

## 7. RECYCLING

### A. Recycling Assessments and Planning

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#### *Participants:*

*This project is conducted as part of a Cooperative Research and Development Agreement (CRADA) among Argonne, USCAR's Vehicle Recycling Partnership<sup>1</sup>, and the Plastics Division (formerly the American Plastics Council) of the American Chemistry Council.*

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*Contractor: Argonne National Laboratory*

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### **Objectives**

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

### **Approach**

- Consult with automotive manufacturers and recycling industries, USCAR and its affiliates, national laboratories, universities, and other relevant organizations to assess critical recycling needs/barriers.
- Develop a recycling research plan that will serve as a "working document" to guide the U.S. Department of Energy (DOE) in establishing priority goals, with an initial emphasis on lightweighting body and chassis materials.

- Establish an outreach/communication function to enable cooperation amongst, and leveraging of, resources with all stakeholders and the international community.
- Assist DOE in establishing advanced recycling research and development (R&D) initiatives and provide technical oversight to ensure that priority objectives/goals are accomplished.

### **Accomplishments During this Reporting Period (FY 2006)**

- Conducted quarterly progress reviews with CRADA team.
- Conducted annual project review and gap analysis with CRADA team.
- Developed CRADA team presentation brochure (was prepared by Energetics) and one-pager.
- Conducted one-day peer review progress review. It was attended by experts in the field, in addition to the CRADA partners.
- Conducted one-day Roadmap workshop to update the 2001 Roadmap for Recycling End-of-Life Vehicles of the Future. The updated Roadmap will be issued in the first quarter of FY 2007.
- Launched 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). It includes an overview of the CRADA team activities, downloadable CRADA team brochures, a bibliography of recycle literature and presentations and annual reports of the team.
- Presented papers outlining the industry/government collaboration at international conferences.
- The CRADA team held a media event for America Recycles Day. Press releases and related news stories are accessible through the CRADA team website.
- Continued liaison with the Institute of Scrap Recycling Industries (ISRI) and the Automotive Recycling Association (ARA) and held several meetings with the CRADA partners and representatives of ISRI and ARA.

### **Prior Accomplishments**

#### FY 2005

- Conducted quarterly progress reviews with CRADA team.
- Conducted annual project review and gap analysis with CRADA team.
- Continued liaison with the Institute of Scrap Recycling Industries (ISRI) and held several meetings with the CRADA partners and representatives of ISRI.

#### FY 2004

- Conducted quarterly progress reviews with CRADA team.
- Conducted annual project review and gap analysis with CRADA team.
- Held a CRADA announcement event at Argonne on December 2, 2004 — the event was attended by representatives of the press, industry, and government.
- Established liaison with the Institute of Scrap Recycling Industries (ISRI) and held several meetings with the CRADA partners and representatives of ISRI.

#### FY 2003

- Developed 5-year project plan.
- Negotiated a CRADA with the VRP, the American Plastics Council (APC ... now the Plastics Division of the American Chemistry Council) and ANL, as partners; effort under the CRADA was initiated in August 2003.

### **Future Direction**

- Conduct gap analysis and continue development and management of the R&D plan with the CRADA partners consistent with the recommendations of the updated Roadmap. As appropriate, new recycle R&D needs that are identified will be incorporated into the plan and projects for conducting the requisite R&D will be developed.

- Conduct scheduled progress reviews.
- Maintain and update the US ELV CRADA team website.
- Continue ongoing efforts toward the milestones and objectives of the CRADA statement-of-work.
- Continue outreach efforts to broaden the basis for cooperation among stakeholders.
- Continue ongoing project efforts to assist DOE in preparation of planning documents, priority recycling R&D needs, proposal reviews, and related tasks.
- Update the ELV Roadmap as necessary.
- The team will prepare papers for presentation at the SAE Congress in FY 2007.

## **Summary**

The objective of this project is to establish priorities and develop cost-effective recycling technologies and strategies in support of the U.S. Department of Energy (DOE's) FreedomCAR and Vehicle Technologies (FCVT) Program's long-term objectives and goals. The major goals of this research are to (1) enable the optimum recycling of all automotive materials, (2) ensure that advanced automotive materials that improve the life-cycle energy use of vehicles are not precluded from use as a result of a perception that those materials are not recyclable, and (3) continue to enable market-driven vehicle recycling.

Today, cars that reach the end of their useful service life in the United States are profitably processed for materials and parts recovery by an existing recycling infrastructure. That infrastructure includes automotive dismantlers, which recover useable parts for repair and reuse; automotive remanufacturers, which remanufacture a full range of components, including starters, alternators, and engines to replace defective parts; and, ultimately, the scrap processor, which recovers raw materials such as iron, steel, aluminum, and copper from the remaining auto "hulk" after components have been recovered for recycling. Today, more than 75% of the materials from obsolete cars are profitably recoverable for recycling.

The recyclability of the remaining 25% of the end-of-life vehicles (ELVs) is limited at present by the lack of (1) commercially-proven technologies to identify and cost-effectively separate materials and components and (2) profitable post-use markets. During the next 20 years, both the number and complexity of ELVs are expected to increase, posing

significant challenges to the existing recycling infrastructure. The automobile of the future will use significantly greater amounts of lightweight materials (e.g., ultra-light steels, aluminum, plastics, and composites) and more sophisticated/complex components.

## **Roadmap Recommendations**

A workshop to update the original roadmap, which was published in 2001, was held on September 14, 2005, at Argonne. Representatives from DOE, key stakeholders, universities and other experts attended the meeting (Exhibit 1). A draft of the new roadmap has been prepared and is being reviewed by the CRADA partners. The updated roadmap will be published during the first quarter of FY 2007. The workshop evaluated the original Roadmap and its recommendations.

The following were identified as some of the factors that can affect the recyclability of future shredder residue:

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

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

- Come together as a unified recycling community to cost-share in the development of required new technology.

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

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

- Incorporate reuse, remanufacturing, and recycling into the design phase for cars whenever possible.
- Recycle as early in the recycling stream as possible, while relying on the market to optimize the value and amount recycled at each step.
- Maintain a flexible recycling process that can adapt to diverse model lines fabricated with different techniques and materials from various suppliers.
- Develop automated ways to recover bulk materials.

- Emphasize R&D on post-shred material identification, sorting, and product recovery.
- Focus R&D efforts on materials not recycled today by sorters (e.g., post-shred glass, rubber, fluids, textiles, plastics).
- Develop uses for recovered materials (whether in the same or different applications) and testing specifications.
- Encourage investment in the infrastructure needed to achieve the recyclability goal. Build on the existing infrastructure.
- Develop a means to prevent the entry of polychlorinated biphenyls and other hazardous materials into the recycling stream and promote acceptable limits in shredder residues.
- Consider the recycling requirements of new technologies entering fleets as early as possible.

**The Five-Year R&D Plan**

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

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

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

**Area 2. Materials Recovery Technology Development and Demonstration**

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

ensure the recyclability of these very advanced automotive components.

### **Area 3. Recovered Materials Performance and Market Evaluation**

Understanding and enhancing recovered materials performance is an essential ingredient to a successful recycling program. This is especially true in automotive systems when the materials and components that are recovered have been in use for an average of from 10–15 years. Area 3 includes projects to quantify the relative performance of recovered materials vis-à-vis new or virgin materials; research on compatibilization of recovered polymers to improve performance properties; development of technologies to upgrade the recovered materials, such as separation of fibers from polymeric substrates; and development of applications for other recovered materials, such as rubber and glass.

#### **CRADA Projects**

A cooperative research and development agreement (CRADA) among Argonne, the VRP and the American Plastics Council (APC – now the Plastics Division of the American Chemistry Council) has been structured to provide a core team of expertise and the resources to enable the optimum recycling of all automotive materials.

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

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

This project (Recycling Assessments and Planning) provides for the overall management of the CRADA team activities and for communication and advocacy with other organizations. The other major projects that have been initiated under the CRADA include the following:

- Baseline Assessment of Recycling Systems and Technology (see 7.B).
- Post-Shred Materials Recovery Technology Development and Demonstration (see 7.E).
- Development of Technology for Removal of PCBs and Other Substances of Concern from Shredder Residue (see 7.C).
- Compatibilization/Compounding Evaluation of Recovered Polymers (see 7.D).

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

#### **Outreach Efforts**

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

A website was launched in March of 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 CRADA team held a media event at Argonne for *America Recycles Day*. It was attended by a number of media organizations. Articles featuring the work done by the CRADA team were written by the media members who attended. CRADA team

members were interviewed by several radio stations after the media event.

Several presentations and publications were made to further communicate with interested parties including a paper “Market Driven Technology Development for Sustainable End-of-Life Vehicle Recycling: A Perspective from the United States,” presented by Edward Daniels at the 6th International Automobile Recycling Congress, Amsterdam, Netherlands, March 15-17, 2006. A joint DOE, USCAR, and APC paper on “Market Driven Recycling in North America” was presented as the keynote paper at the 2004 International Car Recycle Congress in Washington, D.C.

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

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

As previously mentioned, a review of the projects and ongoing efforts of the CRADA team was held September 13, 2005 and a workshop was also held on September 14, 2005, to review and update the ELV Roadmap. The updated roadmap will be issued during the first quarter of FY 2007.

### **Publications**

1. *The R&D of the FreedomCAR Materials Program*, Carpenter, J.A., 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.
2. *Market Driven Technology Development for Sustainable End-of-Life Vehicle Recycling: A Perspective from the United States*, Daniels, E.J., Jody, B. J., Pomykala, J. A. Jr., and Spangenberg, J. S., presented at the 6th International Automobile Recycling Congress, Amsterdam, Netherlands, March 15-17, 2006.
3. *Industry and Government Collaboration to Facilitate Sustainable End-of-Life Vehicle Recycling*, Daniels, E. J., 2005 ASME International Mechanical Engineering Congress & Exposition, BRTD-4: Sustainability Applications in Product Design and Manufacture, Orlando, Florida, November 5-11, 2005
4. *Market Driven Automotive Recycling in North America*, Duranceau, C., presented at the Institute of Scrap Recycling Industries Shredder Meeting, Dallas, TX (Oct. 30, 2004).
5. *Sustainable End-of-Life Vehicle Recycling: R&D Collaboration between Industry and the U.S. DOE*, Daniels, E.J., Carpenter, J.A. Jr., Duranceau, C., Fisher, M., Wheeler, C., and Winslow, G., JOM, The Mineral, Metals & Materials Society, vol. 56, no 8, pp 28-32 (Aug. 2004).
6. *Market Driven Automotive Recycling in North America*, Duranceau, C., USCAR, Carpenter, J., U.S. DOE, Fisher, M., American Plastics Council, keynote at the 2004 International Car Recycling Workshop, May 19, 2004, Washington D.C.
7. *Automotive Materials Recycling: A Status Report of U.S. DOE and Industry Collaboration*, Daniels, E. J., Ecomaterials and Ecoprocesses, Proc. of the International Symposium on Ecomaterials and Ecoprocesses, August 24-27, 2003, Vancouver, BC, Canada, pp 389-402.
8. *Effects of Transportation on the Ecosystem*, Carpenter, J.A., Jr., Ecomaterials and Ecoprocesses, Proc. of the International Symposium on Ecomaterials and Ecoprocesses, August 24-27, 2003, Vancouver, BC, Canada, pp 13-22.
9. *Automotive Technology: Looking Forward*, Sullivan, R., D. Hamilton and J.A. Carpenter, Jr., Ecomaterials and Ecoprocesses, Proc. of the International Symposium on Ecomaterials and Ecoprocesses, August 24-27, 2003, Vancouver, BC, Canada, pp 49-67.

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

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<sup>i</sup> One of the formal consortia of the United States Council for Automotive Research (USCAR) set up by the “Big Three” traditionally U.S.-based automakers to conduct joint pre-competitive research and development.

## B. Baseline Assessment of Recycling Systems and Technology

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### *Participants:*

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*Michael Fisher, American Chemistry Council, (703) 741-5599, e-mail: Mike\_Fisher@americanchemistry.com*

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*Contractor: Argonne National Laboratory*

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

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### **Objective**

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

### **Approach**

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

### **Accomplishments During this Reporting Period (FY 2006)**

- Completed compilation of recycle bibliography, structured as a pull down PDF, posted on 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).
- Completed Changing World Technologies (CWT) life-cycle case study.
- Completed life-cycle study of Argonne process technology.
- Completed second draft of state-of-the-art assessment in recycling of vehicles and automotive materials. The final document will be published in the first quarter of FY 2007.



## Prior Accomplishments

### FY 2005

- Conducted a literature search that identified mechanical, thermo-chemical conversion, and energy-recovery technologies and completed first draft of state-of-the-art assessment.
- Completed Salyp life-cycle case study, initiated CWT life-cycle case study.

### FY 2004

- Compiled and structured recycle bibliography.
- Characterized North American recycle infrastructure.
- Conducted a review of U.S. regulatory issues.
- Initiated life-cycle studies of end-of-life recycle technologies (Salyp case study).
- Completed reference recyclability calculations for reference cases and three lightweight alternatives: lightweight steel, composite materials, and aluminum.

## Future Direction

The focus of this task in FY 2007 will be on:

- Updating the database of recycle technologies
- Complete the life-cycle study of current shredding operations
- Update the document reviewing technologies for recycling shredder residue

## Summary

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

The focus of the work under this activity is (1) to develop the tools and document the information necessary to make effective decisions relative to technology needs to facilitate sustainable future vehicle recycling and (2) to make effective decisions regarding allocation of R&D resources.

The state-of-the-art of worldwide automotive-materials-recovery/recycling technologies and associated resource-recovery infrastructures have been reviewed to identify technology gaps and needs and to identify differences in automotive-recycling strategies among the North America, Europe, and Asia. Technologies 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.

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

Regulations at the international, federal, and state levels are examined to identify the impact that proposed and existing regulations may have regarding recycling of automotive materials. Reference-case recyclability calculations are made to quantify the expected recyclability of alternative vehicle designs.

## Infrastructure

The North American recycling infrastructure has been characterized and a representative figure was shown in previous annual reports.

**Technology Profiles**

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

A bibliography of abstracts of papers that discuss automotive-recycling issues has been compiled; see Table 1. The bibliography is organized into the fifteen sections shown.

The bibliography was compiled from an extensive literature search, which included the following sources:

1. Society of Automotive Engineers (International) World Congresses from 1997 to 2004
2. Environmental Sustainability Conference and Exhibition, 2001
3. Society of Plastics Engineers:
  - ARC '98 Conference
  - ARC '99 Conference
  - ARC '00 Conference
  - GPEC 2002 Conference
  - GPEC 2003 Conference
4. Other conference proceedings:
  - International Automobile Recycling Congress 2001, 2002, 2003, 2004
  - TMS Fourth International Symposium of Recycling of Metals and Engineered Materials, 2000.
  - Ecomaterials and Ecoprocesses, The Conference of Metallurgists, COM 2003

The complete bibliography has been 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).

More references have been identified and will be added to the bibliography.

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

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

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

A draft document describing the state-of-the-art in recycling technologies for end-of-life vehicles, post-shred residue, and automotive materials has been prepared and it has been reviewed twice by the CRADA partners. The final document will be published in the 1st quarter of FY 2007. Because post-shred residue contains residue from shredded white goods and other obsolete items (in addition to vehicles), these were also discussed in the document. The table of contents of this document is shown in Table 2.

**Regulatory Situation**

The European Union has issued End-of-Life Vehicle Recycle Directives. The enforcement of these directives is, however, the responsibility of each member state. Although the United States has not developed a federal policy or mandate, regulations at the federal and state level can impact the technology needs for recycling automotive materials. For example, U.S. Environmental Protection Agency (EPA) regulations regarding polychlorinated

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

### **Life-Cycle Studies**

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

PE Europe GmbH, a company that is experienced in conducting life-cycle assessments and in model development using its own GaBi (Ganzheitliche Bilanzierung) software, was contracted to perform these analyses. Three analyses have been completed for: (1) Salyp NV's mechanical separation process, (2) Changing World Technologies' (CWT's) thermal-conversion process, and (3) Argonne mechanical and froth-flotation process. PE Europe has developed a flexible end-of-life model, and the model was used to compare the two different approaches to recycling shredder residue. The model allows the user to run simulations on shredder-residue separation within different boundary conditions. The following boundary conditions can be modified: (1) shredder-residue composition, (2) location of the facility, (3) type and distance of transportation, (4) market values for the separated fractions, (5) new potential applications for separated fractions, and (6) utilization ratio of the facility.

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

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

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<b>1.0. Introduction and Background</b>
<b>2.0. The Process of Recycling Automobiles</b>
— <i>Dismantling for Direct Resale</i>
— <i>Shredding</i>
<b>3.0. The Process for Recycling White Goods</b>
— <i>Refurbishing of Units for Resale</i>
— <i>De-Pollution of the Units</i>
— <i>Shredding</i>
<b>4.0. Shredder Residue</b>
— <i>Composition</i>
— <i>Recycling of Materials from Shredder Residue</i>
<b>5.0. Technologies for Concentrating Recyclables from Shredder Residue</b>
— <i>Mechanical Separation Systems</i>
— <i>Gravity Separators</i>
— <i>Electrostatic Separators</i>
<b>6.0. Technologies for Separating and Recovering Products from Shredder Residue</b>
— <i>Argonne's Separation and Recovery of Flexible Polyurethane Foam</i>
— <i>Separation and Recovery of Plastics from Shredder Residue</i>
• <i>Argonne's Froth Flotation Process</i>
• <i>The RPI Process</i>
• <i>The Salyp Process</i>
• <i>The VW/SiCon Process</i>
• <i>The Galloo Process</i>
• <i>The MBA Process</i>
• <i>The Toyota Process</i>
<b>7.0. Thermochemical Processes for Recycling Shredder Residue</b>
• <i>CWT Hydrolysis Process</i>
• <i>TPI Glycolysis Process</i>
• <i>Other</i>
<b>8.0. Energy Recovery from Shredder Residue</b>
<b>9.0. Substances of Concern</b>
— <i>Polychlorinated Biphenyls (PCBs)</i>
— <i>Heavy Metals</i>
— <i>Flame Retardants</i>
<b>10.0. Recycling of Advanced Vehicles</b>
— <i>Recycling of Fuel Cell vehicles</i>
— <i>Recycling of Electric and Hybrid Vehicles</i>
— <i>Recycling of Aluminum and Magnesium from New Generation vehicles</i>
— <i>Recycling of Composites</i>
<b>11.0. Chemical Recycling of Shredder Residue</b>
<b>12.0. Conclusions</b>

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Data were collected for each of the three processes, including all energy, water, and material inputs, plus data on emissions to air and water, wastes, and products produced. The three sets of data were entered into the GaBi software to create a flexible model of the process.

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 had the greatest benefit. However, if the mixed plastic stream was used to replace wood (e.g., decking material, park benches, wood pallets, etc.), the benefits to primary energy demand were less than if the recovered materials were simply used for energy recovery. In terms of CO<sub>2</sub> emissions, the PP application again showed the greatest benefit. Substituting PP for wood applications was next with a lower benefit, while the energy-recovery scenario showed 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. In the case of CO<sub>2</sub> emissions, all scenarios again showed an overall benefit. However, the diesel-substitution case had a greater benefit than the fuel-oil-substitution case.

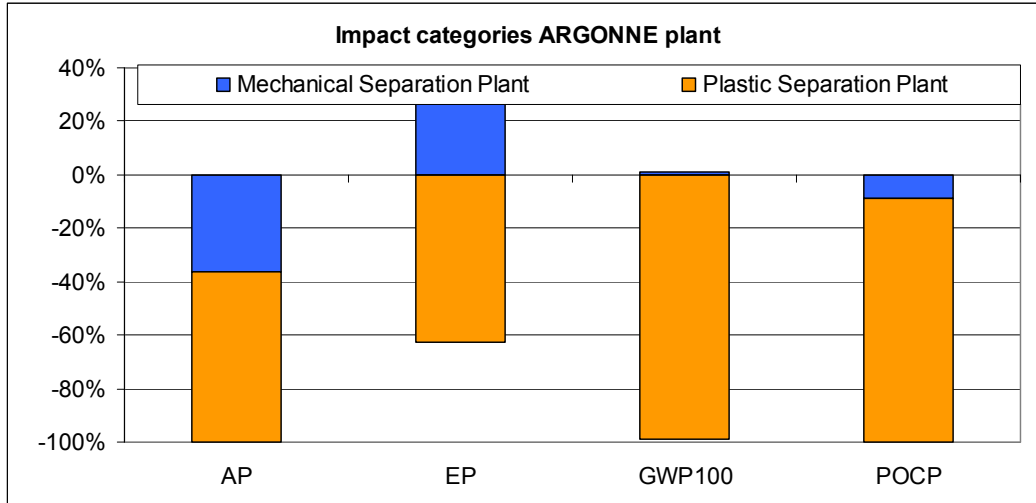
Life-cycle analysis of the Argonne process considered both the mechanical separation of the shredder residue to produce a polymer concentrate

and recover residual metals, followed by froth flotation to separate plastics from the polymer concentrate for recycling as plastics (material substitution). The analysis concluded 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 3) and CWT processes (Table 4). The environmental benefits are higher for the Argonne process compared to the Salyp process except for the acidification potential and higher for the Argonne process compare to the CWT process except for the impact category EP and NO<sub>x</sub> emissions. Energy-wise, the Argonne process was the most advantageous. Interestingly, the best results can be obtained by combining both (Argonne and CWT) processes, where organic fractions separated by Argonne which do not meet the requirements for material substitution (such as mixed plastics and rubber by-products) are processed by CWT for fuel production.

### **Recyclability Studies**

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

In collaboration with Johnson Controls, Inc. (JCI), the VRP dismantled the vehicle according to its 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 5. In comparison, the materials composition of a production Ford Taurus is summarized in Table 6.



**Figure 1.** Impact categories of the Argonne plant. (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). (Y axis indicates increase (+) or decrease (-) in the impact of the different categories).

**Table 3.** 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).

	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

**Table 4.** Comparison of the Argonne froth-flotation and CWT processes - Relative Environmental Impact. Both processes require mechanical separation of the inorganic fraction. (A negative value indicates a reduction in the pollution category (an environmental benefit) while a positive value indicates an increase in the pollution category).

	ARGONNE process (Froth Flotation*)	CWT process
AP [lb SO <sub>2</sub> -Equiv.]	-0.01103	-0.00662
EP [lb Phosphate-Equiv.]	-0.00055	-0.00079
GWP100 [lb CO <sub>2</sub> -Equiv.]	-4.167	-0.309
POCP [lb Ethene-Equiv.]	-0.0088	-0.0044

\* Comparison is done here only with the froth-flotation process because both Argonne’s froth-flotation process and CWT’s process require mechanical separation of the inorganic materials.

**Table 5.** 2004 Toyota Prius materials breakdown.

Materials	Mass (lb)	Percent
Ferrous metals	1713	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)	2829	100.0

**Table 6.** 2004 Ford Taurus materials breakdown.

Materials	Mass (lb)	Percent
Ferrous metals	2223	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)	3159	100.0

Three different recyclability calculations were made (Table 7). The Federal Trade Commission (FTC) recyclability number is the percentage by weight of the material that is currently being recycled, and it includes metals, fluids less fuel, and batteries. The European guidelines include FTC materials plus fuel at 90% of a full tank, plastics that could be recycled, and up to 10% by weight energy recovery. Note that Europe requires 95% recyclability for new vehicles. The feasibility-to-recycle number includes the FTC materials plus plastics that can be recycled. Changes to the current infrastructure would be required to increase recycling beyond the current FTC percentage.

To establish an indication of the impact of lightweight materials on the reference-case recyclability calculations, the 2004 Toyota Prius is compared with a proposed aluminum-intensive lightweight vehicle and a proposed composite lightweight vehicle, both of which are also based on the 2004 Prius. The production 2004 Toyota Prius hybrid vehicle body was steel with an aluminum

**Table 7.** 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

hood and decklid. The suspension was of steel, except for an aluminum steering knuckle on the front suspension. This vehicle was used as the base for this study.

The aluminum alternative is for a 2004 Toyota Prius with an aluminum body and a magnesium engine cradle and a rear axle substituted for the production parts. In addition, seat frames, body brackets, and the instrument panel cross car beam have been changed from steel to aluminum. As a result, the weight has been reduced by approximately 630 lb or 21%. Because the weight reduction is entirely in the currently recycled portion of the vehicle, the recyclability is adversely affected and is reduced from 80.86% to 76.10%. No changes were made to the currently 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 adversely affected and is reduced from 80.86% to 57.20% if none of the composite is recycled or 74% if all of the composite material is recycled. No changes were made to the currently non-recycled portion of the vehicle. The composite material replaced steel at 40 wt% of the original steel.

There are reductions in all three recyclability calculations for lightweighted vehicles, even though the rest of the vehicle is not changed (Table 8). Where the aluminum and composite material is being recycled, the same amount of material would be disposed of in landfills in each of the three scenarios. The only difference is that the recycled portion of the lightweighted vehicles would be lighter. Although the recyclability would be less, there would be no difference in the amount of material disposed of in landfills, and the lighter vehicles would use less fuel during their life. As can be seen, lightweighting presents challenges in the European market. Note that these calculations do not take into account the downsizing of related components that would accompany any lightweight vehicle, such as powertrains, brakes, and tires. Because the downsized components are high in metallic content, downsizing will further reduce recyclability and make it difficult to meet the European 95% requirement.

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

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

A seminar to address recyclability and recycled content in view of changing automotive materials has been planned.

**Table 8.** 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.

### **Publications**

1. *A Life Cycle Look at Making Oil From End-of-Life Vehicles.*, Wheeler, C.S., Simon, N.L., Binder, M., Winslow, G.R., Duranceau, C.M., SAE 2006 World Congress, Detroit, Michigan, 2006. SAE-2006-01-0374.
2. *Modular Life Cycle Model — Basis for Analyzing the Environmental Performance of Different Vehicle End-of-Life Options*, Binder, M.; Simon, N.L.; Duranceau, C.M.; Wheeler, C.S.; Winslow, G.R., Proc. of the 5<sup>th</sup> International Automobile Recycling Congress, Amsterdam (Mar. 9-11, 2005).
3. *Modular Life Cycle Model of Vehicle End-of-Life Phase — Basis for Analysis of Environmental Performance*, Wheeler, C.S.; Simon, N.L.; Duranceau, C.M.; Winslow, G.R.; Binder, M., SAE Paper 2005-01-0847.
4. *United States National Life Cycle Inventory Database Project, A Status Report*, Sullivan, J.L.; Wheeler, C.S.; and Simon, N.L., SAE Paper 2005-01-0852.

<sup>i</sup> One of the formal consortia of the United States Council for Automotive Research (USCAR) set up by the “Big Three” traditionally U.S.-based automakers to conduct joint pre-competitive research and development.

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

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### *Participants:*

*This project is conducted as part of a Cooperative Research and Development Agreement (CRADA) among Argonne, USCAR's Vehicle Recycling Partnership, and the Plastics Division (formerly the American Plastics Council) of the American Chemistry Council.*

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*Contractor: Argonne National Laboratory*

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

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## **Objective**

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

## **Approach**

- Identify efficient and environmentally-acceptable process solutions for removal of contaminants, including PCBs, from materials recovered from shredder residue.
- Define variances in analytical procedures/test results for PCB analysis.
- Accomplishments During this Reporting Period (FY 2006)
- Argonne developed a two-stage cleaning process which in bench-scale tests has consistently produced plastics from the PP/PE product with <2 ppm PCBs.
- Completed tests in the commercial-solvent washing equipment using proprietary solvent-based solutions and in CO<sub>2</sub>.
- Cooperated with the Bromine Science and Environmental Forum (BSEF) in preparing the BSEF brochure entitled "Deca-BDE Flame Retardant."



## Prior Accomplishments

### FY 2005

- Completed the study to explain discrepancies in PCBs analytical results.
- Initiated testing of commercial-solvent washing processes for cleaning plastics.
- Conducted a study to understand the interactions between PCBs and plastics.
- Identified and initiated testing of alternative methods for PCB removal.

### FY 2004

- Completed the solvent/detergent screening study for removing PCBs and heavy metals from plastics.
- Completed aqueous cleaning tests in commercially-available equipment.
- Initiated a study to explain discrepancies in PCBs analytical results.

## Future Direction

The FY 2007 plan includes:

- Develop experimental design and test Argonne's two-stage process at a larger scale (1-pound test) for the cleaning of the polyolefin concentrate.
- Develop a conceptual design and perform cost analysis of the process.
- Incorporate the process into the overall process design for recovering materials from shredder residue.

Argonne's two-stage process has successfully produced recovered plastics, at least PP/PE materials, with less than 2 ppm PCBs in multiple tests. However, this has been shown only in small-scale experiments. In FY 2007, larger-scale experiments will be conducted to investigate the scalability of the process including required residence time and operating temperatures.

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## Summary

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

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

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

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

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

**Development and Testing of a 2-Stage Process at Argonne**

The work done so far on washing of polymers recovered from shredder residue suggests that different washing methods appear to reduce the PCBs concentration down to about 5-10 ppm in a reasonably short time. Further reduction in the concentration of PCBs requires more extensive and prolonged washing in fresh solution, Figure 1. The prolonged washing is further complicated by the adsorption of the cleaning solution by the plastics. This suggests that the PCBs on the plastics are adsorbed by two different mechanisms. First, some are in the oils and dirt that are on the plastics. Second, some of the PCBs are adsorbed on the plastics and they do not desorb easily during washing. We tested this hypothesis in the lab. We conducted washing tests using a non-flammable solvent to wash the plastics under conditions that minimized the absorption of the solvent by the plastics. This reduced the concentrations of PCBs from about 30 ppm to about 5 ppm under a range of operating conditions. The washed plastics were then processed in an environment that induces desorption. The PCBs concentration in several tests was reduced to below 2 ppm. Tests were also conducted where unwashed samples were exposed to the same environment that induces desorption. The PCBs concentration could not be reduced below 2 ppm. We are filing for a patent on the process.

A 2-stage process, based on this concept, has been developed and tested at Argonne which has repeatedly reduced the PCBs concentration in polypropylene/polyethylene samples recovered from

shredder residue to less than 2 ppm. We are filing for a patent on the process.

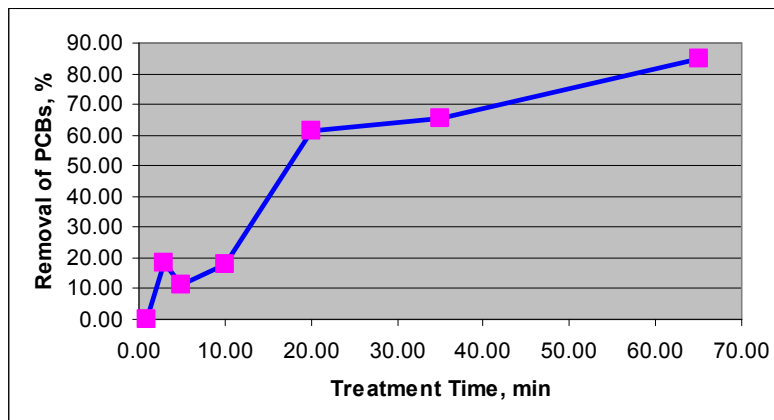
**Evaluation and Testing of Solvent-Based Washing Systems**

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

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

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

Environmental Technology Unlimited uses a proprietary METHEX solvent-based system and aqueous-based systems. Environmental Technology Unlimited performed six treatments of shredder residue plastics, and five out of the six washed samples reduced the PCBs concentration to below 2 ppm. The METHEX solvent-based system was superior to the aqueous system. Unfortunately, the company does not have equipment to conduct large-scale testing of the process using plastics.



**Figure 1.** Removal of PCBs with time using a non-flammable organic solvent.

Cool Clean Technologies technology used CO<sub>2</sub> only. The washing failed to remove the PCBs. itec Environmental Group reduced PCB levels in the plastics from 11 ppm to 2.8 ppm via solvent washing; no CO<sub>2</sub> treatment, which normally follows the basic process, was used.

Further testing was conducted by itec in their new facilities in California, using plastics recovered by the Argonne process. The plastics were washed using itec's proprietary solvent and then with liquid CO<sub>2</sub>. Two samples received by Argonne were analyzed and both showed residual PCBs concentration on the order of 5 ppm. Another series of trials were conducted at itec using different process conditions. Analysis showed the residual concentration of PCBs was still higher than 2 ppm.

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

Before testing the solvent-based systems, large-scale cleaning/washing tests were conducted using plastics from shredder residue by means of aqueous solutions and a surfactant previously identified earlier as the most promising from among many tested. The objective was to identify the limitations of the various types of existing washing equipment. Testing was done by using an ALMCO rotary-drum washer equipped with a dryer and SeKoN centrifuge equipment. The tests were carried out on about 100 lbs of plastic chips each. The particles were between 0.2 and 0.5 in. in size. Under a CRADA contract, GraPar Corporation built, for Troy Polymers, Inc. (TPI), and tested a specially-designed machine that has a design capacity of about 300 lbs/hour of plastics. TPI conducted further testing on this machine in its facilities.

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

The results suggest that existing aqueous-based equipment, as is, is not likely to reduce the concentration of PCBs to acceptable levels. Modifications are necessary to wash small chips

(1/8 to 1/2 in.) of plastics — such as what will be recovered from shredder residue.

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

The large variability in the analytical results raised questions about the analytical sampling and analyses procedures. Therefore, experiments were performed to develop an understanding of the variability in PCB analytical procedures, explain the variability in the results, and 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, plastics particle size, PCBs extraction procedure, analytical procedures, and/or interference from other compounds. A one-day seminar was held and attended by analytical experts from the United States and overseas to develop recommendations for improved sampling and analysis techniques specific to plastics chips recovered from shredder residue.

To investigate the possible interference of phthalates in the PCBs analysis, a sample of plastics chips derived from shredder residue was thoroughly mixed and then divided into four parts. The first part was analyzed by using gas chromatography and an electron-capture detector (GC-ECD) and by using gas chromatography/mass spectroscopy (GC/MS). The other three parts were spiked with different quantities of phthalates, as shown in Table 1, and the spiked samples were analyzed by using the same two methods. The results show no interference of the phthalates in the PCBs analysis. Interestingly, the GC/MS results were always higher than the GC-ECD results.

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

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

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

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

1. The three labs are fairly consistent for each set of samples.

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

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

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

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

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

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

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

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

- Direct analysis of the samples from the three labs showed that the concentration of PCBs in the granulated plastics was about 5 ppm, and for the 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 PCB results. Further, the results indicate that the PCBs are on the surface of the plastics and not absorbed in the plastics. After extraction, the samples all had less than 2 ppm of PCBs, except for one sample that showed 2.8 ppm.
- Calculation of the concentration of PCBs in the original samples based on the determined PCBs in the hexane extracts (prepared via 9 sonications of 300-g samples) showed that the concentrations of PCBs in the granulated samples were comparable with those of the ungranulated samples. These results further indicate that the PCBs are predominantly on the surface of the plastics and not absorbed in the plastics, otherwise the granulated samples would have shown higher concentrations.

In addition, two of the laboratories identified Aroclor 1242 as the only PCB present, while the third laboratory identified Aroclors 1232 and 1254 as the only two present. TPI also conducted an analysis of various plastics samples by using GC-ECD and GC-MS methods. The results are

compared in Table 6. Results from the two methods are in reasonable agreement, even though the GC-MS method showed higher values.

### 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 7). Limited experiments to define the operating conditions for the Soxhlet method were conducted. The results are discussed below.

### Selection of a Solvent

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

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

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

**Table 7.** Protocols for PCBs analysis.

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

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

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

**Determination of Extraction Time**

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

**Determination of Adequate Sample Size**

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

Sample preparation was also investigated. The results indicated that a well-mixed plastics sample of at least one pound should be granulated to a size of 1 mm and mixed before sampling is done.

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

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

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

**Publications**

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

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

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

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



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

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

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<sup>i</sup> One of the formal consortia of the United States Council for Automotive Research (USCAR) set up by the “Big Three” traditionally U.S.-based automakers to conduct joint pre-competitive research and development.

## D. Compatibilization/Compounding Evaluation of Recovered Polymers

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*This project is conducted as part of a Cooperative Research and Development Agreement (CRADA) among Argonne, USCAR's Vehicle Recycling Partnership<sup>1</sup>, and the Plastics Division (formerly the American Plastics Council) of the American Chemistry Council.*

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*Contractor: Argonne National Laboratory*

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

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### Objectives

- Evaluate the market opportunity for polymers recovered from shredder residue.
- Identify limitations associated with the reuse of the materials as recovered and determine the need for post-processing technology to upgrade the recovered materials to meet the requirements of the market.

### Approach

- Specify standard protocols for material testing, content characterization, and performance properties.
- Determine properties of recovered polymers.
- Conduct blending and pelletizing trials of the recovered polymers.
- Conduct mold trials using recovered polymers.

### Accomplishments During this Reporting Period (FY 2006)

- Determined the physical properties of the 70% filled acrylonitrile-butadiene-styrene (ABS) fraction .

- Determined the physical properties of two blends of the 70% filled ABS fraction with virgin ABS (10% recovered/90% virgin and 25% recovered/75% virgin).

### **Prior Accomplishments**

#### FY 2005

- Midland Compounding developed a protocol for evaluating the physical properties of recovered plastics.
- Compiled a physical properties database for virgin plastics.
- Determined physical properties of the PP/PE product recovered from the Argonne froth-flotation process and from the polypropylene/polyethylene (PP/PE) fraction recovered by the Salyp process.
- Pelletized 1000 pounds of a blend of the Argonne recovered PP/PE product.
- Conducted mold trials of the recovered PP/PE product.

### **Future Direction**

FY 2007 activities will focus on:

- Determine physical properties of the upgraded filled ABS fraction.
- Determine physical properties of the upgraded unfilled ABS and PS recovered from the unfilled ABS/PS concentrate.
- Determine physical properties of the 85% PC-ABS/PC alloy.
- Pelletize a blend of recovered filled ABS with virgin ABS and compare the properties of the blend with the properties of the virgin material.

### **Summary**

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

The project will initially focus on establishing the properties of polymeric materials that are recovered as part of the Post-Shred Materials Recovery Technology Development project (see 7.E).

Regardless of the effectiveness of any automotive-materials recovery technology, the materials that will be recovered will be on average 10–15 years old and derived from different sources (automobiles, home appliances and others). In this project, the performance properties of recovered polymers will be compared vis-à-vis new or virgin materials to establish a database of the properties of recovered automotive polymers. At present, there are few data about the physical properties of polymers recovered from post-consumer durable goods. Absent such data, it is unlikely that sustainable applications for

recycled materials will be either identified or developed.

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

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

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

Three additional companies — Collins and Aikman Corporation, Enviro-Plas Corporation, and Mayco Plastics, Inc. — have agreed to evaluate, compound,

and run mold trials by using recovered materials, subject to the physical properties of the recovered materials.

### **Polymer Physical Properties and Materials Composition Analysis**

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

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

Common physical properties that are measured for each sample include the following:

- Melt flow rate (MFR),
- Izod impact,
- Flexural modulus,
- Tensile strength at yield,
- Tensile strength at rupture,
- Elongation at rupture,
- Deflection temperature under load (DTUL),
- Gardner impact, and
- Specific gravity (SG).

### **Physical Properties and Composition of the Recovered PP/PE**

The physical properties of PP/PE recovered from different shredder residues by Argonne and by Salyp were determined for several samples. The results for the Argonne materials are given in Table 1.

Properties of commercially-available PP and PE virgin resins and for PP from dismantled automobiles are presented in Table 2 for comparison. The Izod impact of the recovered material is about three times that of the virgin resins, while the tensile strength of the recovered material is lower than the tensile strength of the virgin resins by about 30%. This phenomenon may be attributed, at least in part, to the presence of thermoplastic olefins (TPO) and rubber in the recovered material, which act as impact modifiers. Recovered samples 8, 9,

and 10 listed in Table 1 contained about 2% rubber, while samples 1 through 7 contained about 4% rubber.

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

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

Filled ABS recovered by the Argonne froth-fotation 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% others. The physical properties of this recovered filled ABS were determined. The results are given in Table 4 and are compared with properties of a commercially-available virgin ABS. Table 4 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. Operating condition to upgrade the recovered filled ABS to over 90% has been determined. Properties of the upgraded material will also be established.

### **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

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

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

\*\* Not tested

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

Property	PP-Homo Polymer	PP-Co Polymer	PP-FR	Standard PP-Co	LDPE	HDPE
MFR, (g/10 min), 230°C	0.5-136*					
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 @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*					

\* 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 3.** 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, 66 psi, °F	150–169
Gardner impact, 73°F, in.-lb	190–240
Specific Gravity, g/cc	0.93

**Table 4.** 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/10min, 230C, 3.8 kg	3.9	6.5	7.6	6.4
Izod Impact, ft.lbs./in., 73F	0.9	3.8	3.0	2.6
Flex Mod, 1% secant, ksi	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, 264 psi, °F	162	165	166	164
Gardner Impact, 73F, in.lbs.	0	>320	32	8
SG, g/cc	1.08	1.05	1.05	1.06

- Polyethylene, low-density polyethylene [LDPE], high-density polyethylene [HDPE], ultra-high-molecular-weight [UHMW] polyethylene,
- Polypropylene,
- Polystyrene (general purpose, high impact), and
- Polyvinyl chloride (PVC).

The VRP 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, Table 5 (“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 # 2003-01-0645, 2003).

Table 5 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 it is 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 5.

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 compare 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.

**Table 5.** Properties of PP Dismantled of Cars as Part of the USCAR U.S. Trial. (SAE Paper # 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).

Property	Recovered, Extruded	Recovered Flakes, Sample #1	Average Properties of Recovered PP/PE*
MFR, (g/10 min), 230°C	19.9	17	9.4
Izod impact (ft-lb/in.) 73°F	1.8	1.8	8.6
Flx. 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	129.7	136.5	145

\* From Table 1

to about 11 when 10% of an impact modifier was added, and to about 14 when 20% were added (USCAR U.S. Field Trial for Automotive Polymers Recycling: Interim Findings”, by W. W. Orr, SAE Paper # 2000-01-0735, 2000).

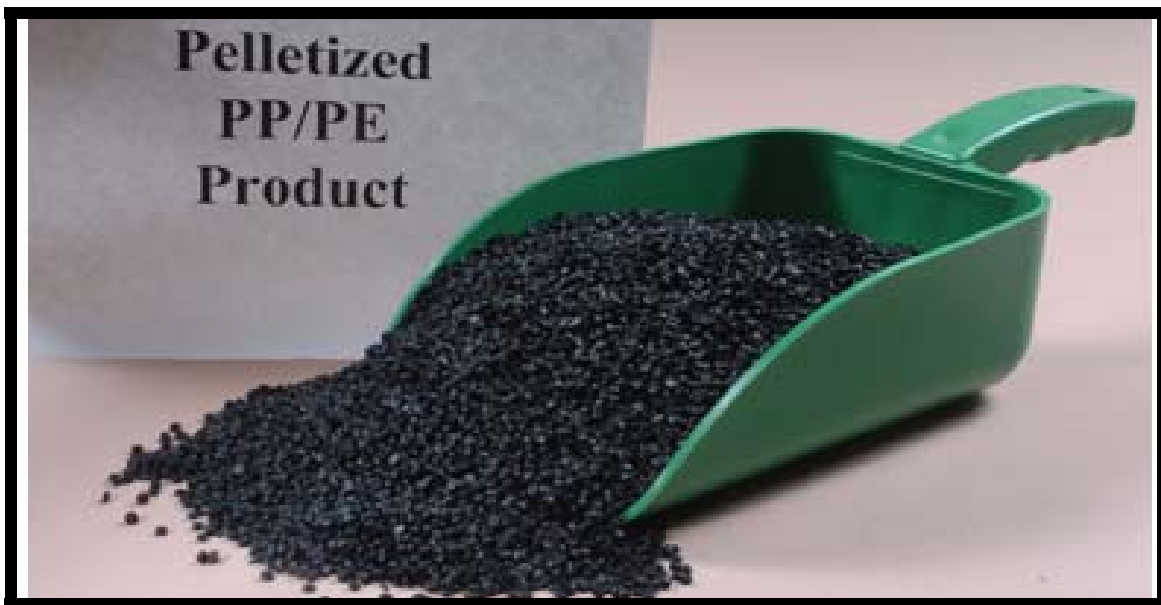
### **Blending and Pelletizing of Recovered PP/PE**

250 lbs. of PP/PE recovered by Argonne were blended with 750 lbs. of supplemental PP copolymer regrind for 15 minutes. The blended material was then run through an extruder and pelletized. The general appearance of the final pellet was excellent (Figure 1). Properties of the recovered material used in blending and the properties of the regrind and of the resulting pellets are shown in Table 6. Standard pelletizing conditions were used. Barrel heats were set from 365°F at the rear barrel zone and increased progressively to 390°F at the front, with six heat zones in between. Screen-changer and breaker-plate heats were set at 405°F, and die heats were set at 395°F. Melt temperature was recorded as 460°F, and drive load and screw speed were set at 60% and 67.5% of the maximum values, respectively. Material output was recorded as 1,400 lb/h. Extra-fine screen packs were used (20/20/20/60/100/20 mesh screens) to remove impurities because this was the first time this material has been tried.

In addition, while screen changes are typically performed at pressure differences between 500 psi and 1,000 psi, in this test, changes were performed when the pressure exceeded 500 psi to safeguard against puncturing a screen pack and losing material. Because extra-fine screen packs were used in the test, screen changes were required approximately every five minutes. The results indicated that the recovered PP/PE can be blended with other olefinic regrind and pelletized by using standard processes and equipment.

### **Mold Trials**

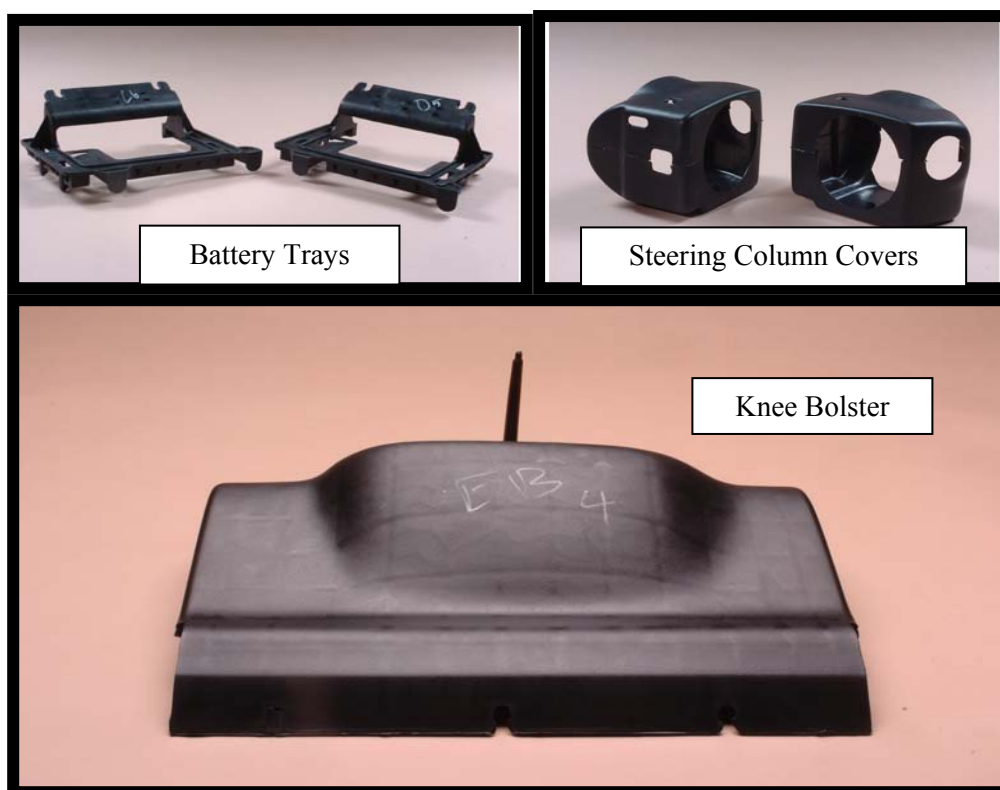
Three types of auto parts were molded by MGV Enterprises by using Argonne-recovered PP/PE from shredder residue: knee bolsters, battery trays, and steering column covers (Figure 2). A standard molding machine was used in these trails. No changes to the standard conditions were required to run the recovered 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 1.** Pelletized PP/PE product recovered from shredder residue.

**Table 6.** Properties of recovered PP/PE when mixed with regrind.

Property	Argonne, As Recovered Sample 9 (see Table 1)	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, 66 psi, °F	171	197	176
Gardner impact, 73°F, in.-lb	32	>320	132
SG, g/cc	0.94	0.91	0.92



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

**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.

<sup>1</sup> One of the formal consortia of the United States Council for Automotive Research (USCAR) set up by the “Big Three” traditionally U.S.-based automakers to conduct joint pre-competitive research and development.



## **E. Post-Shred Materials-Recovery Technology Development**

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### *Participants:*

*This project is conducted as part of a Cooperative Research and Development Agreement (CRADA) among Argonne, USCAR's Vehicle Recycling Partnership<sup>1</sup>, and the Plastics Division (formerly the American Plastics Council) of the American Chemistry Council.*

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*This project is conducted as part of the CRADA among Argonne, USCAR's Vehicle Recycling Partnership, and the*

*Changing World Technologies is cost-sharing on the evaluation of its thermal depolymerization process.*

*The Polyurethanes Recycle and Recovery Council (PURCC) is also participating and cost-sharing on the evaluation of the Troy Polymers, Inc., polyurethane glycolysis process.*

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*Contractor: Argonne National Laboratory*

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

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### **Objective**

- Develop technology for the cost-effective recovery of materials from post-shred residues.

### **Approach**

- Characterize shredder residue from a number of sources to determine composition variability.
- Conduct bench-scale and large-scale process/technology tests to benchmark technology.
- Build and operate a pilot-plant for the separation of shredder residue to produce recovered materials for market evaluation and to provide "control" samples of materials for testing of alternative technologies, as appropriate.
- Conduct cost and performance analyses of alternative technologies to establish the business case for the technologies and to identify technology gaps.

## Accomplishments During this Reporting Period (FY 2006)

### Mechanical Separation of Shredder Residue

- Ran one 10-ton production campaign (fractions supplied to commercial equipment vendors for performance verification).
- Initiated engineering design for full-scale bulk-separation system--three process options in collaboration with a major shredder operator.
- Obtained budgetary quotes from vendors for major equipment.
- Confirmed performance of commercial equipment (including shredder and granulator) with field trials by vendors/Argonne of the as-is shredder residue and of the fractions generated in the Argonne pilot-plant.
- Designed, built and tested physical rubber separation system.
- Conducted preliminary investigation of costs and performance of commercial color sorters, electrostatic separators, and infrared (IR) sorters for removal of wood and rubber (also evaluated relative to plastics separation).

### Froth-Flotation Process for Recovering Plastics

- Ran first campaign of the middling plastics fraction.
- Recovered a 60% unfilled acrylonitrile-butadiene-styrene/polystyrene (ABS/PS) concentrate and a 50% filled ABS concentrate from the middling plastics.
- Upgraded the filled ABS concentrate from 50% to 70% and defined process conditions to further upgrade this fraction to 90%.
- Defined process conditions for separating and recovering unfilled ABS and PS from the unfilled ABS/PS concentrate, to greater than 90% and 85%, respectively.
- Defined process conditions for separating and recovering an 85% polycarbonate (PC)-ABS/PC alloy from the middling plastics fraction.

### Other Accomplishments

- Completed testing of Troy Polymer, Inc.'s (TPI's), glycolysis process for conversion of polyurethane (PU) foam to polyol initiators. Over 1,200 lbs. of foam were used, and over 100 gallons of polyol initiators were produced.
- Conducted pilot-scale testing of Changing World Technologies' (CWT's) thermal-depolymerization process for converting shredder residue to fuels. Pre-processed shredder residue from another shredder has been evaluated and shipped to CWT for further testing.
- Completed a large-scale plastics-separation test at MBA Polymers Inc. using a plastic concentrate produced by Salyp's mechanical separation system.
- Completed testing of the VW-SiCon plastics-separation process.

## Prior Accomplishments

### Argonne Pilot-Plant

- Construction of the pilot-plant at Argonne was initiated in FY 2003 and was completed in FY 2004. The pilot-plant consists of two major parts: a mechanical separation facility and a wet separation/froth-flotation facility.

### Mechanical Separation Facility

#### FY 2005

- Ran four 15-ton production campaigns.
- Conducted complete materials loss analysis on all runs.

- Modified the bulk-separation operation resulting in an increase in polymer yield in concentrate from 40% (runs 1-2) to over 90% (runs 3-4).

#### FY 2004

- Completed construction, shakedown and start-up of the bulk-separation facility.
- Ran six (6) 5-ton trial campaigns, 4th quarter.

#### FY 2003 3<sup>rd</sup> quarter

- Initiated construction of bulk-separation facility.

#### Froth-Flotation Process for Recovering Plastics

#### FY 2005

- Conducted trials on gravity tables, mineral jigs, and a kinetic-density separator in the U.S. and Europe primarily for removal of wood and rubber.
- Conducted bench-scale research on settling velocities and density distributions of actual shredder-residue polymers including the wood and rubber.
- Ran a production campaign of the base process with shredder-residue polymer concentrate to yield three polymer fractions; the polyolefin fraction, middling plastic fraction, and the heavies plastic fraction.
- Developed a two-stage, wet-separation process for removal of wood and rubber from the recovered polyolefin fraction.
- Upgraded the polyolefin fraction, recovered 5000 pounds of polyethylene/polypropylene (PE/PP) product essentially free of wood and rubber.

#### FY 2004

- Completed construction and shakedown with electronics plastics, 2nd quarter.
- Redesigned and modified materials-handling equipment.
- Ran a shakedown campaign with shredder-residue polymer concentrate.

#### FY 2003, 3<sup>rd</sup> quarter

- Initiated construction of froth-flotation pilot-plant.

#### Other Accomplishments

- Conducted bench-scale tests and in a five-gallon reactor of Troy Polymer, Inc.'s (TPI's) glycolysis process for conversion of polyurethane (PU) foam to polyol initiators.
- Conducted bench- and pilot-scale testing of Changing World Technologies' (CWT's) thermal-depolymerization process for converting shredder residue to fuels.
- Completed large-scale tests of Salyp's "thermoplastics-sorting" technology by using residue from two European locations and one U.S. location as feed materials.
- Developed an Excel-based process cost model that incorporates two primary modules for the recovery of automotive plastics: the first module includes the unit operations required for recovering a plastics concentrate from shredder residues, and the second module includes the unit operations required to recover selected plastics from the mixed plastics concentrates.

### **Future Direction**

- Efforts in FY 2007 will be as follows:
- Bulk Separation of Shredder Residue
- Complete engineering designs (3 process options) of bulk-separation system to include equipment specifications, equipment cost, operating requirements, and utility requirements (design basis 20 ton/hour, 1-shift, 2-shift, 3-shift).

- Conduct cost analysis including sensitivity of the cost of polymer concentrate as a function of: 1) yield per ton of shredder residue, 2) value of the by-products (ferrous, non-ferrous, and foam), 3) cost of utilities, 4) cost-of-capital, etc.
- Conduct performance trade-off and cost analyses of color sorter for wood and rubber removal vis-à-vis Argonne physical rubber separation and wet-wood separation; specify preferred process (dry or wet) for separation of wood and rubber from the polymer concentrate.

#### Froth-Flotation Separation of the Plastics

- Upgrade the filled ABS concentrate from 70% to greater than 90%.
- Upgrade the unfilled ABS and PS from the unfilled ABS/PS concentrate to greater than 90% and 85% respectively.
- Recover an 85% PC-ABS/PC alloy concentrate.
- Define process conditions for upgrading the PC-ABS/PC alloy concentrate to 90-95%.
- Initiate engineering designs of the froth-flotation process to include equipment specifications, equipment cost, operating requirements, and utility requirements (design basis 8 ton/hour of polymer concentrate, 1-shift, 2-shift, and 3-shift).
- Initiate development of a predictive simulation model for determining appropriate separation operating and solution conditions that can affect gravity and froth-flotation separation of selected polymer materials for separation and recovery of polymers from a shredder-residue concentrate.
- Development of bench-scale experimental design to provide requisite empirical data for the predictive simulation model.

#### CWT's Thermochemical Process for Producing Hydrocarbon Liquids

- Complete the 2000-lb sample run. Evaluation of the CWT technology will be completed and recommendations for path forward will be made.

#### Evaluation of Emerging Technologies for the Rapid Identification and Sorting of Plastics

- Evaluation of the applicability of color sorters and IR sortation technologies for further refinement of selected process streams from the Argonne physical separation and froth-flotation processes will be completed in FY 2007.

In FY 2007, evaluation of the following technologies will also be completed and recommendations for path-forward will be made.

- TPI's hydrolysis/glycolysis process for producing polyol initiators.
- VW-SiCon technology for separation of shredder residue.
- MBA Plastics separation technology.

### **Summary**

The objective of this project is to develop technology for the cost-effective recovery of materials from post-shred residues. Research will provide data essential to establishing a business case for sustainable recycling of automotive materials from post-shred residue. Technologies specific to the recovery of materials from post-shred material streams are being evaluated and demonstrated to determine their commercial viability. The performance (e.g., yield, purity, efficiency, and cost) of these emerging technologies will be

determined to enable the development of an integrated process for recovering materials from shredder residue.

Research has been completed on the Salyp process and on Argonne's physical separation process. Testing of the VW-Sicon and of the MBA Polymers processes were completed in FY 2006 and final reports will be prepared in FY 2007. Research is ongoing on the Argonne froth-flotation process, the Changing World Technologies (CWT) process, and the Troy Polymers process.

### **Characterization of Shredder Residue**

Over 90 tons of shredder residues from five shredders were processed in Argonne's mechanical separation plant. Table 1 shows the composition of the different fractions that were produced. We observed:

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

The mass fractions of the polymer concentrate separated from different shredder residues showed little variation, and the weight percent (wt%) of the polymer concentrate recovered from eight runs totaling 80,000 lbs 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 similar (Figure 1).

### **Argonne Pilot-Plant**

Argonne's pilot-plant consists of two major facilities: a mechanical separation facility and a density/froth-flotation facility. The pilot -plant is used to:

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

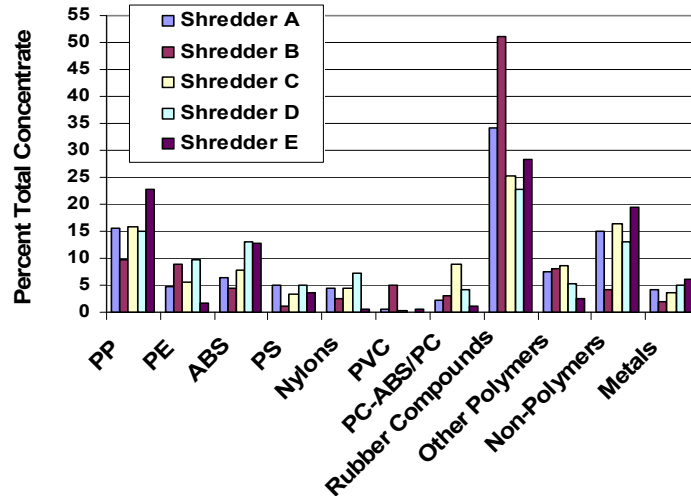
### **Mechanical Separation Pilot-Plant**

The mechanical separation facility processes raw shredder residue to yield a polymer concentrate, ferrous and non-ferrous concentrates and other fractions. Initially, the average yield of polymer concentrate recovered was only 17% of the weight of the shredder residue. The recovery of the

**Table 1.** Streams produced by mechanical separation of an average shredder residue.

	Shredder Residue	Oversized Heavies	Oversized Foam rich	Fines +	Ferrous Rich	Non-Ferrous Rich	Lights	Polymer Concentrate
Weight (lbs)	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

+ Fines are material smaller than 0.25 inch in size and also contain some polymers and metals.  
HIPS = high-impact polystyrene. PVC = polyvinyl chloride. PPO = polyphenylene oxide.



**Figure 1.** Composition of polymer concentrates from different shredder residues.

polymers in the polymer concentrate was also low (40–70%) for the different source materials. A loss analysis was undertaken including quantification of polymers in each of the fractions that are generated in the bulk processing of shredder residue.

On the basis of this analysis, process modifications were made, and some of the fractions were reprocessed. As a result, the yield of polymer concentrate more than doubled. The analyses also indicated that the recovery of polymers larger than 6 mm in size targeted for recovery in the polymer concentrate was over 90%.

The polymer concentrate included high and varying amounts of wood and rubber. Wood was about 1–4 wt%. In Figure 1, the wood is included in the “non-polymers.”

**Separation of Wood and Rubber**

Trials were conducted by using commercially-available air aspirators, classifiers, air-gravity tables, and mineral jigs to remove wood and/or rubber from the polymer concentrate. This equipment did not yield satisfactory results. Conventional sink/float techniques did not work either. Trials using modified wet-separation approaches ultimately yielded a set of conditions to remove almost 100% of the wood and over 90% of the rubber with a nominal loss (~ 5%) of the plastics. This approach was integrated with the froth-flotation facility.

A dry process has been tested at Argonne, at a rate of up to 100 lb/hr of polymer concentrate, for separating the rubber in the polymer concentrate from recovered plastics concentrates. The process has been able to separate over 75% of the rubber and produce a rubber fraction containing less than 10% of non-rubber material. Further testing and scale-up of the process is on-going.

**Froth-Flotation Pilot-Plant**

This facility includes six continuous stages for the separation of targeted plastics from the polymer concentrate. A shakedown of the facility was conducted using 4,000 lb of post-consumer electronics and appliance mixed plastics and by using a mixture of colored plastics. These trials confirmed the effectiveness of the basic system.

Over 20,000 lbs of polymer concentrate from shredder residue have been processed in this facility. The recovered fractions include PP/PE, filled ABS and an unfilled ABS/PS concentrate. These are described below.

**Recovered PP/PE Fraction:** More than 5,000 lbs. of an unfilled PP/PE fraction that is over 95% PP/PE have been consistently produced. It contains less than 0.2% wood and less than 4% rubber. The recovered PP/PE has properties similar to those of some commercially-available PP materials. The recovered unfilled PP/PE product constituted about 5%–6% of the starting shredder-residue weight.

Table 2 summarizes the recoverable unfilled PP/PE and other plastics from 10,000 pounds of typical shredder residue.

**Filled ABS Fraction:** Filled ABS that has a specific gravity between 1.07 and 1.1 was isolated by the basic froth-flotation process as an ABS concentrate, Table 2. It contains 50% ABS, 20% rubber, 10% rigid urethane rubber, 8% PPO, 3% filled PP and 9% of other materials. Processing of this fraction to remove the wood and rubber increased the ABS concentration to 70% and reduced the rubber and urethane concentrations 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%.

**Unfilled ABS and PS:** A fraction containing unfilled or slightly filled ABS, PS and PPO (43% ABS, 22% PS, 7% PPO, 12% rubber, 7% wood, 5% filled PP and 4% other materials) was produced by the basic process. This fraction is being used to

recover the unfilled ABS and the PS/PPO. Laboratory tests defined process conditions to separate this fraction and produce fractions with over 90% ABS and over 85% PS/PPO.

**PC-ABS/PC Alloy:** Work is ongoing to isolate an ABS/PC-PC fraction. Laboratory tests produced a PC-ABS/PC fraction having a combined concentration of over 85%.

**PVC:** Recovery of these fractions leaves behind a fraction made of high specific-gravity materials. Rubber constitutes over 50% of the total and metals about 5%. After the rubber and the metals were separated, a PVC fraction having over 50% PVC and rich in glass-filled nylons can be produced.

**Rubber:** Recovered rubber concentrate was also evaluated by rubber recyclers. It was determined that the presence of thermoplastics in the rubber improves certain properties of the recycled rubber when used to make construction products (such as roofing shingles). The Argonne dry rubber separation process has been able to increase the rubber content of this fraction to over 90%.

**Table 2.** Composition of an average polymer concentrate and recovered polymer fractions.

	Polymer Concentrate	PP/PE Product	ABS Product	ABS/PC Product	Rubber Product	HIPS/ABS Concentrate	Mixed Plastics	Mixed Stream*
Weight (lbs)	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	830	787	0	0	10	12	21	0
HIPS	234	0	2	0	0	186	25	21
Nylon	347	0	5	0	0	5	42	296
PVC	511	0	0	0	3	0	123	385
PPO	135	0	13	1	0	62	21	37
PC-ABS	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	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 and others	59	10	0	0	0	1	5	42
Total	10,044	1,736	141	108	689	856	1,203	5,311

\* Rubber and metals are to be recovered from these streams

In summary, we have recovered the unfilled polyolefins as a potentially useable product, and isolated the filled ABS, unfilled ABS/PS, PC-ABS/PC and PVC into more manageable fractions. The objective now is to produce enough of these materials to determine their physical properties and conduct mold tests when warranted.

A 2000 lb/hr, continuous, flotation module has been designed and is being built. Testing of this module will provide valuable and necessary information for designing and building the first commercial plant.

### **Development of a Process Flowsheet**

A process conceptual design for a 20 ton/ hr mechanical separation system has been developed. The key steps in the process include 1) a de-stoner to separate bulky components such as metal chunks and 2) a screen separator, such as a trommel, to separate pieces larger than 3 inches. This contains most of the foam as well as fabrics, tire-rubber pieces and some plastics, 3) a shredder to size reduce the material to 1 inch, 4) a vibrating screen or a trommel to separate “fines” that are smaller than ¼ inch, 5) a magnetic separator to recover ferrous metals, 6) an eddy current separator to recover non-ferrous metals, 7) a granulator to size-reduce the material to about 3/8 inch and 8) an air classifier to remove “lights” from the granulated material. Tests, using shredder residue, were conducted to evaluate the cost, performance and maintenance requirements of various equipment that was proposed for the conceptual design. The cost of a plant having a design capacity of 20 tons/hr of shredder residue is estimated, based on quotes from manufacturers, to be under a million dollars.

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

Salyp built a mechanical separation system that started with Argonne’s original mechanical separation system. Salyp added an optical sorter to remove wood and a plastics-washing system that also separated heavy polymers from the polymer concentrate. Salyp’s starting shredder residue also contained substantially less rubber and wood than the U.S. residue. It was decided to test the Salyp plastics concentrate using the MBA process. MBA processed the material on its pilot lines in Richmond, CA. Five materials grades were recovered: 1) Polyolefin “A”, 2) Polyolefin “B”,

3) filled PP, 4) ABS and 5) HIPS. The total yield of these products was estimated to be about 48.5% of the plastics-rich fraction. This yield is approximately 88% of the amounts of these plastics predicted from characterization of the feed material. The products were characterized and extruded on a small laboratory extruder, molded and tested. The purities and properties of the recovered plastics were reported to be “encouraging” and it is expected that most of the products could be used in some type of durable-good applications without modification. MBA also compounded modified versions of the recovered ABS and HIPS to enhance their properties. Their properties are being evaluated.

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

CWT has developed a thermal-conversion process that converts organic material into high-hydrocarbon oil. CWT built a pilot-scale apparatus to process a mixed shredder-residue waste stream. A 1/16-in. screen was used to separate the fines (~36% by weight). About 700 lbs. of the remaining material were processed along with 80 lbs. of tires and 1,700 lbs. of used motor oil. Thermal- cracking tests of the produced hydrocarbon fuel were performed. 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.

The products were analyzed to determine the fate of the inert solids and contaminants. Polychlorinated biphenyls (PCBs) in the input shredder residue was 21.8 ppm. PCBs in the products including the hydrolysis oils, cracked oil, distillates, hydrolysis water, wash water, and char were below the detection limits. This indicated that PCBs degrade during the CWT process.

Several heavy metals were found in the heavy-oil dissolver. Heavy metals decreased gradually in liquid output materials from the thermal-conversion processes. Cracked oil and distillates contained only traces of one or two metals. No measurable concentrations of heavy metals were found in distillate-cut #3. The char contained significant amounts of several metals and their salts.

The heavy oil from the dissolver contained about 3,200 parts per million (ppm) of total chlorine.



Chlorine decreased in the organic output products. No chlorine was found in the light distillates (Cuts #1 and #2), and only 14 ppm were found in the heavier distillate-cut #3 and 11 ppm in the distillate bottoms.

Bromine was found in the heavy oil from the dissolver (~135 ppm). No bromine was found in the output liquid products. Bromine was found in char (87 ppm).

The tire-rubber sample used with the shredder residue contained 17,200 ppm of sulfur. Total sulfur in the motor oil used in the dissolver was 1,600 ppm. Sulfur in the cracked oil was 621 ppm, and 2,696 ppm in the treated hydrolysis oil. This indicates that sulfur compounds degraded in the process.

The cracked oil contained 0.06% of ash and the treated hydrolysis oil contained 0.7% of ash.

A pre-processed organic fraction (about 2,000 pounds) derived from shredder residue has been characterized and shipped to CWT for next trials.

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

TPI has developed a process for the conversion of mixed polyurethane (PU) foams into polyol initiators. Bench-scale testing demonstrated the technical feasibility of the process. Clean mixed foam and dirty foam from shredder residue were converted to polyol initiators at yields of about 88% and 72%, respectively. Commercially-available activated carbons reduced the concentration of PCBs in the products to < 2 ppm.

The process was scaled up in a 5-gal reactor. Over 1,200 lbs of foam separated from shredder residue have been processed, and over 100 gal of polyol initiator have been produced. By using optimized reaction conditions with diethylene glycol and potassium hydroxide, the yields were increased to over 90%.

Twenty gallons of the polyol initiator, (equivalent weight 163), was propoxylated and two lots of polyols were produced (equivalent weights 354 and 173). The recycled polyols were also tested in

making rigid foams. The recycled polyols were more reactive in that they required less or no catalysts, and had better flame resistance than the foams made with virgin polyols.

Initial economic analysis of the process to produce polyol initiator indicated that the glycolysis process is potentially economical.

### **Recycling of Fines**

As more lightweight materials are used in future vehicles, the amount and value of fines (<0.25 in.), which presently constitute about 50% of the weight of shredder residue, will increase. Therefore, recycling the fines is necessary to increase the recyclability of future vehicles.

Argonne conducted preliminary tests to recover metals and polymers from these fines. The results are summarized below.

1. The polymer concentrate recovered from the material in the 2-6 mm size range was 21 wt% of the starting shredder residue, or ~50 wt% of the weight of the fines fraction.
2. The composition of the recovered polymer concentrate is shown in Table 3.
3. 20 wt% of the plastics had specific gravity < 1.

**Table 3.** Composition of the 2-6 mm fines.

<b>Fraction</b>	<b>Weight % of Polymer Concentrate</b>
Rubber	52.1
Plastics	18.6
Non-Ferrous metals	8.3
Wood	6.7
Fibers	6.1
Foams	2.6
Ferrous metals	1.8
Glass	0.9
Others	2.9
<b>Total</b>	<b>100.0</b>

Evaluation of the plastics and the metals in this material will be conducted to decide if they should be recovered.

Trip Allen, a consultant to the Plastics Division of the American Chemistry Council, also conducted tests on 300 pound samples of fines (smaller than about 1 inch). In these tests, shredder residue was screened using a 7/8-in. (2.2-cm) screen. The material that passed the 2.2-cm screen was processed to yield organic- and inorganic-rich products. A combination of hydrocycloning, screening, rising current, wet tabling, magnet, and grinding technologies was utilized to give ferrous and non-ferrous metal, organic, and inorganic/sand separations at four different size distributions. Economic modeling of the process showed that recovery of the metal and sand may be viable.

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2. *Recycling of Polyurethane Foams Recovered From Shredder Residue Via Glycolysis Process Into Polyurethanes*, Sendijarevic, V., Sendijarevic, I., Mayne, K., Winslow, G.R., Duranceau, C.M., Simon, N.L. Wheeler, C.S., paper # SAE-2006-01-1579.
3. *Chemical Recycling of Mixed Polyurethane Foam Recovered from Shredder Residue into Polyurethane Polyols*, Sendijarevic, V.; Sendijarevic, I.; Winslow, G.R.; Duranceau, C.M.; Simon, N.I.; and Wheeler, C.S., SAE paper # 2005-01-0850.
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5. *Advanced Separation of Plastics from Shredder Residue*, Winslow, G.R., Simon, N.I., Duranceau, C.M., Williams, R., Wheeler, C.S., Fisher, M., Kistenmacher, A., and VanHerpe, I., SAE Paper No. 2004-01-0469.
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10. *Separation and Recovery of Thermoplastics From Mixed-Scrap Plastics*, Pomykala, J.A. Jr., Jody, B.J., Daniels, E.J., and Greminger, J., Proc. of the 9<sup>th</sup> Annual Global Plastics Environmental Conference (GPEC), Detroit, MI, February 26-27, 2003, pp 7-16.

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<sup>i</sup> One of the formal consortia of the United States Council for Automotive Research (USCAR) set up by the “Big Three” traditionally U.S.-based automakers to conduct joint pre-competitive research and development.