11. Recycling

A. Development of Technology for Recycling Polymers from Shredder Residue

Principal Investigator: Bassam Jody
Argonne National Laboratory (ANL)
9700 S. Cass Ave., Argonne, IL 60439
(630) 252-4206; e-mail: bjody@anl.gov

Industrial Partner Principal Investigators:
John Haubert, VRP, Chrysler LLC., (248) 576-7458; e-mail: jah59@chrysler.com
Jacquiline Quinn, VRP, General Motors Corp., (586) 575-7078; e-mail: jacquiline.quinn@gm.com
Bing Xu, VRP, Ford Motor Co., (313) 805-4888; e-mail: bxu1@ford.com
James Kolb, ACC-PD, (248) 244-8920; e-mail: james_kolb@americanchemistry.com

Technology Area Development Manager: Carol Schutte
(202) 586-1022; e-mail carol.schutte@ee.doe.gov

Contractor: Argonne National Laboratory
Contract No.: DE-AC02-06CH11357

Objective

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

Approach

- Characterize shredder residues to determine composition variability
- Benchmark alternative technologies
- Build and operate pilot plants for the separation and recovery of materials from shredder residue
- Conduct cost and performance analysis of alternative technologies to establish the business case for the technologies and to identify technology gaps.
- Develop technology to remove the substances of concern from the polymers
- Determine properties of the recovered polymers
- Validate the best available technology in a large scale plant at an industrial site

Milestones, Metrics and Accomplishments (10/1/08-9/30/09)

- A 20 ton/hr validation plant has been built and started up by industry at a commercial recycler's facility. The plant is based on ANL's process for recovering polymers and residual metals from shredder residue
- Completed testing of the modifications to the flotation process to minimize the use of chemicals and minimize waste water production, and incorporated that in the design of the validation plant
- Completed shredding of four categories of vehicles to investigate any changes in the composition of the resulting shredder residues
- Completed testing of the potential release of nano particles during the shredding of automotive materials
- Completed evaluation of the Changing World Technologies, Inc. (CWT) process for converting the organic fraction of shredder residue into hydrocarbon liquids and of the Troy Polymers, Inc. (TPI) process for converting automotive polyurethane foam into polyols
- Completed testing of ANL's two-stage process for cleaning the plastics

Prior Accomplishments

- Designed, built and operated a 2 ton/hr dry mechanical separation pilot facility and processed 150 tons of shredder residue from 10 different yards
- Designed, built and operated a 1000 lb/hr flotation pilot facility and processed about 15 tons of polymer concentrate
- Designed built and tested a 5000-lb/hr plastics-separation module
- Conducted economic analysis of the process.
- Designed a full scale system for separating wood and rubber from plastics.
- Determined physical properties of polymers recovered by different processes
- Determined properties of polyolefin after cleaning by different methods to remove the polychlorinated biphenyls (PCBs)
- Pelletized 1000 pounds of a blend containing 25% of the ANL recovered PP/PE product
- Conducted mold trials of the recovered PP/PE product
- Conducted testing and evaluation of a number of processes for recycling materials from shredder residue
- Developed an Excel-based process cost model for the recovery of automotive plastics.

Future Direction

- Support the shredder in the testing and initial operation of the validation plant
- Analyze and evaluate data and products from the validation plant.

- Conduct blending tests and mold trials using polymers recovered by the validation plant
- Determine the economics of the process based on the full-scale validation-plant operation to define the business case for the commercialization of the technology.
- Conduct process improvement studies to optimize validation plant activities and support commercialization of the technology.

Introduction

The objective of this project is to develop and demonstrate technology for the cost-effective recovery of polymers and other materials from post-shred residues. The research that has been conducted culminated in the design, construction and start-up of a full-scale field validation plant in 2009. Research conducted at ANL's pilot-plant provided data essential to establishing the business case for sustainable recycling of automotive materials from post-shred residue. Because the research has focused on the recovery of materials for re-use in automotive applications, extensive research was also conducted to evaluate the physical properties of the recovered polymers and to remove residual contamination such as PCB's from these materials. Supporting research has also been conducted to improve the economic performance of the materials recovery process technology and to evaluate other market opportunities such as conversion of materials to hydrocarbons for possible use as fuel or chemical precursors.

FY 2009 Accomplishments

Validation Plant Activities

Construction of a 20-ton/hr design capacity plant to validate the ANL technology was completed in September of fiscal year (FY) 2009. The process conceptual design for the validation plant was developed by ANL based on trials conducted in the ANL pilot-plant using actual shredder residues. Shake-down and start-up of the plant was initiated in September. ANL staff has been assigned full time in the field during construction and start-up to provide technical assistance and to enable transfer of the technology to industry.

In FY 2009 the following activities related to the validation plant were also conducted:

- Testing to evaluate the performance and cost of various commercial equipment suitable for use in the validation plant
- Economic analyses of the process for a full-scale commercial plant including equipment cost, operating cost, revenues and payback.

Experimental research in ANL's Pilot plant

Research was continued in the ANL pilot-plant to support the development of the design for the 20 ton/hr validation plant. Testing was concentrated primarily on modification to the flotation process that resulted in over 90% reduction in the amount of chemical used and the modification was incorporated in the design of the validation plant. Additional testing was conducted to optimize the operating conditions of the new flotation technology. In the process several design modifications to the internals of the flotation tanks were made in order to accommodate the resulting water flow rates and the stratification of the "light" polymers in the feed line. Special components for the flotation tanks were tested in order to design the units for the validation plant. Because some of these are not commercially available they were built by ANL and sent for installation in the validation plant.

In addition tests were conducted to recover polymers and metals from the <0.25-in. fines. The polymer concentrate recovered from the material in the 2-6 mm range was about 40 wt % of the weight of the fines. It contained up to 50% by weight rubber and about 20 wt% plastics. A sample of this concentrate was processed to produce a polyolefin concentrate, a styrenics concentrate, a mixed plastic and rubber concentrate, and recover the residual metals. It was also observed that the ferrous material, including oxides, in the fines has been reduced significantly compared to years ago. Today, shredders use more-efficient magnets and vehicles form less rust. Although polymers can be recovered from this fraction, the overall yield is low relative to the balance of the residue.

Shredding only vehicles to investigate any changes in the composition of the resulting shredder residue

A study involving shredding only well inspected vehicles of selected ages and categories was conducted in order to investigate composition differences in the resulting shredder residues compared to typical shredder residues. These trials were conducted at a new shredder facility under controlled conditions and provided a unique opportunity for compositional comparisons. Four categories of vehicles were shredded. These are: 1) late model domestic - 2002-2005 model- year vehicles from Chrysler, Ford and General Motors, 2) late-model transplants - 2002-2005 model- year vehicles from foreign companies which are manufactured in the United States, 3) 1983-2000 normal end-of-life vehicles (ELVs) which are typical of what is shredded currently, and 4) imported vehicles that were retrofitted to qualify for sale in the U.S. Five tons of the resulting residues were processed and samples were analyzed. Even though a small number of vehicles and models were used in the study, and the vehicles were very carefully de-polluted, inspected and all non-auto materials were removed from them prior to shredding in a newly installed shredder, the study lead to following observations:

- The compositions of the resulting shredder residues were similar to each other and are approximately equal to the composition of typical shredder residue.
- The composition and materials content of the separated streams were essentially the same as those produced from typical shredder residue.
- The shredder residues contained very low levels of PCBs. This demonstrates that autos, at least newer than 1983 models, are not a major source of PCBs in shredder residue. No pre-1983 vehicles were included in the test.

In general, the information from the “all auto” trials described above indicated that the basic process design for recovering materials from typical shredder residue is valid for all end-of-life vehicles.

Testing of the potential release of nanoparticles when automotive parts are recycled

Of recent concern to industry in general is the potential impact of nanoparticle release during manufacturing and recycling operations. To address the concern relative to recycling of materials, USCAR and ANL conducted a study for testing the potential release of nanoparticles during the shredding of automotive materials. NIOSH participated in the experimental design and University of Minnesota conducted the analysis. ANL designed and built the experimental apparatus, and conducted the tests using plain, talc filled, and nanoclay filled polypropylene plaques in a high speed granulator. The airborne particles were analyzed to determine if there is an increased health risk from the nanoclay filled polymer. The University of Minnesota team prepared the report and concluded that “the results suggest that “there is not a strong potential to generate more airborne nanoparticles than recycling of conventional plastics, nor does it have a strong potential to generate unique airborne nanoparticles of the composited nano material."

Evaluation of the Changing World Technologies, Inc. (CWT)

Evaluation of the Changing World Technologies, Inc. (CWT) process for converting the organic fraction of shredder residue into hydrocarbon liquids was completed in FY 2009 and the final report was issued. The main conclusions of the study are:

- Converting shredder residue to hydrocarbon fuels is feasible. The process produced a pumpable heavy hydrocarbon liquid; carbon fines and a gaseous stream.
- Preprocessing of the shredder residue to remove the inorganics is necessary
- The produced oil has an acceptable viscosity and distillation profile for fuel use.

Conversion of the organics in shredder residue was also discussed with other groups that are developing technology for converting the material to "fuels." While these processes are technically feasible the economics are yet to be established.

Troy Polymers, Inc. (TPI) process for converting automotive polyurethane foam into polyols

Evaluation of the Troy Polymers, Inc. (TPI) process for converting automotive polyurethane foam into polyols was also completed in FY 2009. TPI started working with industry to commercialize the technology, and construction of the first large scale plant was started in FY 2009.

Completed laboratory testing of ANL's two-stage process for cleaning the plastics

The objective is to develop technology to cost-effectively remove PCBs and other substances of concern (SOCs) from recycled automotive materials. Because commercial cleaning equipment, solvents and detergents could not remove the residual PCB's to less than 2 ppm we continued and substantially completed:

- Testing of the two-stage process for cleaning the plastics
- Testing of different solvents for cleaning the plastics.

In the first stage of the two-stage process the polymers were washed in a solvent. Several solvents were able to reduce the concentrations of PCBs from about 30 ppm to about 10 ppm under a range of operating conditions. Washed plastics were then processed in a high temperature desorbing environment. The process was tested in a 5-lb batch reactor using recovered PP/PE, Figure 1, in the later part of FY 2008 and the samples were analyzed in FY 2009. The plastics were washed using perchloroethylene (perc) and then transferred to an oven at 250°C to desorb the residual PCBs. Samples were sent for PCBs analysis and for evaluating the mechanical properties of the plastics. The results are shown in Table 1 and 2. The results demonstrated that the two stages reduced the PCBs to <2 ppm. The results show that the concentration of PCBs was reduced to < 2 ppm given high enough temperatures and long enough residence times. Aroclor 1242 and, to a lesser extent Aroclor 1254 are the persistent PCBs groups. Washing increased the Izod number, had no impact on the tensile strength and reduced the elongation properties of the washed plastics. However, desorption reduced all three properties.

Figure 1. Experimental apparatus used in testing the ANL two-stage process for PCB removal.

Table 1. Concentration of PCBs in the recovered PP/PE before and after cleaning.

Recovered Olefin Feed

Trial 1

Sample	PCB concentration		Sample	PCB concentration		Sample	PCB concentration
1	25	Wash	1	10	Desorb	1	1.1
2	25		2	27		2	1.9
3	30		3	9		3	2.9
Average	27		Average	15		Average	2

Trial 2

Sample	PCB concentration		Sample	PCB concentration		Sample	PCB concentration
1	25	Wash	1	9	Desorb	1	0.6
			2	11		2	0.5
			3	6		3	<0.4
Average	25		Average	8		Average	1

Trial 3

Sample	PCB concentration		Sample	PCB concentration		Sample	PCB concentration
1	23	Wash	1	7	Desorb	1	1.0
			2	8		2	<0.4
			3	10		3	<0.4
Average	23		Average	8		Average	1

Starting Feed (Ave=26 ppm)	After Washing (Ave=10, ppm)	After Desorption (Ave=1 ppm)

In FY 2009 we also developed conceptual process designs using different unit operations in order to evaluate the process economics. The results indicated that the process equipment is costly especially for the desorption stage especially in view of the degradation of the properties of the plastics which will reduce their market value. It was concluded that process improvements are necessary to reduce cost and prevent degradation of the properties of the cleaned plastics. Therefore, we:

- Considered different more economical equipment options, and
- Tested different washing solutions and multi-stage washing arrangements to see if the plastics can be cleaned without desorption at such high temperatures.

Table 2. Properties of recovered PP/PE before and after cleaning

Property	Range Before	Average of 10 Samples	After Washing	After Desorption
MFR, g/10min, 230°C, 2.16 kg	7.2-11.4	9.4	7.2	16.7
Izod impact, ft-lb/in., 73°F	1.7-13.2	8.6	11	1.5
Flex mod., 1% secant, 1,000 psi	73-127	99	98	85
Tensile strength at yield, 1,000 psi	2.2-3.4	2.8	2.8	1.9
Tensile strength at rupture, 1,000 psi	0.8-3.1	2.1	2.3	1.9
Elongation at yield, %	17.2-23.0	24.3	12.5	3
Elongation at rupture, %	12-251	119.8	26	3
DTUL, 66 psi, °F	131-171	145	146.5	133
Gardner impact, 73°F, in.- lb	20-184	90	72	6
SG, g/cc	0.94	0.94	0.94	0.95

It was concluded that process improvements are necessary to reduce cost and prevent degradation of the properties of the cleaned plastics. Therefore, we:

- Considered different more economical equipment, and
- Tested different washing solutions to see if the plastics can be cleaned without desorption at such high temperatures.

Considering new equipment and different heating mechanisms reduced the capital cost of the equipment but not enough to make it cost effective. This effort is continued in FY 2010. Testing was also conducted using multi-stage washing in hot solvents. However, the results were not satisfactory.

Prior Accomplishments

ANL Pilot-Plant Research

ANL designed and built a 2-ton/hr pilot plant. The pilot-plant consists of a dry mechanical-separation facility and a wet flotation facility. The pilot-plant is used to:

- Recover materials from shredder residue
- Conduct process improvement studies
- Generate design and scale-up data
- Produce samples for the evaluation of alternative separation technologies
- Serve as a user/demonstration facility.

The mechanical separation facility processes raw shredder residue to yield a polymer concentrate, ferrous and non-ferrous metal concentrates and other fractions. The plant processed over 150 tons of residues from 10 facilities and achieved > 90% recovery of the plastics as a polymer concentrate and > 95% of the residual metals. Table 3 shows the average composition of the different fractions produced. Large variations in the fines, metals, rubber and wood and less variation in the composition of the plastics fraction were observed. The weight percent (wt%) of the polymer concentrate recovered from eight runs totaling 80,000 lbs of shredder residue from one source over a six-month period was reasonably consistent and the composition was also similar.

The flotation facility had six separation stages. Its design capacity was 1000 lbs/hr. The facility processed over 30,000 lbs. of polymer concentrate. The recovered fractions are summarized in Table 4 based on 10,000 pounds of typical shredder residue. Over 5000 pounds of polyethylene/polypropylene (PP/PE) fraction that is > 95% PP/PE were produced. The recovered PP/PE has properties similar to those of commercially-available PP. The PP/PE product is about 5%–6% of the starting shredder-residue weight. ABS is separated as an ABS concentrate. It contains 50% ABS, 20% rubber and 30% of other materials. Removing wood and rubber increased the ABS to >70%. 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. Another recovered fraction contained ABS, PS and PPO (43% ABS, 22% PS, 7% PPO) and 28% other. Small scale tests produced from this fraction > 90% ABS and > 85% PS/PPO.

Table 3. 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
Wt. (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
Others*	21,320	1,008	756	17640+	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, *Foam, fibers, etc.

Table 4. Composition of an average polymer concentrate and of polymer fractions recovered

	Polymer Concentrate	PP/PE Product	ABS Product	ABS/PC Product	Rubber Product	HIPS/ABS Concentrate	Mixed Plastics	Mixed
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
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
Misc. ***	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, **mixed plastics, ***Foam, fibers, etc.

Determination of the Properties of the Recovered Plastics

The objectives are to: (1) determine physical properties of polymers and (2) confirm the technical feasibility of using them in value-added applications.

The physical properties of PP/PE recovered from different shredder residues by ANL and by others were determined. The results for the ANL materials are given in Table 5. The Izod impact of the recovered material is about three times that of the typical general purpose virgin resins, while the tensile strength of the recovered material is lower than the tensile strength of the virgin resins by about 30%.

Table 5. Properties of PP/PE recovered by ANL from different shredder residues

Property	Range of 10 Samples	Average
MFR, g/10min, 230°C, 2.16 kg	7.2-14.9	9.4
Izod impact, ft-lb/in., 73°F	1.7-13.2	8.6
Flex mod., 1% secant, 1,000 psi	73-127	99.0
Tensile strength at yield, 1,000 psi	2.4-3.4	2.8
Tensile strength at rupture, 1,000 psi	0.8-3.1	2.1
Elongation at yield, %	17.1-23.0	24.3
Elongation at rupture, %	12-251	119.8
DTUL, °F (at 66 psi)	131-155	145
Gardner impact, 73°F, in.- lb	20-184	90.0
SG, g/cc	0.93-0.95	0.94

The PP/PE samples recovered by Salyp in previous research from different European and U.S. shredder residues had similar properties to the ANL PP/PE.

Properties of the ABS concentrate recovered by the ANL process after removal of the rubber contained 70% filled ABS, 1.5% PS, 8% PPO, 3% rubber and 17.5% others were determined and compared with properties of a commercially available virgin ABS,Table 6. Table 6 also shows the properties of two blends of the recovered ABS with virgin ABS. Except for elongation at rupture and Gardner Impact the properties of the blends were close to the properties of the virgin material.

Blending and pelletizing of the PP/PE recovered from shredder residue by ANL was also conducted. Two hundred fifty pounds of PP/PE recovered by ANL were blended with 750 lb of supplemental PP copolymer regrind. The blended material was then extruded and pelletized using standard pelletizing equipment and conditions. Properties of the regrind and of the resulting pellets are shown in Table 7. The results indicated that the recovered PP/PE can be blended with other olefinic regrind and pelletized using conventional equipment.

Three types of auto parts were molded using recovered PP/PE: knee bolsters, battery trays, and steering column covers. A standard molding machine was used in these trials. No changes to the standard conditions were required to run the recovered material. The limited testing done shows that quality auto parts may be produced from the recovered material.

Table 6. 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, 1,000 psi	324	296	299	302
Tensile strength at yield, psi	4982	5546	5392	5312
Tensile strength at rupture, psi	4956	4459	4544	4930
Elongation at rupture, %	2	56	9	6
DTUL, °F (at 264 psi)	162	165	166	164
Gardner Impact, 73F, in.lbs.	0	>320	32	8
SG, g/cc	1.08	1.05	1.05	1.06

Table 7. Properties of recovered PP/PE when mixed with regrind

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

Conclusions

Research conducted to date has demonstrated the technical feasibility of recovering polymers and residual metals from shredder residue. The quality of the recovered polymers has been demonstrated; the ability to re-use these materials in automotive applications has been confirmed in mold trials. A full-scale validation plant was designed, built and started-up in 2009. The plant will provide the basis for evaluating the economic feasibility of the process that has been developed and for confirming the market opportunities for the recovered materials.

While research has shown progress in the ability to remove residual contamination (i.e. PCB's) from the recovered materials, complete removal of the PCBs is cost prohibitive and may impact the physical properties of the recovered polymers. This is expected to limit the re-use of these materials.

Presentations/Publications/Patents

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

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

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

4. Thermoplastic Separation and Recovery from Various Mixed Scrap by the ANL Developed Froth Flotation Technology, Pomykala, J. A. Jr., Jody, B. J. and Daniels, E. J., Proc. Of the 13th Annual Global Plastics Environmental Conference (GPEC), Orlando, Florida, March 6-7, 2007.

5. A Mechanical Separation Process to Recover Metals and Polymers from Shredder Residue, Pomykala, J. A. Jr., Jody, B. J., Daniels, E. J., Yang, J. and Spangenberger, J.S. , TMS 2007 Annual Meeting & Exhibition, Orlando, Florida, Feb 25-Mar 1.

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

7. Scale Up Study on Converting and Recycling Shredder Residue Into a Fuel Oil, Winslow, Gerald R. Appel, Brian S. Adams, Terry N. Simon, Nakia L. Duranceau, Claudia M. Wheeler, Candace S., SAE 2006 World Congress, Detroit, Michigan, 2006. SAE-2006-01-1580.

8. Scale Up Study on Converting and Recycling Shredder Residue into a Fuel Oil, Winslow, G. R. Appel, B. S., Adams, T. N., Simon, N. L., Duranceau, C. M., Wheeler, C. S., paper # SAE-2006-01-1580.

9. 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.

10. 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.

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

12. 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.

13. 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

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

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

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

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

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

19. 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 9th Annual Global Plastics Environmental Conference (GPEC), Detroit, MI, February 26-27, 2003, pp 7-16.

B. Development of High Speed Multispectral Imaging for Sorting Automotive Plastics.

Principal Investigator: Edward J. Sommer, Jr.
National Recovery Technologies, Inc.
566 Mainstream Drive, Nashville, TN 372289
(615) 734-6400; e-mail: ejsommer@nrtsorters.com

Technology Area Development Manager: Dr. Carol Schutte
(202) 287-5371; e-mail:carol.schutte@ee.doe.gov

Contractor: National Recovery Technologies, Inc.
Contract No.: DE-FG02-06ER84559

Objective

- Develop a cost-effective technology for the identification of end-of-life automotive plastics and their sortation according to polymer type.

Approach

- Design a primary optical system for imaging the infrared (IR) characteristics of automotive polymers.
- Design a high-speed, IR filtering system which integrates with the optical system and provides the mechanism for isolating a polymer signature.
- Design a secondary optical system which transfers the filter response to a multi-sensor detection array.
- Develop software for high-speed control of the filtering system and detection array utilizing a real-time operating system (RTOS).
- Develop software to identify the unique signatures of various polymers and subsequently segregate these pieces into desired groupings.
- Develop software for system-level configuration and control.
- Integrate and test sortation system.

Accomplishments during this Reporting Period (10/01/2008-09/30/2009)

Accomplishments of the Phase II research program during the period of 10/01/2008 through 09/30/2009 are provided below.

Commercialization Activity

- NRT has realized a Phase III sale of an advanced real-time computing module based upon the Phase II technology under development.
- Development, construction, and testing of the computing module according to specifications

received from the Phase III client was completed during the reporting period.

- The advanced computing module was delivered to the Phase III client.
- NRT is currently working with the Phase III client on the design and construction of an advanced x-ray based metals and alloys sorting system which integrates the computing module and utilizes its sophisticated real time operating system computing capabilities for high speed data acquisition and processing of x-ray data and metals and alloys identification algorithms.

Bench scale Prototype Contruction and Testing

- During the reporting period a bench scale prototype system was designed and constructed integrating a prototype primary optical system, an infrared (IR) filtering system, a prototype secondary optical system, and an InGaAs infrared detection array based upon information and design specifications developed in the previous reporting period.
- Testing was performed with the prototype for verification of the various designs and specifications that had been developed as a preliminary step to final design of a working prototype sorting unit.
- The testing showed that further detailed modeling of the system was needed to optimize system performance. In particular it was found that a more detailed modeling of the IR filtering system was required to better understand system response and parameters needed to obtain successful polymer identifications at the high speeds needed for sorting.

IR Filtering System Modeling

- Re-characterized the physical, optical, and electronic properties of the IR filtering system.
- Modified, in-house, characteristics of the optical design software (OpTaliX) to better model the physical and optical properties of the IR filtering system.
- Complimented the modified optical design software through implementation of a specialized ray-tracing tool developed using MatLab to validate results derived using the optical design software.
- Defined experimental path to validate MatLab and OpTaliX results with the IR filtering system.
- Determined the energy transference through each portion of the optical system and resulting material illumination energy requirements in Watts/cm^2 for the IR range of interest.

Primary Optical System

- Completed specifications for a high-luminance IR lighting system suitable to optimize resolution and enhance sensitivity of the detection system.
- Mechanical, optical, and electrical design of a high-luminance IR lighting system has been completed. A prototype lighting system based on the design is under construction and will be tested during the next reporting period.

Secondary Optical System

- Secondary optical system redesigned to accommodate the revised primary optical system providing a simplified and effective optical interface from the IR filtering system to the detection array system.
- Redesign underway of mechanical components to integrate the primary optical, IR filtering and secondary optical systems and IR detection array.

Detection Array and Data Acquisition Hardware

- Integrated a Camera Link based frame-grabber unit, which enables communication with and data acquisition from the IR detection array, with a QNX real-time computational module from QNX Software Systems.
- Tested the QNX real-time system data acquisition rates and camera control with camera parameter setup through a Windows based system.
- Verified consistent and controllable data acquisition rates suitable for sorting materials at high speeds.

RTOS Software for Filter and Detector Control

- Developed preliminary software drivers and data processing systems suitable to drive the bench scale prototype IR filter and detector array subsystem.

Identification and Sortation Software

- Continued investigation of potential algorithms for identifying polymers. Final selection of algorithm approach will depend upon IR filtering system performance.

Alternative IR Filtering Approaches

- During bench scale testing it was found that the IR filtering system is more complex than originally thought requiring a redesign of the system as described above.
- The redesign effort illustrated to the research team that, as a precaution, alternative IR filtering methods should be investigated in the event that the selected IR filtering method cannot meet the necessary requirements to produce a successful sorting system.
- An alternative IR filtering system is under investigation that can utilize the same detection array, data acquisition, and data processing hardware as for the original IR filtering method.
- A conceptual design has been developed and an alternative work plan is being developed to be implemented in the event it is needed.

Prior Accomplishments

Ph III Commercial Activity

- During the previous reporting period NRT realized a Phase III sale of an advanced real-time computing module based upon the Phase II technology under development.

Design of the Optical Train and IR Detection System

- Designed an optical module for integration with a sensing module.
- Determined specifications and began design of a high-luminance IR lighting system.
- Selected a high-speed, reconfigurable IR filtering system and constructed an optical model for the purpose of simulation and testing.
- Began design of a secondary optical system for interfacing the IR filtering system to the IR detection array.
- Began design of mechanical components to integrate the primary optical, IR filtering and secondary optical systems and IR detection array.

Acquired Detection Array and Data Acquisition Hardware

- Determined specifications for a multi-sensor infrared detection array and for detector data acquisition hardware and acquired the systems.
- Began tests using a QNX real-time system of data acquisition rates and camera control with camera parameter setup through a Windows based system.

RTOS Software for Filter and Detector Control

- Evaluated various aspects of several RTOSs and selected QNX for this project.
- Ordered, received, and activated QNX developments tools essential for programming and interacting with QNX.
- Ordered, received, and put into service a single-board computer (SBC), chassis and other ancillary hardware for hosting QNX and our proprietary software.
- Performed configuration design of real-time operating system and subsystems.

System Configuration and Control Software

- Performed detailed examination of QNX to understand the interactions among its internal components.
- Began development of communications between proprietary software components.
- Primary hardware and software structures defined.
- Began QNX driver developments.

Investigated Complications from Coated Polymers

- Obtained samples of painted polymers from Argonne National Laboratory.
- Testing performed on the samples using a double pulse laser and laser-induced breakdown spectroscopy (LIBS) to analyze underlying polymer materials.

Future Direction

Effort in FY2010 will continue to focus on this SBIR Phase II project. A summary of Phase II plans for this period is provided below.

Redesign of Primary Optical System

- Finish redesign of the primary optical system.
- Fabricate mechanical components.
- Assemble optical and mechanical components and test.

Redesign of IR Filtering System

- Determine optimal physical configuration of the reconfigurable filter through simulations with optical model.
- Order a reconfigurable filter with the desired configuration.
- Verify proper operation of the filtering system.

Redesign of Secondary Optical System

- Finish redesign of the secondary optical system.
- Finish redesign of mechanical components to integrate the primary optical, IR filtering and secondary optical systems and IR camera.
- Assemble integrated systems.
- Verify intended performance of the integrated systems.

Develop RTOS Software for Filter and Detector Control

- Finish development of filter and detector control.
- Test controlling software.

Develop Identification and Sortation Software

- Develop various algorithms for identification.
- Test algorithms for speed, efficiency and accuracy with simulated data.
- Test algorithms with acquired data.
- Develop controlling software for grouping materials.

Develop System Configuration and Control Software

- Finish interface protocols for communication between proprietary software components.
- Implement system control and configuration modules.
- Test system control and configuration software.

Test Integrated Sortation System

- Assemble components into a small but commercial scale prototype sorting system.
- Evaluate overall performance of the assembled system.
- Evaluate sortation performance of the system by sorting shredder residue.

Introduction

The objective of this project is to develop a cost-effective technology for the identification of end-of-life automotive plastics and their sortation according to polymer type. This technology will be capable of simultaneously acquiring polymer spectra from multiple spatial locations, yet operate at high speeds when compared to current state-of-the-art detection systems.

The prospective sortation system may be considered as composed of three sub-systems: an optical filtering unit, a real-time processing unit and a control unit. Specifications, simulations and mechanical designs for the optical filtering unit have begun. Development of the real-time components has progressed significantly, where many of the subtasks (e.g., acquiring hardware and toolsets) are completed. Likewise, significant progress toward implementing the control unit has been made due to investigating the underlying operating system, charting an implementation strategy and testing several concepts with software applications.

Commercialization Progress

Technological developments in this program have enabled the commercial sale to an NRT customer of a computing module based upon the systems being developed under this SBIR program. The unit was delivered to our customer in 2009 and incorporates certain aspects of the RTOS (Real Time Operating System) developments described more fully in this report. NRT is now working with that customer to integrate the unit into an advanced x-ray based sorting system for sorting metals and alloys.

Optical and Filtering Unit

The initial processing segment of the intended sortation system is composed of a complex optical and filtering unit which images the IR characteristics of automotive polymers. It is intended that this unit continuously image the spectral signature of pieces which are larger than 0.25” and lie within a 12” processing width. An inherently low-intensity polymer signature coupled with short acquisition times (required for high-speed and high-volume sorting) requires complex and efficient imaging optics. The tight optical constraints of a high-speed, reconfigurable IR filter further complicate the optical design. Tests with a prototype unit revealed a need to redesign much of the optical system to boost polymer signals. A new high luminance light source has been designed to help in this area. The light source is under construction and will be tested in the upcoming reporting period.

The manufacturer of a reconfigurable IR filter assisted in the development of an optically valid model of a filter for use in simulations. NRT incorporated this model into an optical design software package enabling evaluation of several possible configurations and a bench scale prototype system was constructed. It was tests using this prototype system that revealed the need for the redesign discussed above. The testing showed that further detailed modeling of the system was needed to optimize system performance. In particular it was found that a more detailed modeling of the IR filtering system was required to better understand system response and parameters needed to obtain successful polymer identifications at the high speeds needed for sorting. This detailed modeling was performed and a new optical design was developed and is being implemented.

Alternative IR Filtering Approach

During bench scale testing it was found that the IR filtering system is more complex than originally thought requiring a redesign of the system as described above. The resulting redesign effort prompted the research team to investigate an alternative IR filtering method that could be used in the event that the selected IR filtering method cannot meet the necessary requirements to produce a successful sorting system. The alternative IR filtering system is compatible with the same detection array, data acquisition, and data processing hardware as for the original IR filtering method. A conceptual design has been developed, components identified, and an alternative work plan underway to be implemented in the event it is needed.

Detection Array and Data Acquisition Hardware

During the reporting period a Camera Link based frame-grabber unit, which enables communication with and data acquisition from the IR detection array, was integrated with a QNX real-time computational module. Test verified performance of the QNX real-time system data acquisition system at consistent and controllable data rates required for sorting. A Windows based camera control module with camera parameter setup capabilities was developed and tested.

Real-Time Components

The real-time components may be considered as the hardware and software necessary to effect the high-speed sortation. The hardware components consist of a single board computer (SBC) with a multi-core processor, a high-speed line-scan camera, frame-grabber and digital I/O controller. The software components consist of an RTOS, hardware drivers, polymer identification algorithms and material removal routines.

During the prior reporting period the various real-time components required to develop and build the real-time processing system were specified and acquired. During the reporting period integration and programming of the various components provided capability to deliver a Phase III computational module to a client. Preliminary software drivers were designed and programmed and data processing systems suitable to drive the bench scale prototype IR filter and detector array subsystem were developed.

Conclusion

The research on this Phase II project is generally progressing as intended although the need to redesign major components has resulted in a need to push out in time the completion date for construction and testing of a prototype sorter. During the reporting period the redesigns were generally completed and a new work path developed to implement the new designs. It is anticipated that in the upcoming reporting period progress toward building a working prototype sorter can now move ahead at a significant pace.

Publications

Phase I Final Report, Development of High Speed Multispectral Imaging for Sorting Automotive Plastics, U.S. Department of Energy SBIR Program, Contract DE-FG02-06ER84559, National Recovery Technologies, Inc., Nashville, TN, March 2007.

SBIR Phase I: Development of High Speed Multispectral Imaging for Sorting Automotive Plastics, U.S. Department of Energy SBIR Program, Contract DE-FG02-06ER84559, National Recovery Technologies, Inc., Nashville, TN, March 2008.