	<b>7.87 +/- 2.06</b>	<b>N/D</b>	<b>7.87 +/- 2.06</b>

**Table 5.** Comparison of PCBs concentration (ppm) in the starting plastics samples by direct analysis and by calculation based on the amounts in the hexane extracts

Plastics Sample	PCB Concentration by Direct Analysis	PCB Concentration Calculated from PCBs in the Hexane Extracts
Ungranulated, Lab-1	11.6 +/- 1.51	15.19 +/- 2.57
Ungranulated, Lab-2	8.69 +/- 1.02	9.67 +/- 0.65
Ungranulated, Lab-3	9.93 +/- 4.67	8.71 +/- 0.92
Granulated, Lab-1	5.14 +/- 0.98	24.07 +/- 12.25
Granulated, Lab-2	5.31 +/- 2.04	8.67 +/- 0.4
Granulated, Lab-3	3.07 +/- 0.26	7.87 +/- 2.06

**Table 6.** Comparison of PCBs analysis using GC-ECD and GC-MS methods (extraction was carried out using hexane at 2,000 PSIA and 100°C)

Sample Type	PCB Concentration, Using GC-ECD (ppm)	PCB Concentration, Using GC-MS (ppm)
Ungranulated Chips	7.55	9.67
Ungranulated Chips	3.70	5.07
Ungranulated Chips	1.50	3.3
Ungranulated Chips	1.35	2.66
Granulated Chips	7.56	9.37
Granulated Chips	0.93	1.82
Granulated Chips	0.82	2.11
Hexane Solution	9.93	9.50
Hexane Solution	8.3	11.13
Hexane Solution	1.41	1.72
Hexane Solution	0.78	0.92
Hexane Solution	0.53	0.65

**Table 7.** Protocols for PCBs analysis

Parameter	European Protocols	U.S. EPA's Protocols	Recommended Protocols
Particle size (mm)	0.5	Not specified	1
Sample size for extraction (g)	3	30	30
Extraction equipment	Soxhlet	Sonication Soxhlet Pressurized fluid	Soxhlet
Extraction time	Not specified	Not specified	>= 4 h Siphoning cycles at 8-10-min intervals
Solvent	Toluene	Hexane 50/50 Hexane/acetone 50/50 Methylene chloride/acetone	Hexane
Analytical method	MS	GC/ECD MS	MS
Quantification method	6 congeners multiplied by 5	Aroclors	Aroclors

**Table 8.** Results of the extractions of the 120-g samples with hexane and toluene

Solvent	Extraction Time (h)	Average PCBs in Extract (ppm)	Standard Deviation (ppm)	Average PCBs in Extracted plastics (ppm)	Standard Deviation (ppm)
Hexane	24	9.4	1.5	N.D	0
Hexane	8	9.3	0.8	N.D.	0
Toluene	24	9.8	2.4	1.4	0.2
Toluene	8	9.7	0.9	3.0	0.6
Hexane	4	14.5	2.9	N.D. in samples no. 1 and 2; 1.0 in no. 3	1.0

**Table 9.** Results of the 24-h extractions with hexane of different size samples

Sample size (g)	Average PCBs in Extract (ppm)	Standard Deviation (ppm)	Average PCBs in Extracted Plastics (ppm)	Standard Deviation (ppm)
30	10.8	1.9	N.D	0
60	25.5	12.6	N.D.	0
120	9.4	1.5	N.D.	0

**Table 10.** Comparison of the U.S. EPA and the European quantification methods

Extraction Time (h)	PCBs According to the EPA Method (ppm)	PCBs According to the European Method (ppm)
24	10.8	9.8
24	9.8	10.9
24	8.0	10.7
24	11.2	11.5
8	11.7	12.3
8	10.8	10.8

## E. Compatibilization/Compounding Evaluation of Recovered Polymers

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

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### **Objectives**

- Evaluate the market opportunity for polymers recovered from shredder residue.
- Identify limitations associated with the reuse of the materials as recovered and determine the need for post-processing 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.
- Determine properties of recovered polymers.
- Conduct blending and pelletizing trials of the recovered polymers.
- Conduct mold trials using recovered polymers.

### **Accomplishments**

- Molded auto parts using recovered PP/PE.
- Conducted blending and pelletizing trial.

- Determined physical properties of polypropylene/polyethylene (PP/PE) recovered from shredder residue. Found that PP/PE recovered by the Argonne process and the Salyp (sink/float) process and recovered in U.S. field trials exhibit equivalent physical properties that are reasonably consistent with those of many virgin PP formulations and co-polymers.
- Compiled a database of physical properties of virgin polymers for comparison with the physical properties of recovered plastics.
- Established a test protocol for material testing, content characterization, and physical properties testing of polymeric materials.

### **Future Direction**

- Continue physical properties testing of recovered polymers.
- Evaluate the market potential for clean mixed plastics streams recovered from shredder residue.
- Update the database of properties of recovered polymers vis-à-vis general purpose virgin polymers.
- Identify candidate automotive applications for recovered polymers.
- Conduct more blending, pelletizing, compounding, and mold trials by 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 10–15 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 about 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.

Physical properties testing has been conducted by Midland Compounding, Inc. Midland also conducts composition testing, the results of which are compared with the results of compositional analysis done on recovered materials by Argonne.

Blending and pelletizing of the PP/PE recovered from shredder residue by Argonne has been tested by Palmer Plastics, Inc. More blending and compounding tests will be done, as required, to achieve the desired performance properties of the recovered materials for target applications.

Mold trials using the recovered PP/PE were also done by MGV Enterprises. More molding tests are planned to confirm the technical and economic feasibility of using recycled polymers in specific applications.

Three additional companies — Collins and Aikman Corporation, Enviro-Plas Corporation, and Mayco Plastics, Inc. — have agreed to evaluate, compound, and run mold trials by 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 used to define physical properties and to characterize the composition of the material.

To quantify the physical properties of the recovered material, a 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 by using infrared spectroscopy.

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.

The physical properties of PP/PE recovered from different shredder residues by Argonne and by Salyp were determined for several samples. The results for the Argonne materials are given in Table 1. Properties of commercially available PP and PE virgin resins and for PP from dismantled automobiles are presented in Table 2 for comparison. The Izod impact of the recovered material is about three times that of the virgin resins, while the tensile strength of the recovered material is lower than the tensile strength of the virgin resins by about 30%. This phenomenon may be attributed, at least in part, to the presence of thermoplastic olefins (TPO) and rubber in the recovered material, which act as impact modifiers. Recovered samples 8, 9, and 10 listed in Table 1 contained about 2% rubber, while samples 1 through 7 contained about 4% rubber.

The results for the more than 20 PP/PE samples recovered by Salyp from different European and U.S. shredder residues are given in Table 3. The properties of the Salyp recovered PP/PE are equivalent to the properties of the Argonne-recovered PP/PE.

### **Polymer Physical Properties Database**

A physical properties database has been compiled so that the physical properties of the recovered polymers can be compared with general purpose virgin polymers.

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

- ABS,
- Nylon (6 cast, 6/6 extruded, 30% glass filled),

- PPO [polyphenylene oxide] (unfilled, 30% glass filled),
- Polycarbonate,
- Polyethylene, low-density polyethylene [LDPE], high-density polyethylene [HDPE], ultra-high-molecular-weight [UHMW] polyethylene,
- Polypropylene,
- Polystyrene (general purpose, high impact), and
- Polyvinyl chloride (PVC).

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. The data from these polymers will also be included in the database so that the physical properties of materials recovered by disassembly can be compared with those of materials that are recovered from post-shred operations.

### **Blending and Pelletizing of Recovered PP/PE**

Two hundred fifty pounds of PP/PE recovered by Argonne were blended with 750 lb of supplemental PP copolymer regrind for 15 minutes. The blended material was then run through an extruder and pelletized. The general appearance of the final pellet was excellent (Figure 1). Properties of the recovered material used in blending and the properties of the regrind and of the resulting pellets are shown in Table 4. Standard pelletizing conditions were used. Barrel heats were set from 365°F at the rear barrel zone and increased progressively to 390°F at the front, with six heat zones in between. Screen changer and breaker plate heats were set at 405°F, and die heats were set at 395°F. Melt temperature was recorded as 460°F, and drive load and screw speed were set at 60% and 67.5% of the maximum values, respectively. Material output was recorded as 1,400 lb/h. Extra fine screen packs were used (20/20/20/60/100/20 mesh screens) to remove impurities because this was the first time this material has been tried.

In addition, while screen changes are typically performed at pressure differences between 500 psi and 1,000 psi, in this test,

changes were performed when the pressure exceeded 500 psi to safeguard against puncturing a screen pack and losing material. Because extra fine screen packs were used in the test, screen changes were required approximately every five minutes. The results indicated that the recovered PP/PE can be blended with other olefinic regrind and pelletized by using standard processes and equipment.

### **Mold Trials**

Three types of auto parts were molded by MGV Enterprises by using Argonne-recovered PP/PE from shredder residue: knee bolsters, battery trays, and steering column covers (Figure 2). A standard molding machine was used in these trials (Figure 3). No changes to the standard conditions were required to run the recovered material. The limited testing done on the recovered PP/PE fraction shows that quality products, including auto parts, may be produced from the recovered materials. Additives and/or modifiers may be added to meet the specifications of some products.

### **Recovered Rubber/Plastics Material**

A mixed-rubber fraction with about 20% by weight mixed plastics was recovered. A sample of the recovered material was sent for testing by the "TireCycle" process used for recycling rubber. Preliminary tests done on the recovered material indicated that it may be suitable for making construction products, such as roofing shingles. The presence of the plastics in the mixed-rubber material appeared to improve its overall properties, especially its stiffness.

**Table 1.** Properties of PP/PE recovered by Argonne from different shredder residues

Property	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Average
MFR, g/10min, 230°C, 2.16 kg	10.5	14.9	7.7	10.1	11.4	7.2	8.7	7.2	8.7	7.2	9.4
Izod impact, ft-lb/in., 73°F	12.3	10.5	11.9	10.8	9	10.7	13.2	1.7	2.8	3.3	8.6
Flex mod., 1% secant, 1,000 psi	83	73	89	84	82	101	112	126	127	113	99.0
Tensile strength at yield, 1,000 psi	2.6	2.2	2.7	2.6	2.4	2.8	3.1	3.4	3.3	3.1	2.8
Tensile strength at rupture, 1,000 psi	0.8	1.2	2.1	1.9	1.4	2.5	2.0	3.1	3.1	2.9	2.1
Elongation at yield, %	23.0	20.8	21.1	22.8	20.6	20.6	17.1	**	**	**	24.3
Elongation at rupture, %	132	78	233	154	82	251	229	12	14	13	119.8
DTUL, 66 psi, °F	131	131	134	134	138	147	155	**	171	160	145
Gardner impact, 73°F, in.-lb	104	88	136	96	56	144	184	20	32	40	90.0
SG, g/cc	0.94	0.95	0.94	0.95	0.94	0.93	0.93	0.94	0.94	0.94	0.94

\*\* Not tested

**Table 2.** Comparison of recovered PP/PE with commercial grades of PP & PE (Boedeker) (<http://www.boedeker.com/mtable.htm>), unless specified otherwise.

Property	PP-Homo Polymer	PP-Co Polymer	PP-FR	Dismantled PP**	Standard PP-Co	LDPE	HDPE
MFR, (g/10 min), 230°C	0.5-136*			17			
Izod impact, ft-lb/in.	1.9	7.5	0.65	1.8	0.7	No Break	3
Flex Mod, 1,000 psi	180	160	145	131.9	120	200	125
Tensile Strength, 1,000 psi	4.8	4.8	4.3	3.1	5.2	2.0	4.6
Elongation, %	12	23	28	18	600	600	900
DTUL, °F @66 psi	210	173	106	136.5	210	110	--
SG, g/cc	0.905	0.897	0.988		0.90	0.92	0.95
Gardner impact, 73°F, in.-lb	0.9-22*						

\* Data from [http://www.ed-cam.com/materials/propylene\\_molded.asp](http://www.ed-cam.com/materials/propylene_molded.asp). Ranges are for with and without additives.

\*\* Gallmeyer, W.W.; Duranceau, C.M.; Williams, R.L.; and Winslow, G.R., USCAR U.S. Field Trial for Automotive Polymers Recycling, SAE paper # 2003-01-0645, 2003.

**Table 3.** Properties of PP/PE recovered by Salyp from different shredder residues

<b>Property</b>	<b>Salyp Data</b>
MFR (g/10 min), 230°C	2.3–4.6
Izod impact (ft-lb/in.) 73°F	4.7–13.3
Flex mod., 1%, secant, 1,000 psi	81.7–116.5
Tensile strength at yield, 10,00 psi	2.4–2.9
Tensile strength at rupture, 1000 psi	2.2–2.8
Elongation at rupture, %	19–57
DTUL, 66 psi, °F	150–169
Gardner impact, 73°F, in.-lb	190–240
SG, g/cc	0.93

**Table 4.** Properties of recovered PP/PE when mixed with regrind

<b>Property</b>	<b>Argonne, As Recovered Sample 9 (see Table 1)</b>	<b>Regrind, As Is</b>	<b>Pelletized Blend</b>
MFR (g/10 min), 230°C	8.7	3.1	9.2
Izod impact (ft-lb/in.) 73°F	2.8	13.6	10.4
Flex mod., 1%, secant, 1,000 psi	127	157	136
Tensile strength at yield, 1,000 psi	3.3	3.7	3.4
Tensile strength at rupture, 1,000 psi	3.1	2.9	2.3
Elongation at rupture, %	14	125	57
DTUL, 66 psi, °F	171	197	176
Gardner impact, 73°F, in.-lb	32	>320	132
SG, g/cc	0.94	0.91	0.92

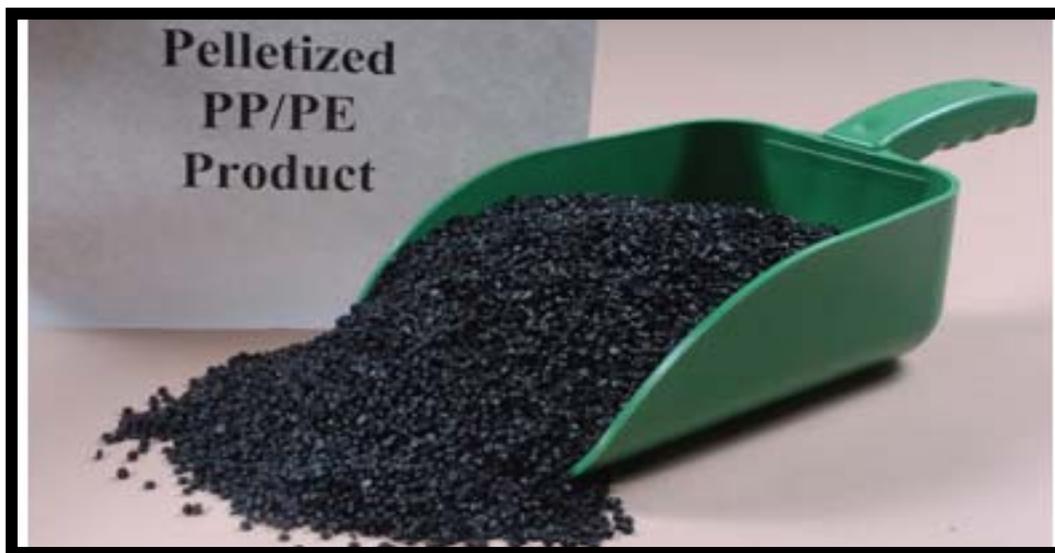


Figure 1. Pelletized PP/PE product recovered from shredder residue.

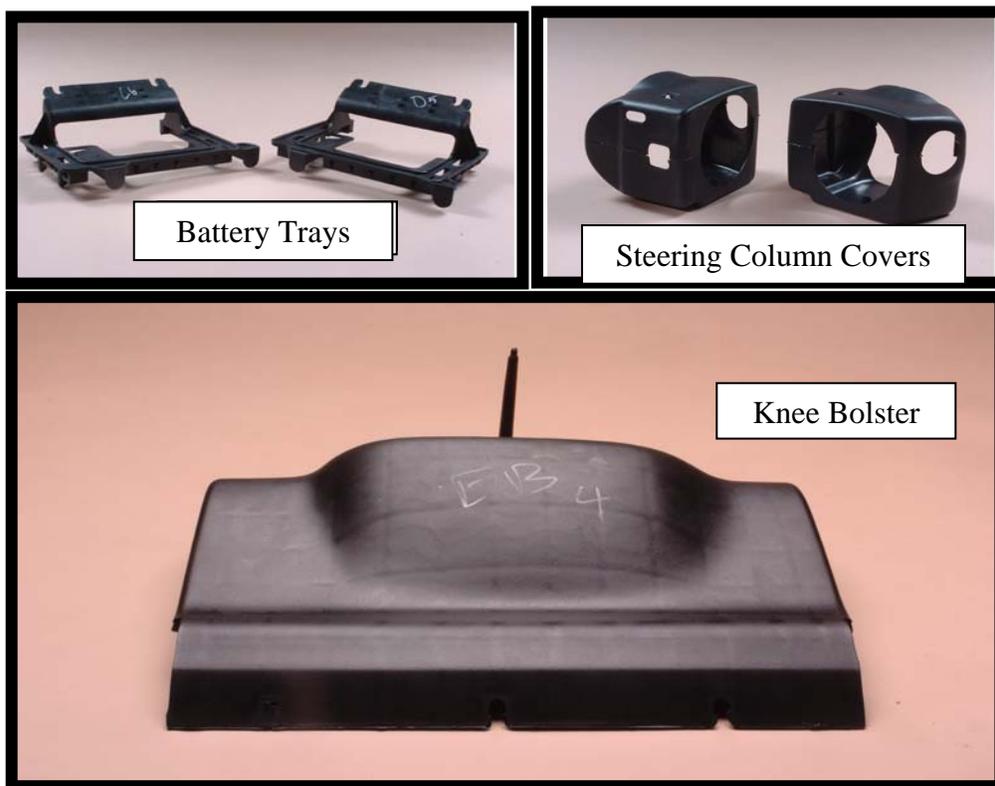


Figure 2. Auto parts molded from PP/PE recovered from shredder residue.



**Figure 3.** Standard molding machine used in molding auto parts using recovered PP/PE.