

# **Recycling End-of-Life Vehicles of the Future**

---

**Energy Systems Division**

**About Argonne National Laboratory**

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see [www.anl.gov](http://www.anl.gov).

**Availability of This Report**

This report is available, at no cost, at <http://www.osti.gov/bridge>. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy

Office of Scientific and Technical Information

P.O. Box 62

Oak Ridge, TN 37831-0062

phone (865) 576-8401

fax (865) 576-5728

[reports@adonis.osti.gov](mailto:reports@adonis.osti.gov)

**Disclaimer**

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

## **Recycling End-of-Life Vehicles of the Future**

---

prepared for  
Office of Technology Transfer, Argonne National Laboratory

prepared by  
B.J. Jody, J.A. Pomykala, Jr., J.S. Spangenberg, and E.J. Daniels  
Energy Systems Division, Argonne National Laboratory

December 1, 2009



# CONTENTS

1	INTRODUCTION .....	1
1.1	Background .....	1
1.2	Objective .....	1
1.3	Approach .....	1
1.4	Scope .....	2
2	TASK 1. BASELINE TECHNOLOGY ASSESSMENT AND INFRASTRUCTURE ANALYSIS .....	3
2.1	Review Report on the State of the Art .....	3
2.2	Bibliography of Relevant Publications .....	5
2.3	Life-Cycle Analysis Studies .....	6
2.4	Recyclability Calculations .....	8
2.5	Website Development and Launching .....	12
2.6	Infrastructure Analysis .....	12
3	TASK 2. MATERIAL RECOVERY TECHNOLOGY DEVELOPMENT AND DEMONSTRATION .....	14
3.1	Post-Shred Materials Recovery Technology Demonstration and Development .....	14
3.1.1	Characterization of Shredder Residue .....	15
3.1.2	Argonne Pilot Plant .....	16
3.1.2.1	Mechanical Separation Pilot Facility .....	17
3.1.2.2	Wet Density/Froth Flotation Facility .....	18
3.1.3	Recovered Fractions from Pilot Plant Operation .....	20
3.1.3.1	Recovered Polyethylene/Polypropylene (PP/PE) Fraction .....	20
3.1.3.2	Separation of Wood and Rubber from the Recovered PP/PE .....	21
3.1.3.3	Filled ABS Fraction .....	21
3.1.3.4	Unfilled ABS and PS .....	22
3.1.3.5	PC-ABS/PC Alloy .....	22
3.1.3.6	PVC .....	22
3.1.3.7	Rubber .....	22
3.1.4	Development of a Large-Scale Validation Plant .....	22
3.1.5	Benchmarking and Evaluation of Other Technologies .....	23
3.1.5.1	Evaluation of Color and Infra-Red (IR) Sorters .....	23
3.1.5.2	Processing of Polymer Concentrate at MBA Polymers .....	23
3.1.5.3	Changing World Technologies (CWT) .....	23
3.1.5.4	Troy Polymers Glycolysis Process (TPI) .....	24
3.1.5.5	Energy Anew Recycling of Fines .....	24
3.1.5.6	Co-Combustion of Plastics Containing Material with Biomass .....	24
3.2	Development of Technology for Removal of PCBs and Other Toxics from Shredder Residues .....	25
3.2.1	Bench-Scale Testing .....	25

## CONTENTS (CONT.)

3.2.2	Testing of Commercially Available Equipment .....	26
3.2.3	Testing of Proprietary Processes.....	26
3.2.4	Testing of Other Potential Routes.....	26
3.2.5	Testing a Devolatilization Process with a Vacuum Extruder .....	26
3.2.6	Development of a New Process at Argonne .....	29
3.2.7	Evaluation of the Variability of PCB Sampling and Analytical Procedures .....	30
3.2.7.1	Evaluation of Soxhlet Method for PCBs Extraction.....	32
3.2.7.2	Selection of a Solvent .....	33
3.2.7.3	Determination of Required Extraction Time .....	33
3.2.7.4	Determination of Adequate Sample Size.....	34
3.2.7.5	Comparison of the U.S. EPA and the European Quantification Methods.....	34
3.3	Integration of the Technologies .....	35
3.4	Improvements to Dismantling Process .....	35
4	TASK 3. RECOVERED MATERIAL PERFORMANCE AND MARKET EVALUATION.....	39
4.1	Polymer Physical Properties and Materials Composition Analysis.....	39
4.1.1	Physical Properties and Composition of the PP/PE Recovered from Shredder Residue .....	40
4.1.2	Physical Properties and Composition of the Recovered Filled ABS.....	42
4.1.3	Physical Properties of the Polymers Recovered by MBA Polymers .....	42
4.1.4	Physical Properties of Polymers after Processing to Remove the PCBs .....	42
4.2	Polymer Physical Properties Database.....	42
4.3	Recovered Rubber/Plastics Material.....	46
4.4	Blending and Pelletizing of Recovered PP/PE .....	46
4.5	Molding Trials .....	47
5	TASK 4. CRADA REPORTING.....	48
6	CRADA TEAM PUBLICATIONS .....	49

## FIGURES

1	Impact Categories of the Argonne Plant.....	7
2	Infrastructure of the Automotive Recycling Industry in the United States .....	13
3	Picture of Typical Shredder Residue Samples.....	15
4	Picture of Argonne’s Mechanical Separation Facility .....	17
5	Sequence of Operation of the Basic Mechanical Separation Plant.....	18
6	Product Fractions from the Mechanical Separation Plant.....	18
7	A Picture of the Original Wet Density/Froth Flotation Facility .....	19
8	Sequence of Operation of the Basic Mechanical-Separation Plant .....	19
9	Flotation Characteristics of Shredder Residue Polymers based on Density Gradients .....	21
10	Extruder with Die and Vacuum Knockout Pot Used in the Devolatilization Testing .....	27
11	Experimental Apparatus for Testing the Argonne Two-Stage Process .....	29
12	Pelletized PP/PE Product Recovered from Shredder Residue.....	46
13	Auto Parts Molded from PP/PE Recovered from Shredder Residue.....	47

## TABLES

1	Comparison of the Argonne and Salyp Processes — Relative Environmental Impact .....	8
2	Comparison of the Argonne and CWT Processes — Relative Environmental Impact .....	8
3	Materials Breakdown for 2004 Toyota Prius.....	9
4	Materials Breakdown for 2004 Ford Taurus.....	10
5	Reference Case Recyclability: 2004 Toyota Prius.....	10
6	2004 Toyota Prius Recyclability, Reference Case vs. Aluminum and Composite Body Materials .....	11

**TABLES (CONT.)**

7	Streams Produced by Mechanical Separation of an Average Shredder Residue.....	16
8	Composition of an Average Polymer Concentrate and Recovered Polymer Fractions .....	20
9	PCBs and Impact Test Results from Vacuum Devolatilization Testing.....	28
10	Physical Test Results with Water and Water/Ethylene Glycol (50:50) Addition.....	28
11	Results of Argonne’s Two-Stage PCB Removal Process.....	30
12	Effect of Phthalates on Analysis of PCBs.....	31
13	PCBs Analysis by GC-ECD and GC-MS .....	32
14	Protocols for PCBs Analysis.....	33
15	Comparison of the U.S. EPA and the European Quantification Methods .....	34
16	Properties of PP/PE Recovered by Argonne from Different Shredder Residues .....	40
17	Commercial Grades of PP and PE, Unless Specified Otherwise.....	41
18	Properties of PP/PE Recovered by Salyp from Different Shredder Residues .....	41
19	Properties of Recovered Filled ABS, Virgin ABS, and Blends of the Two Materials .....	43
20	Properties of Plastics Recovered by MBA.....	43
21	Impact Test Results from Vacuum Devolatilization Testing.....	44
22	Comparison of the Properties of PP Dismantled of Cars as Part of the USCAR U.S. Trial with PP Recovered by the Argonne Process from Shredder Residue.....	45
23	Properties of Recovered PP/PE when Mixed with Re grind.....	45

# 1 INTRODUCTION

## 1.1 BACKGROUND

Argonne National Laboratory (the Contractor) entered into a Cooperative Research and Development Agreement (CRADA) with the following Participants: Vehicle Recycling Partnership, LLC (VRP, which consists of General Motors [GM], Ford, and Chrysler), and the American Chemistry Council – Plastics Division (ACC-PD). The purpose of this CRADA is to provide for the effective recycling of automotive materials.

The long-term goals are to (1) enable the optimum recycling of automotive materials, thereby obviating the need for legislative mandates or directives; (2) enable the recovery of automotive materials in a cost-competitive manner while meeting the performance requirements of the applications and markets for the materials; and (3) remove recycling barriers/reasons, real or perceived, to the use of advanced lightweighting materials or systems in future vehicles. The issues, technical requirements, and cost and institutional considerations in achieving that goal are complex and will require a concerted, focused, and systematic analysis, together with a technology development program.

The scope and tasks of this program are derived from “A Roadmap for Recycling End-of-Life Vehicles of the Future,” prepared in May 2001 for the DOE Office of Energy, Efficiency, and Renewable Energy (EERE)-Vehicle Technologies Program.

## 1.2 OBJECTIVE

The objective of this research program is to enable the maximum recycling of automotive materials and obsolete vehicles through the development and commercialization of technologies for the separation and recovery of materials from end-of-life vehicles (ELVs). The long-term goals are to (1) enable the optimum recycling of automotive materials, thereby obviating the need for legislative mandates or directives; (2) enable the recovery of automotive materials in a cost-competitive manner while meeting the performance requirements of the applications and markets for the materials; and (3) remove recycling barriers/reasons, real or perceived, to the use of advanced lightweighting materials or systems in future vehicles.

## 1.3 APPROACH

Argonne has been conducting research directed toward the development of cost-effective technologies to facilitate automotive materials recycling under sponsorship of the U.S. Department of Energy since the early 1990s. The VRP had established an Engineering Project Oversight Committee (EPOC), which represented a consolidation of the former three VRP Operating Groups, which were (1) the Shredder Residue Group, (2) the Disassembly Group, and (3) the Design Guidelines Group. The ACC-PD (formerly called American Plastics Council [APC]) is also actively engaged in various aspects of automotive and other plastics

recycling. This CRADA coordinated the various research activities of the respective organizations to ensure that the work complements current research and to maximize the benefits relative to committed funding of each organization. The CRADA partners have identified key technology gaps, conducted research to address these gaps, and determined the technical and economic feasibility of the various technologies needed to fill those gaps.

## **1.4 SCOPE**

The scope of the research encompassed the following items: (1) examination of the issues and factors that prevent total recycling of scrap cars; (2) identification of desirable but undeveloped or unavailable technology that, if successfully developed and implemented, would enable recycling of components of scrap cars that are not recycled at present; (3) development and demonstration of separation technologies to recover materials and resources from automotive shredder residue; (4) examination of options for design modifications that could provide for more effective disassembly of components for recycling; and (5) examination of alternative materials to increase materials recycling. The effort conducted under this CRADA consisted of four key tasks:

- Task 1. Baseline Technology Assessment and Infrastructure Analysis
- Task 2. Material Recovery Technology Development and Demonstration
- Task 3. Recovered Material Performance and Market Evaluation
- Task 4. CRADA Reporting

The progress achieved on these Tasks is discussed in Sections 2–4. Section 6 lists the publications resulting from this work.

## **2 TASK 1. BASELINE TECHNOLOGY ASSESSMENT AND INFRASTRUCTURE ANALYSIS**

The objective of this task was to establish the baseline or state of the art for automotive materials recovery/recycling technology. More specifically, this task involved (1) benchmarking the automotive materials recycling industry and (2) compiling information on the status of existing and emerging recycling technology and research in an accessible format. The focus of the work under this task was to (1) develop the tools and document the information necessary to make effective decisions relative to technology needs to facilitate sustainable future vehicle recycling and (2) make effective decisions regarding allocation of R&D resources. The following main products resulted from this task:

- Report reviewing the state of the art,
- An annotated bibliography of relevant publications,
- Life-cycle analysis studies,
- Recyclability calculations,
- A website for dissemination of information to the automotive recycling community, and
- Infrastructure analysis.

### **2.1 REVIEW REPORT ON THE STATE OF THE ART**

We reviewed the state of the art of worldwide automotive materials recovery/recycling technologies and associated resource recovery infrastructures to identify available technologies, technologies under development, and technology gaps and needs and to identify differences in automotive recycling strategies between the United States, 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 thermochemical conversion technologies. Promising technologies that need further development and/or demonstration to fully understand the technical and economic feasibility of the technology were identified. Conclusions of the study are summarized below.

1. The complexity of the composition of shredder residue, the entanglement of its numerous constituents, and the substances of concern that it contains hamper efforts to recover materials from it for reuse.

2. The lack of sustainable markets for materials that could be recovered from shredder residue (such as plastics) is an additional hurdle to overcome.
3. Despite the difficulties stated in items 1 and 2, several technologies have reached an advanced stage of development. The two areas that received most attention are:
  - Recovery and recycling of polymers and
  - Conversion to fuels and energy.
4. The consensus among many of the workers in this field is that organic material must be separated from the inorganic material in shredder residue through some degree of bulk mechanical separation before technologies to separate and recover polymers or to convert the shredder residue to fuels can be implemented.
5. A pre-separated fraction of shredder residue has been used in many places as a landfill cover.
6. Several separation technologies have been tested for possible application to automotive materials. Mechanical separation technologies have been able to separate the mostly inorganic fines and residual ferrous and non-ferrous metals from shredder residue and produce a polymer concentrate.
7. Polymer separation technologies (such as froth flotation) have successfully separated and recovered the polyolefins and engineered plastics (such as acrylonitrile-butadiene-styrene, or ABS) from the polymer concentrate. Dry and wet processes can also recover a mixed-rubber fraction.
8. Gasification, pyrolysis, and depolymerization/hydrolysis processes proved that diesel-grade and other fuels can be produced from shredder residue.
9. The organic fraction of shredder residue has been showing promising results as a reducing agent (as well as an energy source) when used in blast furnaces.
10. In spite of recent technical advancements, essentially all of the about 5 million tons of shredder residue generated every year in the United States is disposed of in landfills. In Europe and Japan, some of shredder residue is disposed of by incineration. The primary reason for incineration is that available recycling technologies are not economical.
11. Recently proposed regulations (most of which are not implemented) in Europe have increased interest in developing recycling technologies for shredder residue. However, economic drivers are likely to continue to lead the way to successful implementation of the recycling technologies.

12. In the United States, developing reliable and economic technologies for removing the polychlorinated biphenyls (PCBs) is necessary for recycling the automotive polymers.
13. An economical solution to recycling shredder residue is likely to be an integrated system of many technologies to produce quality products at the lowest cost.

The report is posted on the CRADA team website and can be accessed at [http://www.es.anl.gov/Energy\\_systems/CRADA\\_Team\\_Link/publications/Recycling\\_Report\\_\(print\).pdf](http://www.es.anl.gov/Energy_systems/CRADA_Team_Link/publications/Recycling_Report_(print).pdf)

## **2.2 BIBLIOGRAPHY OF RELEVANT PUBLICATIONS**

An extensive literature search was conducted, and summaries and publications and profiles of available and emerging recycle technologies were compiled into a working document that was updated as new information became available. The bibliography is an expandable PDF that provides abstracts and references to publications relevant to the recycling of ELVs. It has 240 entries and is organized into the following 17 sections.

- Recycle Infrastructure
- Legal and Regulatory Issues
- Disassembly Technologies and Case Studies
- Reuse of Automotive Parts and Subassemblies
- Recycling Case Studies
- Mechanical Separation Technology
- Thermo-Chemical Conversion Technology
- Advanced Materials Recycle Technology
- Environmental Issues
- Design for Recycle
- Research Programs
- Remanufacturing
- Substances of Concern
- Life Cycle Analysis
- Lightweighting Metals
- Energy Recovery Technology
- Other Technology

The bibliography is posted on the US ELV CRADA Team website: [http://www.es.anl.gov/Energy\\_systems/CRADA\\_Team\\_Link/Index.html](http://www.es.anl.gov/Energy_systems/CRADA_Team_Link/Index.html) and can be accessed at [http://www.es.anl.gov/Energy\\_systems/CRADA\\_Team\\_Link/recycle\\_bibliography/Recycle%20Reference%2001-31-09%20web%20version.pdf](http://www.es.anl.gov/Energy_systems/CRADA_Team_Link/recycle_bibliography/Recycle%20Reference%2001-31-09%20web%20version.pdf)

## 2.3 LIFE-CYCLE ANALYSIS STUDIES

The objective is to use life-cycle analysis to assess the environmental impacts of various separation 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 analysis 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.

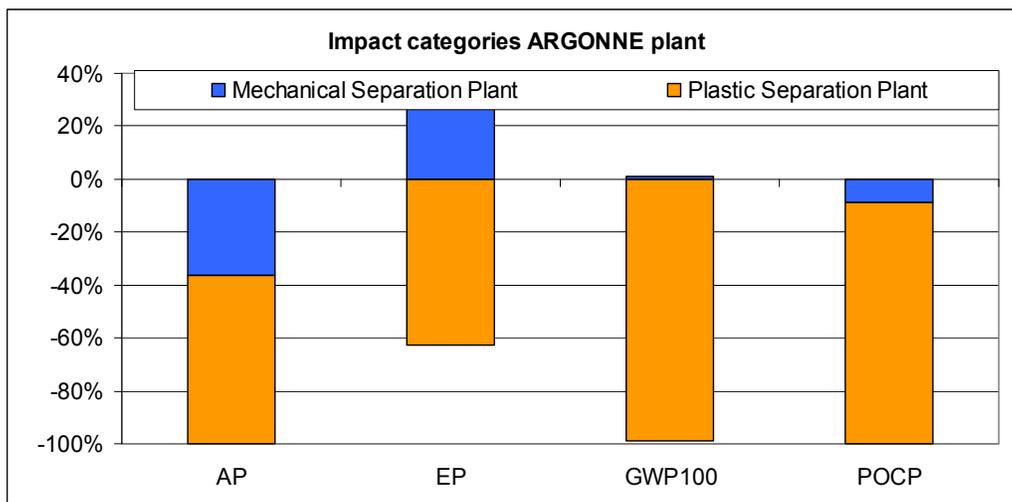
PE Europe GmbH, a company that is experienced in conducting life-cycle assessments and in model development using its own GaBi (Ganzheitliche Bilanzierung) software, was contracted to perform these analyses. Four analyses have been completed for (1) Salyp NV's mechanical separation process, (2) Changing World Technologies' (CWT's) thermal conversion process, (3) Argonne mechanical and froth flotation process, and (4) automotive recycling infrastructure analysis. Data were collected for each of the analysis, including all energy, water, and material inputs, plus data on emissions to air and water, wastes, and products produced. The four sets of data were entered into the GaBi software to create a flexible model of the process. PE Europe developed a flexible end-of-life model, and the model was used to compare the 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

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 polypropylene/polyethylene (PP/PE) in a new PP application yielded the greatest benefit. However, if the mixed plastic stream was used to replace wood (e.g., decking material, park benches, wood pallets, and other products), 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 resulted in the greatest benefit. Substituting PP for wood applications was next with a lower benefit, while the energy recovery scenario showed an increase in CO<sub>2</sub> emissions.

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. All scenarios showed a reduction in CO<sub>2</sub> emissions. However, in terms of CO<sub>2</sub> emissions, the diesel substitution case had a greater benefit than the fuel oil substitution case.

Life-cycle analysis of the Argonne process considered both the mechanical separation of the shredder residue to produce a polymer concentrate and recover residual metals, followed by froth flotation to separate plastics from the polymer concentrate for recycling as plastics (material substitution). The report is available at the CRADA team website.<sup>1</sup> The analysis concluded that both the mechanical and the froth flotation processes resulted in environmental benefits (Figure 1). The environmental benefits of the Argonne process were also compared with those of Salyp (Table 1) and CWT processes (Table 2). The environmental benefits associated with the Argonne process are greater than those for the Salyp process (except for the acidification potential) and for the CWT process (except for the impact category EP and NO<sub>x</sub> emissions). In terms of energy use, the Argonne process was the most advantageous. Interestingly, the analyses concluded that the best results can be obtained by combining both the Argonne and CWT processes, in which the organic fractions separated by Argonne that do not meet the requirements for material substitution (such as mixed plastics and rubber by-products) are processed by CWT for fuel production.



**FIGURE 1 Impact Categories of the Argonne Plant. (AP is acidification potential, EP is eutrophication [depletion of oxygen in water] potential, GWP is global warming potential, and POCP is photochemical ozone creation potential). (Y axis indicates impact.)**

<sup>1</sup> [http://www.es.anl.gov/Energy\\_systems/CRADA\\_Team\\_Link/publications/Final%20Report\\_ANL%20LCA%20report\\_09292006.pdf](http://www.es.anl.gov/Energy_systems/CRADA_Team_Link/publications/Final%20Report_ANL%20LCA%20report_09292006.pdf).

**TABLE 1 Comparison of the Argonne and Salyp Processes — Relative Environmental Impact. (A negative value indicates a reduction in the pollution category [an environmental benefit], while a positive value indicates an increase in the pollution category.)**

Parameter <sup>a</sup>	Argonne Process (mechanical and froth flotation)	Salyp Process
AP (lb SO <sub>2</sub> -equivalent)	-0.0060	-0.0165
EP (lb phosphate-equivalent)	-0.00011	0.00148
GWP100 (lb CO <sub>2</sub> -equivalent)	-1.354	0.861
POCP (lb ethene-equivalent)	-0.0026	0.0126

<sup>a</sup> AP is acidification potential, EP is eutrophication (depletion of oxygen in water) potential, GWP is global warning potential, and POCP is photochemical ozone creation potential

**TABLE 2 Comparison of the Argonne and CWT Processes — Relative Environmental Impact. Both processes require mechanical separation of the inorganic fraction. (A negative value indicates a reduction in pollution category [a benefit], while a positive value indicates an increase.)**

Parameter <sup>a</sup>	Argonne Process (Froth Flotation <sup>b</sup> )	CWT Process
AP (lb SO <sub>2</sub> -equivalent)	-0.01103	-0.00662
EP (lb phosphate-equivalent)	-0.00055	-0.00079
GWP100 (lb CO <sub>2</sub> -equivalent)	-4.167	-0.309
POCP (lb ethene-equivalent)	-0.0088	-0.0044

<sup>a</sup> AP is acidification potential, EP is eutrophication (depletion of oxygen in water) potential, GWP is global warning potential, and POCP is photochemical ozone creation potential

<sup>b</sup> Comparison is done here only with the froth flotation process because both Argonne's froth flotation process and the CWT process require mechanical separation of the inorganic materials

## 2.4 RECYCLABILITY CALCULATIONS

Recyclability studies were 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 was 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. For comparison, the materials composition of a production Ford Taurus is summarized in Table 4.

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 estimate the impact of lightweighting 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 case for this study.

**TABLE 3 Materials Breakdown for 2004 Toyota Prius**

Materials	Mass (lb)	Percent
Ferrous metals	1,713	60.6
Nonferrous metals	507	17.9
Plastics	341	12.1
Elastomers	87	3.1
Inorganic material	77	2.7
Other	62	2.2
Organic materials	42	1.5
Vehicle mass (less fluids)	2,829	100.0

**TABLE 4 Materials Breakdown for 2004 Ford Taurus**

Materials	Mass (lb)	Percent
Ferrous metals	2,223	70.4
Plastics	340	10.8
Nonferrous metals	312	9.9
Elastomers	152	4.8
Inorganic material	90	2.9
Other	38	1.2
Organic materials	4	0.1
Vehicle mass (less fluids)	3,159	100.0

**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 reduced from 80.86% to 76.10%. No changes were made to the currently non-recycled 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 reduced from 80.86% to 57.20% if none of the composite is recycled or to 74% if all of the composite material is recycled. No changes were made to the currently non-recycled portion of the vehicle. The composite material replaced steel at 40 weight percent (wt%) of the original steel.

There are reductions in all three recyclability calculations for vehicles with lightweighting materials, 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 vehicles with lightweighting materials would be lighter. Although the recyclability would be lower, 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, using lightweighting materials in automobiles 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 requirement of 95% recyclability.

These results demonstrate the need for technology to recycle lightweight automotive materials if recycling mandates are to be met and to ensure that lightweighting materials are not excluded because of the inability to recycle them. Interestingly, even if the lightweighting metals that replace steel and iron are recycled at the same rate as steel and iron, the overall recyclability rate of the obsolete vehicle will decrease because the relative weight of the metals in the vehicle will decrease. Therefore, to maintain high vehicle-recycling rates, it is important that non-metallic materials that are not recycled at present, such as polymers, be recycled.

**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>
European	97.6	96.0	94.5 <sup>a</sup>
Recycling feasibility	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.

## **2.5 WEBSITE DEVELOPMENT AND LAUNCHING**

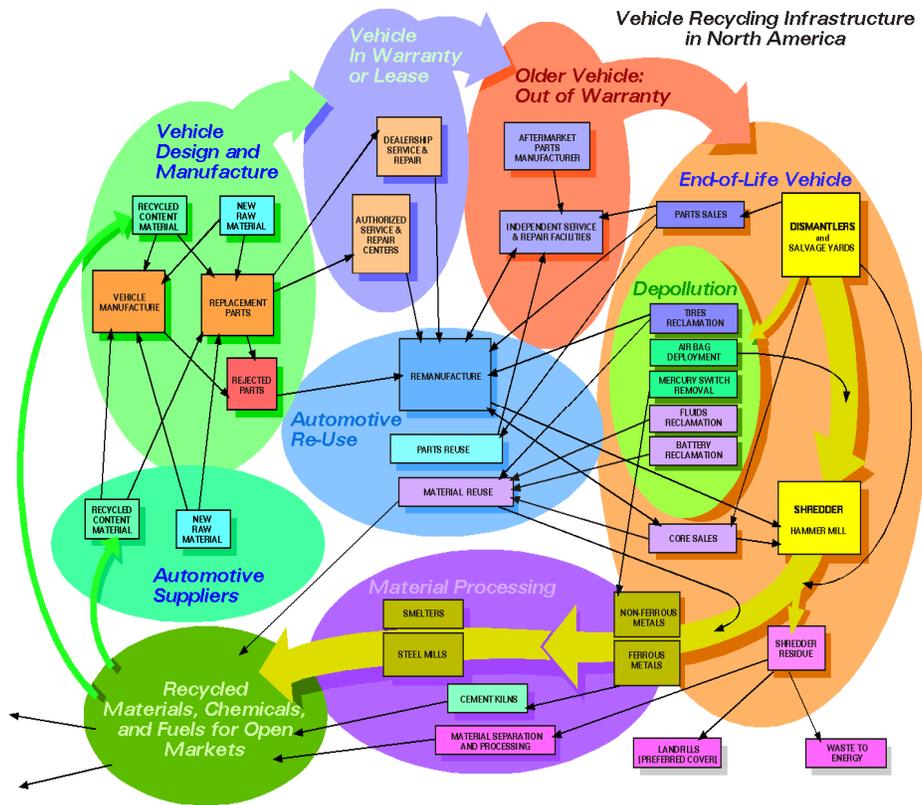
A website was launched in 2006 to provide for better communication and networking with stakeholders and other research teams: [http://www.es.anl.gov/Energy\\_systems/CRADA\\_Team\\_Link/Index.html](http://www.es.anl.gov/Energy_systems/CRADA_Team_Link/Index.html). The website provides an update of the CRADA progress and provides access to relevant information and publications, including a bibliography of mechanical, thermo-chemical conversion, and energy recovery technologies for recycling automotive materials. The website is updated periodically with more information, including access to additional information sources.

In addition, the CRADA team

- Held media events;
- Made numerous presentation and publications;
- Met with representatives of the Institute of Scrap Recycling Industries (ISRI), the Automobile Recycling Association (ARA), and shredder operators to brief them on the CRADA objectives and projects and to encourage their participation;
- Published a one-page CRADA summary and a CRADA brochure; both are available at the website; and
- Conducted project reviews and workshops.

## **2.6 INFRASTRUCTURE ANALYSIS**

The CRADA team conducted a thorough analysis of the infrastructure of the automotive recycling industry. Figure 2 illustrates this infrastructure and summarizes the activities that govern the automotive recycling process. Automobiles are one of the most recycled products in the world. 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 well-established recycling infrastructure. That infrastructure includes over 15,000 automotive dismantlers and automotive remanufacturers and over 200 scrap processors (shredders). The dismantlers recover useable parts for repair and reuse. The dismantlers also recover some of the automotive fluids, including the refrigerants and the engine oil. The refrigerants can be purified and reused. Facilities for recycling engine oil also exist. The oil can be used as an energy source, or it could be refined and used to make new engine oil. Remanufacturers remanufacture a full range of components, including starters, alternators, transmissions, and engines to replace defective parts. The scrap processors recover ferrous and non-ferrous metals from the remaining auto “hulk.”



**FIGURE 2 Infrastructure of the Automotive Recycling Industry in the United States**

The analysis indicated that:

- The recyclability of the plastics and elastomers of 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.
- The presence of PCBs on the plastics severely limits their end use.
- During the next 20 years, ELVs are expected to be more prevalent and complex, posing significant challenges to the existing recycling infrastructure.
- The automobile of the future will use significantly greater amounts of lightweighting materials (e.g., ultra-high-strength steels, aluminum, magnesium, titanium, plastics, and composites) and more sophisticated/complex components, such as fuel cell stacks, hydrogen storage systems, and electronic controls.

### **3 TASK 2. MATERIAL RECOVERY TECHNOLOGY DEVELOPMENT AND DEMONSTRATION**

The goal of this task is to establish the business case for automotive materials recycling of ELVs of the future. Development of technology that can lower the cost of recycling and meet the financial and institutional requirements of the market is critical to improving the recycling rate of automotive materials. Technology development and demonstration, along with an analysis of infrastructure requirements, is the cornerstone of this program and served as the program's focal point. The activities under this task were organized into the following four subtasks:

- Subtask 6.1. Post-Shred Materials Recovery Technology Demonstration and Development
- Subtask 6.2. Development of Technology for Removal of PCBs and Other Toxics (Substances of Concern, or SOCs) from Shredder Residues
- Subtask 6.3. Integration of the Technologies
- Subtask 6.4. Dismantling Process Improvement

The key accomplishments are discussed below.

- Development of technology for the separation of polymers and residual metals from shredder residue,
- Development of technology for removal of PCBs and other toxics (SOCs) from shredder residues, and
- Identification of the needs of the dismantling industry.

#### **3.1 POST-SHRED MATERIALS RECOVERY TECHNOLOGY DEMONSTRATION AND DEVELOPMENT**

The objective of this project was to develop technology for the cost-effective recovery of materials from post-shred residues. Figure 3 is picture of a typical shredder residue sample. Research was conducted to provide data essential to establishing a business case for sustainable recycling of automotive materials from post-shred residue. This includes the determination of the performance (e.g., yield, purity, efficiency, and cost) of these emerging technologies such that an optimized and integrated process for recovering these materials from shredder residues can be developed. The approach followed in this effort consists of:

- Characterization of shredder residue from a number of sources to determine composition variability,
- Building and operating a pilot plant for the separation of shredder residue to recover materials for market evaluation and to provide “control” samples for testing of alternative technologies,



**FIGURE 3** Picture of Typical Shredder Residue Samples

- Conduct of cost and performance analysis of alternative technologies to establish the business case for the technologies and to identify technology gaps, and
- Conduct of bench-scale and large-scale process/technology tests to benchmark other technologies.

A wide range of materials recovery technologies are at various stages of development. Certain technologies specific to the recovery of materials from post-shred materials streams were evaluated to fully understand their commercial viability. Technologies specific to the recovery of materials from post-shred materials were benchmarked to determine their commercial viability. The performance (e.g., yield, purity, efficiency, and cost) of emerging technologies was determined to enable the development of an integrated process for recovering materials from shredder residue. Research was conducted on the Salyp, MBA, Troy Polymers, VW-SiCon, CWT, and Energy Anew approaches, in addition to Argonne's separation processes.

### **3.1.1 Characterization of Shredder Residue**

Over 130 tons of residues from eight facilities were processed in Argonne's mechanical plant. A detailed material balance on the shredder residue and on its major components was also performed. Table 7 summarizes the results after the plant was optimized.

Relatively large variations in fines, metals, rubber, and wood and less variation in the composition of the plastics fraction were observed. The weight percent of the polymer concentrate recovered from eight runs totaling 80,000 lb of shredder residue from a given source conducted over a six-month period was reasonably consistent (41%, 26%, 36%, 39%, 45%, 37%, 43%, and 45%; average 40%). The composition of the different polymer concentrates was also similar. Therefore, a standard design can be developed for the shredding industry.

**TABLE 7 Streams Produced by Mechanical Separation of an Average Shredder Residue**

Component or Parameter	Shredder Residue	Oversized Heavies	Oversized Foam Rich	Fines <sup>a</sup>	Ferrous Rich	Non-Ferrous Rich	Lights	Polymer Concentrate
Weight (lb)	40,000	2,148	756	17,640	656	1,468	1,968	10,044
PP	1,075	0	0	0	17	33	129	897
PP (filled)	403	0	0	0	0	0	9	393
ABS	763	0	0	0	5	9	13	737
PE	941	0	0	0	9	18	85	830
HIPS	261	0	0	0	4	8	15	234
Nylon	379	0	0	0	4	9	19	347
PVC	512	0	0	0	0	0	0	511
PPO	139	0	0	0	0	0	4	135
PC-ABS	151	0	0	0	0	0	1	150
PC	212	0	0	0	0	0	12	200
Other Plastics	597	0	0	0	1	0	17	579
Rubber	4,505	20	0	0	6	172	61	4,246
PU	273	3	0	0	1	23	9	237
Wood	239	0	0	0	0	0	0	239
Metals	2,911	1,117	0	0	590	954	0	249
Foam, fiber, and others	21,320	1,008	756	17,640	19	241	1,597	59
Moisture	5,320	0	0	0	0	0	0	0
Total	40,000	2,148	756	17,640	656	1,468	1,968	10,044

<sup>a</sup> Fines are material smaller than 0.25 in. in size and contain some polymers and metals.

### 3.1.2 Argonne Pilot Plant

A pilot plant having a design capacity of 2 ton/h of shredder residue was built at Argonne and was operated to gather relevant data on recycling materials from shredder residue. The pilot plant consisted of a dry mechanical-separation facility and a wet density/froth-flotation separation facility. The pilot plant was used to:

1. Recover materials from shredder residue,
2. Conduct process improvement studies,
3. Generate design and scale up data,
4. Produce samples for evaluation by other technologies,
5. Define the effectiveness of alternative separation technologies and systems,  
and
6. Serve as a user/demonstration facility.

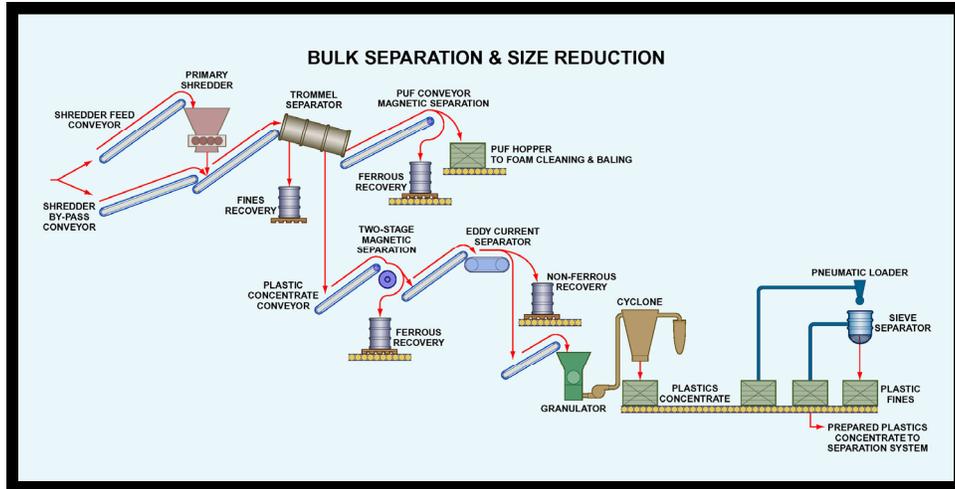
### 3.1.2.1 Mechanical Separation Pilot Facility

The mechanical separation facility processes raw shredder residue to yield a polymer concentrate, ferrous and non-ferrous concentrates, a fines fraction, and other fractions. The plant achieved over 90% recovery of the plastics targeted for recovery as a polymer concentrate and over 95% recovery of the metals in the shredder residue. The polymer concentrate included varying amounts of wood and rubber. Wood was about 1–4 wt%, and rubber was about 10–15% of the shredder residue. Figure 4 is a picture of the mechanical separation facility. The facility equipment includes a 36-in.-diameter two-stage trommel, a 30-hp shredder, a 3,000-lb/h granulator, an eddy current separator, several magnetic separators, and a feeding hopper with a gate valve for feeding the material after it is shredded. Figure 5 illustrates the sequence of operation of the basic plant. The actual sequence varies for different materials.

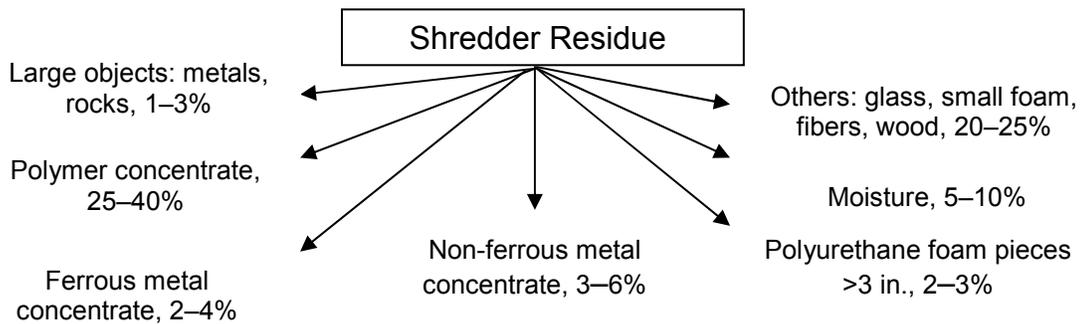
The output streams from the mechanical separation facility are summarized in Figure 6. The polymer concentrate is then fed to the wet density/froth-flotation separation facility to separate the individual plastics or groups of compatible plastics from the concentrate.



**FIGURE 4** Picture of Argonne's Mechanical Separation Facility



**FIGURE 5 Sequence of Operation of the Basic Mechanical Separation Plant**



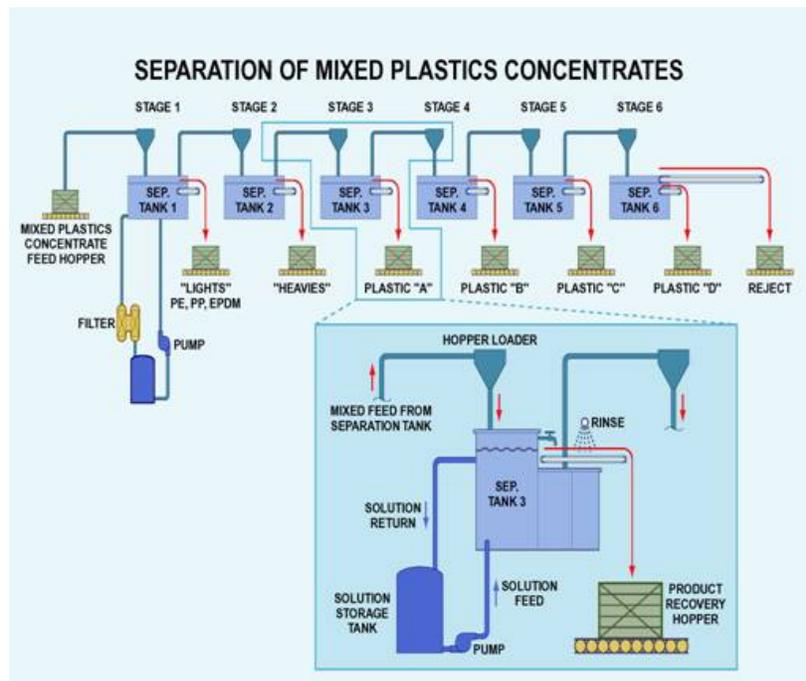
**FIGURE 6 Product Fractions from the Mechanical Separation Plant**

### 3.1.2.2 Wet Density/Froth Flotation Facility

The original facility contained six continuous stages for the separation of targeted plastics. The design capacity of the first two stages was 1,000 lb/h of mixed materials. The design capacity of each of the other four stages was 500 lb/h. Figure 7 is a picture of a section of that facility. A shakedown of the facility was conducted by using 4,000 lb of post-consumer electronics and appliance mixed plastics and by using a mixture of colored plastics. Over 35,000 lb of polymer concentrate from shredder residue were then processed in this facility. The recovered fractions are described below. Figure 8 illustrates the basic operation of the facility. The actual number of stages used depends on the composition of the starting material. Table 8 summarizes the recoverable plastics from a typical shredder residue (based on 10,000 lb of polymer concentrate feed).



**FIGURE 7 A Picture of the Original Wet Density/Froth Flotation Facility**



**FIGURE 8 Sequence of Operation of the Basic Mechanical-Separation Plant**

When conventional gravitational separation techniques were applied to the polymer concentrate from shredder residue, none of the fractions produced a potentially recyclable plastics material. As shown in Figure 9, each fraction contained a number of species. Most species were found in several fractions. For example, polypropylene was found in every fraction. This is because these polymers are not pure resins — they contain fillers, modifiers, and colorants, among other materials, which causes the density of these materials to overlap. Therefore, other techniques are required to separate them. The large number of species present in the polymer concentrate from shredder residue further complicates the development of a separation technique that is selective toward one of the species. Froth flotation techniques were applied after the polymer fractions were further concentrated by using conventional sink/float techniques. The recovered fractions are described below.

**TABLE 8 Composition of an Average Polymer Concentrate and Recovered Polymer Fractions**

Parameter or Component	Polymer Concentrate	PP/PE Product	ABS Product	ABS/PC Product <sup>a</sup>	Rubber Product	HIPS/ABS <sup>b</sup> Concentrate	Mixed Plastics	Mixed Stream <sup>a</sup>
Weight (lb)	10,044	1,736	141	108	689	856	1,203	5,311
PP	897	827	0	0	0	0	63	7
PP (filled)	393	0	0	0	11	43	194	146
ABS	737	0	105	2	0	365	176	88
PE <sup>b</sup>	830	787	0	0	10	12	21	0
HIPS <sup>b</sup>	234	0	2	0	0	186	25	21
Nylon	347	0	5	0	0	5	42	296
PVC <sup>b</sup>	511	0	0	0	3	0	123	385
PPO <sup>b</sup>	135	0	13	1	0	62	21	37
PC-ABS <sup>b</sup>	150	0	0	6	0	0	0	143
PC	200	0	0	85	1	0	19	94
Other Plastics	579	0	9	2	2	12	8	547
Rubber	4,246	90	2	9	628	104	263	3,149
PU <sup>b</sup>	237	21	4	2	18	0	96	96
Wood	239	0	1	0	17	66	146	8
Metals	249	0	0	0	0	0	0	249
Foam, Fiber	59	10	0	0	0	1	5	42
Total	10,044	1,736	141	108	689	856	1,203	5,311

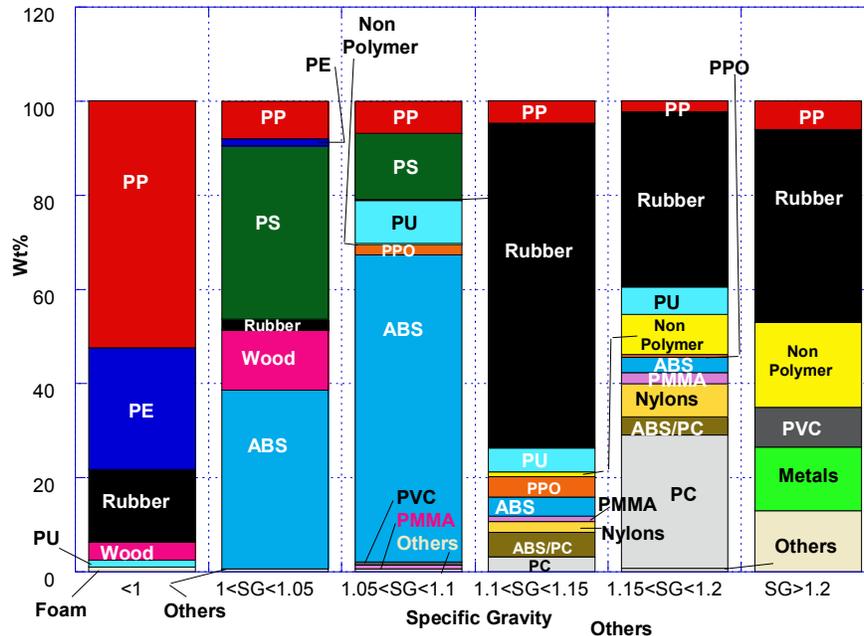
<sup>a</sup> Rubber and metals are recovered from these streams.

<sup>b</sup> PP is polypropylene, HIPS is high-impact polystyrene, PVC is polyvinyl chloride, PPO is polyoxyethylene, PC is polycarbonate, and PU is polyurethane.

### 3.1.3 Recovered Fractions from Pilot Plant Operation

#### 3.1.3.1 Recovered Polyethylene/Polypropylene (PP/PE) Fraction

The basic Argonne process recovered a polyolefins-rich fraction (~65% polyolefins, 10% wood, and 25% rubber, as well as small quantities of other plastics). The conditions in the separation tank were set such that most of the wood will float with the polyolefins so that the wood can be separated in a single step. Wood, rubber, and other plastics were then separated to recover the polyolefins (see Section 3.1.3.2). More than 5,000 lb of an unfilled PP/PE fraction that is over 95% PP/PE was consistently produced. It contained less than 0.2% wood and less than 4% rubber. However, when the material was pelletized, most of the rubber in this fraction was found to be compatible with the PP/PE. The recovered PP/PE has properties similar to those of some commercially available PP materials. The unfilled PP/PE product constituted about 5–6% of the starting shredder residue weight.



**FIGURE 9 Flotation Characteristics of Shredder Residue Polymers based on Density Gradients**

### 3.1.3.2 Separation of Wood and Rubber from the Recovered PP/PE

Trials using commercial air aspirators, air classifiers, gravity tables, and mineral jigs to remove wood and/or rubber from the polymer concentrate, as well as from the PP/PE fraction, did not yield satisfactory results. Trials using wet methods removed almost 100% of the wood and over 90% of the rubber with a nominal loss (~5%) of the polyolefins. The process also separated other plastics, including polystyrene (PS) and ABS, which floated with the polyolefins and the wood in the basic process. The process consisted of altering the density of the porous particles so that their overall density increases, causing them to sink.

A modular dry process for separating rubber from plastics was also tested at rates of up to 200 lb/h of polymer concentrate. The process separated over 75% of the rubber and produced a rubber fraction containing less than 10% of non-rubber material.

### 3.1.3.3 Filled ABS Fraction

ABS that has a specific gravity less than 1.1 was isolated by the basic froth flotation process as an ABS concentrate (Table 8). It contained 50% ABS, 20% rubber, 10% rigid urethane rubber, and 20% of other materials. Removing wood and rubber increased the ABS concentration to 70% and reduced the concentrations of rubber and urethane to 3% and 2%, respectively. When this material was blended with virgin ABS at 10% and 25% recovered material, the properties of the blends were slightly different from the properties of the virgin ABS. Laboratory tests have established process conditions to increase the ABS concentration to

over 90%. MBA polymers established that this fraction can be separated to produce recyclable products.

#### **3.1.3.4 Unfilled ABS and PS**

A fraction of ABS and PS that has a specific gravity between 1.0 and 1.07 (43% ABS, 22% PS, 7% PPO, and 28% other materials, including rubber and some wood) was produced by using the basic process. Laboratory tests separated this fraction and produced fractions with over 90% ABS and over 85% PS/PPO.

#### **3.1.3.5 PC-ABS/PC Alloy**

Laboratory tests produced a PC-ABS/PC fraction that had a combined concentration of over 85%. Work is ongoing to isolate a large sample of ABS/PC-PC fraction for further evaluation.

#### **3.1.3.6 PVC**

Recovery of the above fractions leaves behind a fraction made of high-specific-gravity materials. Rubber constitutes over 50% of the total, and metals represents about 5%. Separating rubber, metals, glass, and rocks from this stream leaves a fraction containing over 50% PVC. It is also rich in filled nylons.

#### **3.1.3.7 Rubber**

The recovered rubber fraction was upgraded by using the Argonne dry rubber separation process to over 90% rubber. The other 10% was mostly plastics.

In summary, we have recovered the unfilled polyolefins and isolated the filled ABS, unfilled ABS/PS, PC-ABS/PC, and PVC into more manageable fractions. A 5,000-lb/h flotation module was built and tested by using over 10,000 lb of mixed polymers.

### **3.1.4 Development of a Large-Scale Validation Plant**

An agreement has been reached with a shredder to build a 20-ton/h validation plant that will perform both mechanical separation and froth flotation on shredder residue to recover plastics and residual metals.

### **3.1.5 Benchmarking and Evaluation of Other Technologies**

In addition to the process development research conducted at Argonne, bench-scale and large-scale tests were conducted to benchmark and evaluate different processes/technologies and evaluate equipment that could be used for recycling certain parts of shredder residue. These are discussed below.

#### **3.1.5.1 Evaluation of Color and Infra-Red (IR) Sorters**

We conducted performance testing and cost analysis of color sorter and IR sorters. The following systems were tested: (1) Satake (chip monochromatic and IR), (2) Key (chip full color and laser), (3) MSS (full color and IR), (4) S+S Separation and Sorting (full color and IR), (5) NRT (chip full spectrum and IR), and (6) PROTEC (chip full spectrum). On the basis of the results of these tests, it appeared that, at this time, these systems cannot recover marketable polymer products from shredder residue, nor can they separate wood and rubber from the recovered polymer fractions without significant loss of the product. The primary reason these processes were not successful is that using the optical sorters resulted in a high loss of the targeted plastics. Argonne's wet separation process for wood and rubber removal appears to be the most economical process for separating the wood and the rubber from the plastics.

#### **3.1.5.2 Processing of Polymer Concentrate at MBA Polymers**

Salyp built a mechanical separation plant that started with Argonne's original mechanical separation system and added an optical sorter and a plastics washing system. Salyp's starting shredder residue contained less rubber and wood than the U.S. residue. MBA processed about 40,000 lb of Salyp's polymer concentrate and recovered five materials: polyolefin "A" and "B", filled PP, ABS, and HIPS. The total yield was estimated to be 48.5% of the plastics-rich fraction. This yield is 88% of the amounts of these plastics in the feed material. The products were extruded, molded, and tested. The properties were reported to be "encouraging," and it is expected that most of the products could be used in some durable goods applications.

#### **3.1.5.3 Changing World Technologies (CWT)**

CWT processed the organic fraction of shredder residue stream after separating the < 1/16-in. fines (~36% by weight). About 700 lb of the remaining material were processed, along with 80 lb of tires and 1,700 lb of used motor oil. The products were hydrocarbon oil (84%), a fuel-gas (10%), and a solid carbon product (6%). Distillation of the oil-generated gasoline (12%), diesel (32%), heavy hydrocarbon oils (15%), and 3% as gas (mainly methane). PCBs in the input shredder residue represented 21.8 ppm, and in the products, PCBs were below the detection limit. These results indicate that the PCBs degraded during the process. The char contained several metals. The heavy oil from the dissolver contained about 3,200 ppm of total chlorine, but no chlorine was found in the light distillates, and only 14 ppm was found in the heavier distillate and 11 ppm in the distillate bottoms. Bromine was found in the heavy oil from the dissolver

(~135 ppm) and in the char (87 ppm). None was found in the output liquid products. The analysis also indicates that sulfur compounds degraded in the process. A test using about 1,000 lb of a pre-processed organic fraction derived from about 2,000 lb of shredder residue has been completed. The results confirmed the ability of the CWT process to produce an 18,000-Btu/lb diesel oil, a 12,000-Btu/lb solid carbon, and a 5,000-Btu/lb fuel gas; the largest fraction was methane. CWT also completed a large-scale (2,000-lb) test using actual shredder residue material. The results confirmed the results of the earlier small-scale tests.

#### **3.1.5.4 Troy Polymers Glycolysis Process (TPI)**

The process converted foam from shredder residue to polyol initiators at yields of 88% and 72%, for clean and dirty foam, respectively. Activated carbon reduced the concentration of PCBs in the products to < 2 ppm. Over 100 gal of polyol initiator were produced from about 1,200 lb of foam. Twenty gallons of the polyol initiator were propoxylated and tested for making rigid foams. They required less or no catalyst and had better flame resistance than the foams made with virgin polyols. Initial economic analysis indicated that the process is potentially economical. TPI is working with an industrial partner to demonstrate the technology in the field.

#### **3.1.5.5 Energy Anew Recycling of Fines**

Energy Anew conducted tests on 300-lb samples of fines (< 1 in.). Shredder residue was screened by using a 7/8-in. screen, and the material that passed the screen was processed to yield organic- and inorganic-rich fractions. Energy Anew subsequently constructed a mobile cyclonic system to process shredder fines with a throughput capability of about 3 ton/h. The system successfully sorted approximately 2,000 lb of fine fraction samples into a non-ferrous metal concentrate, ferrous metal concentrate, polyolefin concentrate, styrenic plastic concentrate, and an organic fluff fraction for energy recovery. The process can be used in combination with coarse size reduction systems to produce enriched plastic products from a wide variety of raw materials, including automotive shredder residue and shredded appliance, electronic, and packaging scrap. Non-ferrous concentrates of greater than 75% metal content have been demonstrated with the use of additional downstream grinding and sorting. Economic analysis of the process shows that recovery of plastic concentrates, metals, and sand from windshield glass may be viable.

#### **3.1.5.6 Co-Combustion of Plastics Containing Material with Biomass**

The ACC-Plastics Division co-funded a study with Plastics Europe to study the synergies of co-combustion of solid recovered fuel (SRF) and biomass. SRF is a fuel prepared from non-hazardous (combustible) waste. It is usually a mix of paper, wood, and plastic waste. The plastics share is usually around 20% by mass and 50% by energy. The study concluded that the benefits include fast drying and ignition of the biomass, higher furnace temperature, and improved combustion efficiency. The study noted that chlorine and metallic aluminum contents in the fuel

mixture should be compatible with the boiler type. The study was presented at the International Thermal treatment Technologies Conference (IT3) in Cincinnati on May 19, 2009.

### **3.2 DEVELOPMENT OF TECHNOLOGY FOR REMOVAL OF PCBs AND OTHER TOXICS (SUBSTANCES OF CONCERN, SOCS) FROM SHREDDER RESIDUES**

The objective of this subtask is to develop techniques and/or technology to identify, quantify, and/or cost-effectively remove 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 the materials source stream impacts 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. The strategy that is required for controlling the SOCs may vary regionally. For example, requirements are different in Europe, North America, and Asia for various SOCs. Strategies for controlling SOCs can also depend on the technology used for recycling the automotive material and the end use of the materials. The focus of the work was on the development of technology for the removal of PCBs from polymers 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, ballasts, and transformers that inadvertently escape the inspection and control process at the shredders. Unless PCBs are removed from the recovered materials, with the exception of metals, introducing the recovered materials into commerce will not be possible. The criteria for the selection of a cleaning method must include (1) impact of the cleaning process on the properties and marketability of the polymers, (2) nature and cost of disposal of the waste generated by the process, and (3) overall cost of the cleaning process.

#### **3.2.1 Bench-Scale Testing**

A review was conducted of available technology options for controlling SOCs. Bench-scale testing of selected processes was then carried out to determine the efficacy of those processes. An important component of this work turned out to be validation of analytical methods for PCBs. Working with Argonne, Troy Polymers, Inc., completed a bench-scale screening study of 11 commercially available surfactants and three organic solvents for the removal of PCBs and other contaminants from dirty plastics and polyurethane foam derived from ASR. Surfactant TRITON RW 50, which is manufactured by Dow Chemicals, was found to be the most efficient surfactant among the ones tried. PCB concentrations in plastics washed with this surfactant were reduced to below 2 ppm. The concentration of PCBs in the washed foam was at 2 ppm. The results for heavy metals were inconclusive. We believe that this is because the heavy metals are not evenly distributed in and on the plastics. A tiny sliver of a given metal or its oxides or salts can render the analyzed sample non-representative.

### **3.2.2 Testing of Commercially Available Equipment**

Cleaning/washing tests were carried out on about 100 lb of plastic chips, and each test involved using aqueous solutions and surfactants in commercially available equipment. 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 chips 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/h of plastics. In each of these tests, the washed material was “visually” clean. However, the results of PCB analyses were highly variable, indicating that in some cases, the PCBs concentration had increased after washing. The results suggest that existing aqueous-based equipment, as is, is not likely to reduce the concentration of PCBs to acceptable levels.

### **3.2.3 Testing of Proprietary Processes**

Three companies with equipment and/or proprietary washing solvents and solutions that could potentially be used for the non-aqueous removal of PCBs from plastics 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 that had a PCB concentration of 11 ppm. Samples were washed at the three companies, and the washed samples were evaluated for PCB levels. 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. Unfortunately, the company did not have equipment to conduct large-scale testing of the process using plastics. Cool Clean Technologies technology used CO<sub>2</sub> only. The washing failed to remove the PCBs. itec Environmental Group (name changed to ECO<sub>2</sub>) 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.

### **3.2.4 Testing of Other Potential Routes**

Bench-scale testing was also conducted on the following processes: catalyzed ozonation/UV treatment, washing using a proprietary bio-degradable solvent, and devolatilization in a vacuum extruder. None of these processes gave satisfactory results.

### **3.2.5 Testing a Devolatilization Process with a Vacuum Extruder**

Energy Anew, with the sponsorship of ACC PD, conducted a series of vacuum devolatilization tests at Midland Compounding on polyolefin samples recovered from shredder residue by using a 30-mm twin-screw vacuum extruder. An experimental design was developed to test the impact of three variables on the PCB removal process: screw speed (high, 300 revolutions per minute [rpm], and low, 100 rpm), feed rate (high, 20 lb/h, and low, 10 lb/h),

and temperature (high, 325°C, and low, 250°C). A mid-point at 200 rpm, 15 lb/h, and 287°C with and without vacuum was also tested. The apparatus is shown in Figure 10. The results are summarized in Table 9. The results indicate that devolatilization alone was not sufficient to remove PCBs from the polyolefin blend. The IZOD property of the treated polymers did not change.

Energy Anew conducted additional tests at Midland Compounding, where high-pressure water or water/glycol/NaOH were injected to help de-chlorinate and steam strip the polymer after the samples were first homogenized by extrusion and post-blending. The extruder was sectioned into three zones: high-pressure liquid injection, atmospheric vent, and then a vacuum vent. The concentration of PCBs was still greater than 2 ppm; however, addition of water and water/glycol mixtures was shown to increase Izod impact strength by as much as 68%. High-temperature water or water ethylene glycol in the extrusion environment appeared to attack inclusions in the polyolefin matrix that had resulted in stress concentrations. Elimination of the inclusions by hydrolysis raised impact properties. Samples with at least 3% water addition also showed a smaller increase in melt flow index, indicating that water may react with or degrade agents that cause a reduction in molecular weight. Table 10 gives the physical properties associated with the addition of water and ethylene glycol during extrusion. The concentration of PCBs was still greater than 2 ppm.



**FIGURE 10 Extruder with Die and Vacuum Knockout Pot Used in the Devolatilization Testing**

**TABLE 9 PCBs and Impact Test Results from Vacuum Devolatilization Testing**

Sample No.	Temperature (°C)	Screw RPM	Feed Rate (lb/h)	PCB 1242 (ppm)
1	325	300	20	18.2
2	325	300	10	13.6
3	325	100	20	16.9
4	325	100	10	16.2
5	287	200	15	12.4
6 <sup>a</sup>	287	200	15	12.6
7	250	300	20	17.9
8	250	300	10	19.7
9	250	100	20	17.7
10	250	100	10	15.4
11 <sup>b</sup>	287	200	15	21.4
12 <sup>c</sup>	-	-	-	22.2

<sup>a</sup> no vacuum

<sup>b</sup> water at feed

<sup>c</sup> raw feed

**TABLE 10 Physical Test Results with Water and Water/Ethylene Glycol (50:50) Addition**

Sample	Starting Material	20 Mesh Screen	Vacuum	Water Injection Mass Fraction	EG/H2O 50:50 Injection Mass Fraction	Melt Flow Rate (230°C/3.8 kg)	Izod Impact (ft-lb/in.)
A	Blended Flake	Yes	No	No	No	7.4	10
B	Blended Flake	No	No	No	No	10.3	6.8
C	B (above)	No	Yes	3.60%	No	10.9	6.7
D	B (above)	No	Yes	5.00%	No	10.9	7.7
E	B (above)	No	Yes	No	No	13.6	4.7
F	B (above)	No	Yes	No	5.00%	13.8	5.7
G	B (above)	No	Yes	No	8.00%	11.6	7.9

### 3.2.6 Development of a New Process at Argonne

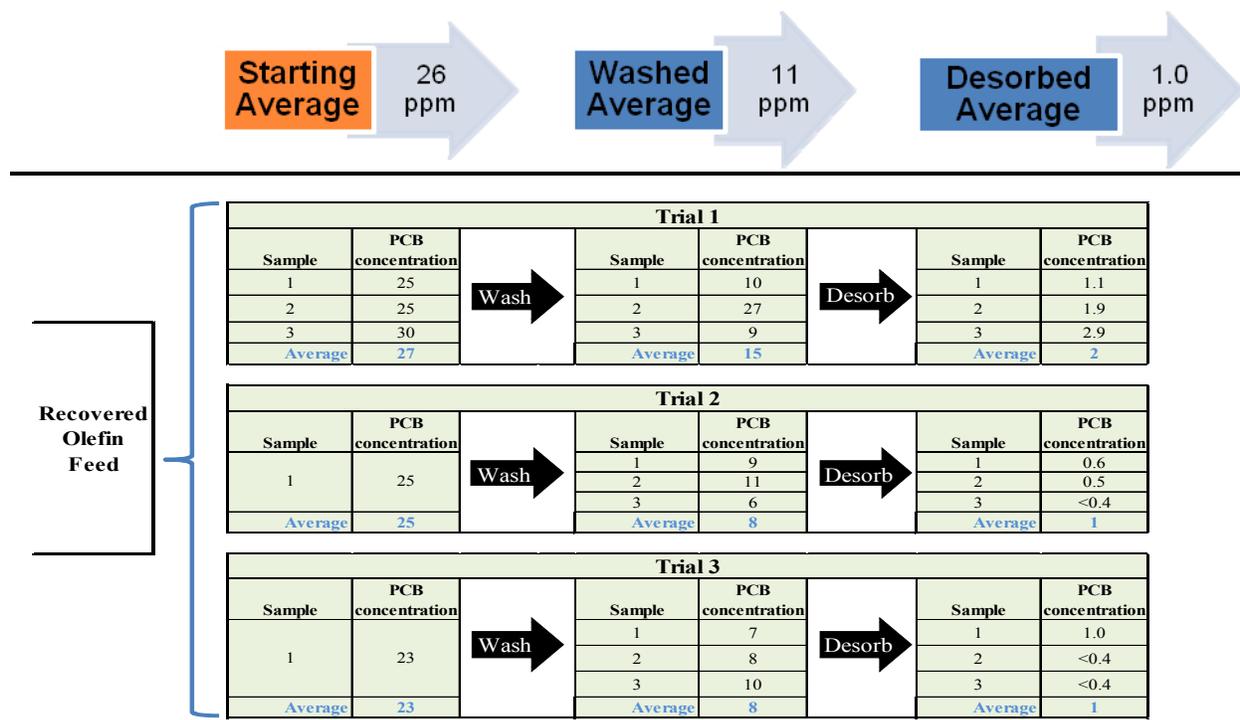
The work done on cleaning polymers recovered from shredder residue suggested that different washing methods and solutions appear to be able to reduce the concentration of PCBs to about 5–10 ppm in a reasonably short time. Further reduction in the concentration of PCBs required more extensive and prolonged washing in fresh solution. In addition to added cost, prolonged washing, particularly in organic solvents, is further complicated by the absorption of the solvent by the plastics, which may alter the properties and the value of the plastics. This behavior suggests that the PCBs on the plastics are present as result of more than one mechanism. Some of the PCBs are in the oils and dirt that are on the plastics, and some are adsorbed on the plastics; they do not desorb easily during washing. We tested this hypothesis in the laboratory. We conducted washing tests by using several washing solutions and solvents, including a non-flammable solvent to wash the plastics under conditions that minimized the absorption of the solvent by the plastics. This process reduced the concentrations of PCBs from about 30 ppm to about 5–10 ppm under a range of operating conditions. The washed plastics were then processed in an environment that induces desorption (high temperature with or without reduced pressure). The concentration of PCBs was consistently reduced from 5–10 ppm to below 2 ppm. Tests were also conducted in which unwashed samples were exposed to the same environment that induces desorption. The PCBs concentration could not be reduced below 2 ppm under the same operating conditions.

A two-stage process, based on this concept, has been developed and tested first at the bench scale at Argonne and then in a 5-lb reactor that processed 5 lb of plastics per test. It has repeatedly reduced the concentration of PCBs in PP/PE samples to less than 2 ppm. For example, at sufficient residence times and temperature conditions that do not cause the plastics to oxidize, we were able to reduce the concentration of PCBs on the recovered polyolefins from about 32 ppm to as low as 0.58 ppm. It was then decided to run larger batch tests (5 lb per test). We designed and built the apparatus (Figure 11) and conducted more tests. Samples of the processed polymers were analyzed, and the results are summarized in Table 11.



**FIGURE 11 Experimental Apparatus for Testing the Argonne Two-Stage Process**

**TABLE 11 Results of Argonne’s Two-Stage PCB Removal Process**



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

Experiments were performed to explain the variability in the results and to develop a consistent procedure for the determination of the concentration of PCBs. The variability may be due to a number of factors, including sample size, size of plastic particles, procedure used for PCB extraction, 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.

To investigate the possible interference of phthalates in the analysis of PCBs, a sample of plastic 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 12, and the spiked samples were analyzed by using the same two methods. The results show no interference of the phthalates in the analysis of PCBs. Interestingly, the GC/MS results were always higher than the GC-ECD results.

**TABLE 12 Effect of Phthalates on Analysis of PCBs**

Weight-Percent of Phthalates Added	PCB Concentration (ppm) by GC/ECD	PCB Concentration (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 0.04–0.08 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 procedures for analyzing PCBs. Extracts from nine sonications of 300-g samples were also analyzed for PCBs by three laboratories. The results showed that:

1. The results from the three laboratories are fairly consistent for each set of samples.
2. Direct analysis of the samples from the three laboratories showed that the concentration of PCBs in the granulated plastics was about 5 ppm, and for the ungranulated, 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 extraction of PCBs. 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 on the basis of 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 ungranulated samples. These results further indicate that the PCBs are predominantly on the surface; otherwise, the granulated samples would have shown higher concentrations.

Two of the laboratories identified Aroclor 1242 as the only PCB present. The third found Aroclors 1232 and 1254 as the only two present. TPI also conducted an analysis of various plastics samples by using GC-ECD and GC-MS methods. The results are compared in Table 13. Results from the two methods are in reasonable agreement, even though the GC-MS method showed higher values.

### 3.2.7.1 Evaluation of Soxhlet Method for PCBs Extraction

Successful commercialization of technology for recovering polymers from shredder residue depends on a reliable and inexpensive technique to analyze samples for PCBs in the field. The U.S. EPA and European protocols for PCBs analysis were reviewed and experiments were conducted to understand the requirements for 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 14). Limited experiments to define the operating conditions for the Soxhlet method were conducted. The results are discussed below.

**TABLE 13 PCBs Analysis by GC-ECD and GC-MS (extraction 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 14 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

### 3.2.7.2 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 h. Similarly, three 120-g samples were extracted with toluene for 8 h, and another three 120-g samples were extracted with toluene for 24 h. 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 indicated that hexane is a better solvent than toluene.

### 3.2.7.3 Determination of Required Extraction Time

Three additional 120-g samples were extracted with hexane for 4 h each. This procedure resulted in six samples of extracts and three samples of extracted plastics that were analyzed. The results indicated that a Soxhlet extraction time of 4 h is adequate because it reduced the concentration of PCBs 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.

### 3.2.7.4 Determination of Adequate Sample Size

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

### 3.2.7.5 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 15). These results lead to the following conclusions:

1. A conventional Soxhlet extractor using hexane is effective for the extraction of PCBs from plastics.
2. A total extraction time of 4 h with siphoning intervals of 8–10 min is adequate for complete extraction of the PCBs.
3. The EPA and the European quantification methodologies yield close results.

**TABLE 15 Comparison of the U.S. EPA and the European Quantification Methods**

Extract Time (h)	PCBs (ppm)	
	EPA Method	European Method
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

### **3.3 INTEGRATION OF THE TECHNOLOGIES**

A general-process conceptual design for a 20-ton/ h plant was developed. The process steps for the conceptual design include (1) a device to separate large metals and rocks; (2) a screen to separate large pieces of fabrics, foam, and tire rubber; (3) a shredder; (4) a screen or a trommel to separate “fines”; (5) a magnet and eddy current to separate metals; (6) a granulator; and (7) an air classifier to remove “lights” from the granulated material. Tests, using shredder residue, were conducted to evaluate the performance and cost of various equipment used in the design. We conducted economic analysis of the process and a sensitivity study of the cost of producing the polymer concentrate to yield per ton of shredder residue, value of the by-products (ferrous, non-ferrous, etc.), cost of utilities, number of operating shifts, and cost of capital, among other parameters. The cost can be as low as \$0.02/lb of polymer concentrate for a plant operating three shifts per day and when the polymer concentrate is about 45% of the shredder residue to over \$0.075/lb for a plant operating one shift per day and when the polymer concentrate is only 15% of the shredder residue. The value of the recovered metals has a significant impact on the overall cost. The value of the metals depends on their concentration in shredder residue and on the composition of the metal fraction produced.

A general-process conceptual design for the flotation part of the plant was also developed for the separation of the polymer concentrate generated from 20 ton/h shredder residue. The process steps for the general-flotation conceptual design include (1) a feeding system to feed the tanks, (2) flotation tanks, (3) conveyors, (4) dewatering units, (5) a wood and rubber separation subsystem, and (5) dryers. Tests were conducted to evaluate the performance and cost of various equipment used in the design.

### **3.4 IMPROVEMENTS TO DISMANTLING PROCESS**

The objective of this project was to identify and evaluate improvements to present automobile-dismantling practices that could result in an overall increase in the recycling of vehicles by overcoming some of the obstacles facing dismantlers related to parts containing lightweighting materials, such as polymers and composites.

ELVs are typically processed first by automotive dismantlers. In North America, there are more than 15,000 auto dismantling facilities. The vast majority of the ELVs that are recycled start their final journey at one of the dismantling facilities in the United States. Some, because of their age or condition, go directly to the shredders. At the dismantling facility, useable parts (such as radios, batteries, bumpers, windshields, whole car seats, door panels, transmissions, and engines) are manually removed for direct resale and reuse. Such parts as starters and alternators may be removed, refurbished, or remanufactured and sold. At the dismantling yard, useable parts are recovered from the vehicle for resale and/or remanufacturing. The dismantling operation provides low-cost replacements parts to repair shops, parts brokers, and individual customers. Direct reuse of a part, such as a door panel or trunk lid, conserves the materials and energy that would otherwise be required to produce the replacement part from virgin materials, as well as the manufacturing energy required to stamp the part and assemble the component.

Remanufacturing is an important component of the existing recycle infrastructure. Many automotive components are remanufactured to supply lower-cost replacement parts to maintain the domestic fleet. For example, most of the replacement starters and alternators are remanufactured. Other automotive parts that are typically remanufactured include engines, transmissions, brake systems, and water pumps. Dismantlers also collect several other items for recycling by others, as described below.

- Car batteries are collected for recycling of their lead, sulfuric acid, and polypropylene content.
- Catalytic converters are recycled for their precious metal catalysts.
- Dismantlers experimented with dismantling bumpers for recycling. Among the problems encountered in recycling the bumpers are the paint on the bumpers and the many different materials sometimes used in making an individual bumper. Repair shops and some dismantlers collect polypropylene and TPO bumpers for recycling.
- Dismantlers tried to manually recover some plastics and seat foam from vehicles for resale. These efforts were quickly terminated because the operations were not economical. The cost was high, and the plastics markets were not readily available. The storage of scrap plastics and foam also required a large amount of space that interfered with more conventional dismantling operations. In addition, the amounts that would be collected by an average dismantler would be small and, therefore, difficult to market.
- Dismantlers also extract refrigerants and fuel from the vehicle. These generally end up being reused in some applications after purification and upgrading. Other automotive fluids, such as engine and transmission oils, are removed when required for environmental reasons.

Dismantling is generally done manually, and therefore, except for items that can be resold as is, dismantling is not economical. Dismantling for the recovery of such materials as polyurethane foam, plastics, and rubber is not cost-effective, primarily because (1) dismantling is labor-intensive and (2) only a small amount of material can be recovered at each of the more than 15,000 dismantling yards in the United States, and, therefore, the storage and transportation costs for most such materials are generally prohibitive. However, future automotive parts and systems that contain expensive materials of construction, such as batteries used in hybrid vehicles, will contain enough value to justify their dismantling. Further, keeping such items on the hulk is not advisable because shredding of such items may introduce new substances of concern in the shredder residue. This will complicate the recycling of materials, such as polymers and even metals, from the shredder residue. Therefore, they are likely to be dismantled before shredding. Potential improvements that can assist the dismantling industry increase the recycling of vehicles include (1) training the dismantler's employees in identifying and recognizing parts and materials of value in ELVs, (2) identifying and recognizing potential hazards, and (3) increasing industry awareness of environmental regulations and guidelines.

Other potential improvements include:

- Automation of the dismantling process to improve efficiency and/or reduce cost;
- Special requirements for dismantling lightweight parts and components;
- Proper tools to dismantle parts, such as bumpers, windshields and window glass, and instrument panels;
- Rapid identification techniques to facilitate the recovery of single material components;
- Technology that can be implemented on-site to upgrade dismantled materials, such as cleaning of parts and materials and separation of impurities;
- Participation of repair shops, dealerships, and remanufacturing shops in recycling damaged lightweight dismantled parts; and
- Design modifications that will facilitate dismantling.

Repair and remanufacturing shops can also play a positive role in repairing and recycling damaged, dismantled lightweight parts (e.g., cracked composite panels, dented aluminum parts). Design modification of vehicles, including reducing the number of materials of construction, to facilitate dismantling has been the subject of discussion for many years. However, little progress has been made, except perhaps in the development of approaches driven by economics, such as replacing some of the more expensive polymers with polypropylene.

Designing vehicles for more efficient recovery of parts and materials from ELVs can have a major impact on dismantling. Such a strategy can include the following:

1. Reduce the number of incompatible materials used (primarily polymers). For example, many gas tanks are made of multiple incompatible layers.
2. Make parts more accessible and easier to dismantle either by design or by developing the appropriate tools (or both). For example, to install a water pump on some models of vehicles, the whole engine needs to be dropped. The operator needs to get under the vehicle to reach many of the parts.
3. Eliminate or minimize the use of hazardous materials.
4. Eliminate or minimize the use of metal fasteners and attachments on polymer parts.

Examples of how dismantling can be made easier by design include the following:

- Instrument panels contain about 25 lb of plastics available for potential recycling (Mark 2001)<sup>2</sup>. If the instrument panel can be built by using a single plastic material (such as polypropylene), then polypropylene will be less expensive to separate and recover. If instrument panels can be made so that they are easy and economical to remove, the dismantler will consider removing them and recycling the plastics. The precious metals can be recycled by precious metal recyclers. The economics of the process will still depend on other costs, including those for storage and transport.
- If all bumpers used by a car company are made of one material, such as TPO, the dismantler will be able to separate those panels by just knowing the car maker.

The USCAR/VRP conducted an extensive dismantling study over several years. The objective was to evaluate the feasibility and viability of collecting and recycling automotive polymers from ELVs. The project identified North American ELV recycling practices; explored scenarios for plastic material handling and local transportation; and evaluated sorting, processing, and compounding of the recovered plastics. Recovered ABS and PP plastic materials were formulated to Original Equipment Manufacturer (OEM) specifications and molded by using production tooling to establish the viability and economics of the pursuit of these materials as a commercial enterprise. The study also examined the way in which reuse contributes to recyclability. The results of this study found that the sale of used parts played a significant role in vehicle recycling and will continue to play an essential role. The study found that while the recovered materials and parts are acceptable (the PP is useful, and the ABS is potentially useful with some additives), the economic incentives and altered logistics needed to support this endeavor will not be borne by existing market economics in North America.

---

<sup>2</sup> Mark, E.E., 2001, "Optimization of Instrument Panels to Assist Recycling Quota Dismantling/Mechanical Recycling vs. ASR Treatment/Chemical Recycling," SAE paper 2001-01-3741.

## **4 TASK 3. RECOVERED MATERIAL PERFORMANCE AND MARKET EVALUATION**

The objective of this task was to evaluate the market opportunity for recycled lightweight automotive materials. The effort involved (1) determination of the properties of recovered automotive materials and (2) molding trials by using recovered materials to confirm the technical and economic feasibility of using those materials in value-added applications. Limitations to the reuse of many of the materials as recovered and the need for post-processing technology to upgrade the recovered materials to meet the requirements of the market were identified. The analysis focused on the feasibility of reuse of the recovered polymers in automotive applications. The properties of recovered polymers were determined, and molding trials of actual parts from recovered polymers to determine their viability for commercialization were conducted. The project focused on establishing the properties of polymeric materials that were recovered from shredder residue. Regardless of the effectiveness of the recovery technology, the recovered materials are, on average, 10–15 years old and derived from different sources (automobiles, home appliances, and others). The performance properties of the recovered polymers were compared vis-à-vis new or virgin materials and blends of virgin and regrind materials. Physical property testing was conducted by Midland Compounding, Inc.

Blending and pelletizing of the PP/PE recovered from shredder residue by Argonne was tested by Palmer Plastics, Inc. Molding trials using the recovered PP/PE were also done by MGV Enterprises.

### **4.1 POLYMER PHYSICAL PROPERTIES AND MATERIALS COMPOSITION ANALYSIS**

Typically, about 10-lb samples of recovered materials are used to define physical properties and to characterize the composition of a material. To quantify the physical properties of a 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. Common 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.

#### 4.1.1 Physical Properties and Composition of the PP/PE Recovered from Shredder Residue

The physical properties of PP/PE recovered from different shredder residues by Argonne and by others were determined for several samples. The results for the Argonne materials are given in Table 16. Properties of commercially available PP and PE virgin resins and for PP from dismantled automobiles are presented in Table 17 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 16 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 18. The properties of the Salyp-recovered PP/PE are equivalent to the properties of the Argonne-recovered PP/PE.

**TABLE 16 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 (°F) (at 66 psi)	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 17 Commercial Grades of PP and PE (Boedeker) (<http://www.boedeker.com/mtable.htm>), Unless Specified Otherwise**

Property	PP Homo-Polymer	PP Co-Polymer	PP-FR	Standard PP Co-polymer	LDPE	HDPE
MFR (g/10 min; 230°C)	0.5–136 <sup>a</sup>					
Izod impact (ft-lb/in.)	1.9	7.5	0.65	0.7	No Break	3
Flex Mod (1,000 psi)	180	160	145	120	200	125
Tensile strength (1,000 psi)	4.8	4.8	4.3	5.2	2.0	4.6
Elongation (%)	12	23	28	600	600	900
DTUL (°F) (at 66 psi)	210	173	106	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*					

<sup>a</sup> 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.

**TABLE 18 Properties of PP/PE Recovered by Salyp from Different Shredder Residues**

Property	Salyp Data
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 (1,000 psi)	2.4–2.9
Tensile strength at rupture (1,000 psi)	2.2–2.8
Elongation at rupture (%)	19–57
DTUL (°F at 66 psi)	150–169
Gardner impact (73°F, in.-lb)	190–240
Specific Gravity (g/cc)	0.93

#### **4.1.2 Physical Properties and Composition of the Recovered Filled ABS**

Filled ABS recovered by the Argonne froth flotation process followed by removal of the rubber by the Argonne dry mechanical process contained 70% filled ABS (specific gravity greater than 1.07 and less than 1.1), 1.5% PS, 8% PPO, 3% rubber, 3% PP, 7% nylon, and 7.5% other materials. The physical properties of this recovered filled ABS were determined (Table 19) and were compared with properties of a commercially available virgin ABS. Table 19 also shows the properties of two blends of the recovered ABS with virgin ABS (25% recovered/75% virgin and 10% recovered/90% virgin). Interestingly, except for elongation at rupture and Gardner Impact, the properties of the blends were very close to the properties of the virgin material.

#### **4.1.3 Physical Properties of the Polymers Recovered by MBA Polymers**

The physical properties of the MBA recovered fractions (see Section 6.1.5.2) were determined by MBA Polymers. The results are given in Table 20.

#### **4.1.4 Physical Properties of Polymers after Processing to Remove the PCBs**

Samples of the polyolefins used in the devolatilization testing at Midland Compounding to remove the PCBs (see Section 3.2.5) were sent for IZOD analysis. The results are summarized in Table 21. The value for the different samples is 10.8 +/-1.8 with a standard deviation of 0.3. The value for the material before processing was 10.2. Therefore, this processing did not negatively impact the IZOD value of the samples.

### **4.2 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), and ultra-high-molecular-weight (UHMW) polyethylene;
- Polypropylene;
- Polystyrene (general purpose, high impact); and
- Polyvinyl chloride (PVC).

**TABLE 19 Properties of Recovered Filled ABS, Virgin ABS, and Blends of the Two Materials**

Property	Recovered Filled ABS	Virgin ABS (342 EZ)	90% Virgin/ 10% Recovered	75% Virgin/ 25% Recovered
MFR (g/10 min; 230°C, 3.8 kg)	3.9	6.5	7.6	6.4
Izod Impact (ft-lb/in.; 73°F)	0.9	3.8	3.0	2.6
Flex Mod (1% secant; 1,000 psi)	324	296	299	302
Tensile strength at yield (psi)	4982	5546	5392	5312
Tensile strength at rupture (psi)	4956	4459	4544	4930
Elongation at rupture (%)	2	56	9	6
DTUL (°F, at 264 psi)	162	165	166	164
Gardner Impact, (73°F; in.-lb)	0	>320	32	8
SG (g/cc)	1.08	1.05	1.05	1.06

**TABLE 20 Properties of Plastics Recovered by MBA**

Sample	ABS	HIPS	PP Filled	PP Unfilled
MFR (g/10 min; 230°C, 3.8 kg)	N/A	N/A	N/A	5.5
MFR (g/10 min; 200°C, 5 kg)	N/A	N/A	2.5	N/A
MFR (g/10 min; 230°C, 2.16 kg)	4.6	7.9	N/A	N/A
Izod Impact (ft-lb/in.; 73°F)	10.3	1.6	1.8	3.4
Flex Mod (1% secant; 1,000 psi)	130	293	315	361
Tensile strength at yield (psi)	3029	3779	4319	6291
Tensile strength at rupture (psi)	1773	2365	4011	5623
Elongation at rupture (%)	50	32	19	6
DTUL (°F, at 264 psi)	N/A	N/A	162	170
DTUL (°F, at 66 psi)	150	232	N/A	N/A
Gardner Impact (73°F; in-lb)	216	64	16	16
SG (g/cc)	0.94	1.07	1.05	1.06

**TABLE 21 Impact Test Results from Vacuum Devolatilization Testing**

Sample Number	Temperature (°C)	Screw RPM	Feed (lb/h)	Notes	IZOD (ft-lb/in)
1	325	300	20		9.94
2	325	300	10		8.97
3	325	100	20		12.6
4	325	100	10		11.11
5	287	200	15		10.65
6	287	200	15	No vacuum	11.55
7	287	200	15	Water added at feed	11.81
8	250	300	20		10.23
9	250	300	10		11.66
10	250	100	20		10.06
11	250	100	10		9.85
12				Polymer flakes before treatment	10.16

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 are 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.<sup>3</sup> Table 22 gives the properties of PP dismantled from automobiles as part of the USCAR U.S. field trial. The recovered PP was reported to have a specific gravity of 0.915 and was made of 99.2% PP, 0.4% PE, and 0.4% ABS. The differences in the properties of the dismantled PP and the PP/PE recovered from shredder residue are also compared in Table 23.

The differences are not significant and do not affect the usefulness of the material. For example, the specific gravity of the material recovered at Argonne is about 0.94 compared to 0.915 for the dismantled material. The MFR reflects the largest difference: 17 for one of the two samples of the dismantled flakes versus about 9.4 for the material recovered from shredder residue. The USCAR study also found that the properties of the dismantled PP responded as expected when additives were added to the PP. For example, the Izod increased from less than 2 ft-lb/in. to about 11 when 10% of an impact modifier was added and to about 14 when 20% was added<sup>4</sup>.

<sup>3</sup> "USCAR U.S. Field Trial for Automotive Polymers Recycling," by W.W. Gallmeyer, C.M. Duranceau, R.L. Williams, and G.R. Winslow, SAE Paper Number 2003-01-0645, 2003

<sup>4</sup> "USCAR U.S. Field Trial for Automotive Polymers Recycling: Interim Findings," by W.W. Orr, SAE Paper Number 2000-01-0735, 2000.

**TABLE 22 Comparison of the Properties of PP Dismantled of Cars as Part of the USCAR U.S. Trial<sup>a</sup> with PP Recovered by the Argonne Process from Shredder Residue**

Property	Recovered, Extruded	Recovered Flakes, Sample #1	Average Properties of Recovered PP/PE <sup>b</sup>
MFR (g/10 min; 230°C 0	19.9	17	9.4
Izod impact (ft-lb/in.); 73°F 0	1.8	1.8	8.6
Flex. Mod. (1%, secant; 1,000 psi)	136.9	131.9	99
Tensile Strength at Yield (1,000 psi)	3.130	3.136	2.8
Elongation at Yield (%)	19	18	24.3
Tensile Strength at Rupture (1000 psi)	2.388	2.384	2.1
Elongation at Rupture (%)	59	60	119.8
DTUL (°F, at 66 psi)	129.7	136.5	145

<sup>a</sup> SAE Paper Number 2003-01-0645, "USCAR U.S. Field Trial for Automotive Polymers Recycling," by W.W. Gallmeyer, C.M. Duranceau, R.L. Williams, and G.R. Winslow

<sup>b</sup> From Table 16

**TABLE 23 Properties of Recovered PP/PE when Mixed with Regrind**

Property	Argonne, As Recovered Sample 9 (see Table 16)	Regrind As Is	Pelletized Blend
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 (°F, at 66 psi)	171	197	176
Gardner impact (73°F; in.-lb)	32	>320	132
SG (g/cc)	0.94	0.91	0.92

### 4.3 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.

### 4.4 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 min. The blended material was then run through an extruder and pelletized. The general appearance of the final pellet was excellent (Figure 12). Properties of the properties of the regrind and of the resulting pellets are shown in Table 23. 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.



**FIGURE 12 Pelletized PP/PE Product Recovered from Shredder Residue**

Screen changes are typically performed at pressure differences between 500 psi and 1,000 psi. In this test, changes were done when it 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.

## 4.5 MOLDING 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 13). A standard molding machine was used in these trials. 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.



**FIGURE 13** Auto Parts Molded from PP/PE Recovered from Shredder Residue

## **5 TASK 4. CRADA REPORTING**

The Contractor, with input from the Participants, prepared and submitted to DOE annual progress reports. This document is the CRADA final report.

## 6 CRADA TEAM PUBLICATIONS

### 2009

*Impact of Recycling Automotive Lightweighting Materials on Sustainability*, B.J. Jody, J.A. Pomykala Jr., J.S. Spangenberg, and E.J. Daniels, 2009 SAE World Congress, Detroit, MI, April 20–23, 2009.

### 2008

*Developing a Technical Roadmap for Automotive Lightweight Metals Recycling*, J.A.S. Green, Light Metal Age, December 2008.

### 2007

*Automotive Recycling in the United States: Energy Conservation and Environmental Benefits*, B.J. Jody, J.A. Pomykala Jr., J.S. Spangenberg, and E.J. Daniels, The Journal of Metals, Vol. 59, No. 11, pp. 41–45, Nov. 2007.

*Technologies for Recycling Shredder Residue*, B.J. Jody and E.J. Daniels, SAE Paper No. 2007-01-0526, SAE World Congress, Detroit, MI, April 2007.

*Mass Balance and Composition Analysis of Shredder Residue*, J.A. Pomykala Jr., B.J. Jody, J.S. Spangenberg, and E.J. Daniels, SAE Paper No. 2007-01-0527, 2007 SAE World Congress, Detroit, MI, April 2007.

*Mass Balance and Composition Analysis of Shredder Residue*, J.A. Pomykala Jr., B.J. Jody, J.S. Spangenberg, and E.J. Daniels, SAE Paper No. 2007-01-0527, 2007 SAE Transactions Journal of Materials & Manufacturing, August 2008.

*Metal Recovery from Shredder Residue Fines*, T. Allen, SAE Paper No. 2007-01-0528, 2007 SAE World Congress, Detroit, MI, April 2007.

*Thermoplastic Separation and Recovery from Various Mixed Scrap by the Argonne Developed Froth Flotation Technology*, J.A. Pomykala Jr., B.J. Jody, and E.J. Daniels, Proc. of the 13<sup>th</sup> Annual Global Plastics Environmental Conference (GPEC), Orlando, FL, March 6–7, 2007.

*A Mechanical Separation Process to Recover Metals and Polymers from Shredder Residue*, J.A. Pomykala Jr., B.J. Jody, E.J. Daniels, J. Yang, and J.S. Spangenberg, TMS 2007 Annual Meeting & Exhibition, Orlando, FL, Feb. 25–March 1, 2007.

## 2006

*Recovery and Recycling of Polymers from Shredder Residue*, B.J. Jody, J.A. Pomykala Jr., J.S. Spangenberg, and E.J. Daniels, *The Journal of Solid Waste Technology and Management*, Vol. 23, No. 4, Nov. 2006, pp. 228–236.

*Scale Up Study on Converting and Recycling Shredder Residue into a Fuel Oil*, G.R. Winslow, G.R. Appel, B.S. Adams, T.N. Simon, N.L. Duranceau, C.M. Wheeler, and S. Candace, SAE Paper No. 2006-01-1580, SAE 2006 World Congress, Detroit, MI, 2006.

*Recycling of Polyurethane Foams Recovered From Shredder Residue Via Glycolysis Process Into Polyurethanes*, V. Sendijarevic, I. Sendijarevic, K. Mayne, G.R. Winslow, C.M. Duranceau, N.L. Simon, and C.S. Wheeler, SAE Paper No. 2006-01-1579.

*A Life Cycle Look at Making Oil from End-of-Life Vehicles*, C.S. Wheeler, N.L. Simon, M. Binder, G.R. Winslow, and C.M. Duranceau, SAE Paper No. 2006-01-0374, SAE 2006 World Congress, Detroit, Michigan, 2006.

*The R&D of the FreedomCAR Materials Program*, J.A. Carpenter Jr., E.J. Daniels, P.S. Sklad, C.D. Warren, and M.T. Smith, Proc. of the International Auto Body Congress, Novi, MI, September 19, 2006.

*Market Driven Technology Development for Sustainable End-of-Life Vehicle Recycling: A Perspective from the United States*, E.J. Daniels, B.J. Jody, J.A. Pomykala Jr., and J.S. Spangenberg, presented at the 6th International Automobile Recycling Congress, Amsterdam, Netherlands, March 15–17, 2006.

## 2005

*Chemical Recycling of Mixed Polyurethane Foam Recovered from Shredder Residue into Polyurethane Polyols*, V. Sendijarevic, I. Sendijarevic, G.R. Winslow, C.M. Duranceau, N.I. Simon, and C.S. Wheeler, SAE Paper No. 2005-01-0850.

*Industry and Government Collaboration to Facilitate Sustainable End-of-Life Vehicle Recycling*, E.J. Daniels, 2005 ASME International Mechanical Engineering Congress & Exposition, BRTD-4: Sustainability Applications in Product Design and Manufacture, Orlando, FL, November 5–11, 2005.

*Modular Life Cycle Model — Basis for Analyzing the Environmental Performance of Different Vehicle End-of-Life Options*, M. Binder, N.L. Simon, C.M. Duranceau, C.S. Wheeler, and G.R. Winslow, Proc. of the 5<sup>th</sup> International Automobile Recycling Congress, Amsterdam, March 9–11, 2005.

*Modular Life Cycle Model of Vehicle End-of-Life Phase — Basis for Analysis of Environmental Performance*, C.S. Wheeler, N.L. Simon, C.M. Duranceau, G.R. Winslow, and M. Binder, SAE Paper No. 2005-01-0847.

*United States National Life Cycle Inventory Database Project, A Status Report*, J.L. Sullivan, C.S. Wheeler, and N.L. Simon, SAE Paper No. 2005-01-0852.

*Recycling Shredder Residue Containing Plastics and Foam Using a Thermal Conversion Process*, G.R. Winslow, B.S. Appel, T. Adams, N.L. Simon, C.M. Duranceau, C.S. Wheeler, and V. Sendijarevic, SAE Paper No. 2005-01-0848.

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

## 2004

*Advanced Separation of Plastics from Shredder Residue*, G.R. Winslow, N.L. Simon, C.M. Duranceau, R. Williams, C.S. Wheeler, M. Fisher, A. Kistenmacher, and I. VanHerpe, SAE Paper No. 2004-01-0469

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

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

*Market Driven Automotive Recycling in North America*, C. Duranceau, 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*, E.J. Daniels, J.A. Carpenter Jr., C. Duranceau, M. Fisher, C. Wheeler, and G. Winslow, JOM, The Mineral, Metals & Materials Society, Vol. 56, No. 8, pp. 28–32, Aug. 2004.

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

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

## 2003

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

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

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

*Processes for Recycling the Non-Metallic Portion of Obsolete Automobiles*, B.J. Jody, E.J. Daniels, and J.A. Pomykala Jr., U.S. Environment-2003 On-Line Conference, July 14–25, 2003.

*Cost Effective Recovery of Thermoplastics From Mixed Scrap*, B.J. Jody, J.A. Pomykala Jr., and E.J. Daniels, Materials Technology, Vol. 18, No. 1, pp. 18–24, March 2003.

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





**Energy Systems Division**

Argonne National Laboratory  
9700 South Cass Avenue, Bldg. 362  
Argonne, IL 60439-4815

[www.anl.gov](http://www.anl.gov)



U.S. DEPARTMENT OF  
**ENERGY**

Argonne National Laboratory is a U.S. Department of Energy  
laboratory managed by UChicago Argonne, LLC