Evaluation of Shredder Residue as Cement Manufacturing Feedstock

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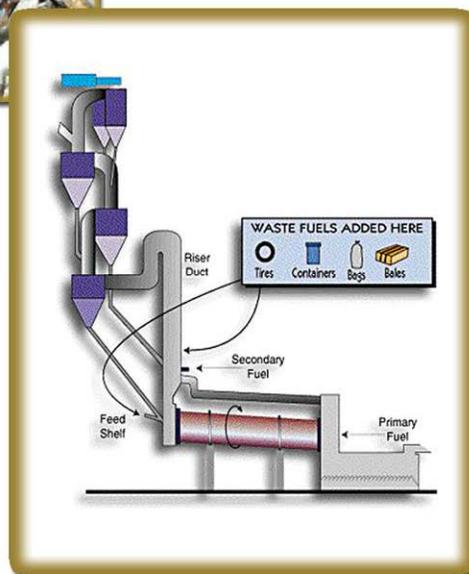

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PROJECT SUMMARY

Shredding 15 million tons of scrap automobiles, appliances and other light metal products results in recycling of about 12 million tons of ferrous and non-ferrous metals in the US each year. However, about 20% of the scrap feed remains after metals recovery (consisting primarily of glass, plastics, rubber, fabrics, dirt and fines). This material is commonly referred to as shredder residue (SR). Nearly all of the over 3 million tons of SR generated in the U.S. each year is landfilled. From both a resource conservation and good business practice perspective, recovery of the energy and mineral value of SR should be examined as an alternative to disposal. Compared to landfilling, material recovery and energy recovery are usually preferred because of conservation of non-renewable resources and reduction of waste disposal (Boughton 2005). However, because many reuse and recycling options may not be environmentally beneficial or cost effective, there is a need for further study.

The main barrier to recovery of energy value from SR has been the perception that it is too contaminated, has a low heating value and is heterogeneous. Recovery of materials and energy from SR has been studied, however past efforts to upgrade and purify SR to a suitable quality have proven uneconomic or impractical. A consumer of SR needs to have a robust process and operational flexibility as well as the capability to use large quantities of materials. For these reasons, cement kilns are the most likely user of SR as a supplemental fuel or for mineral recovery. Simplistic methods to separate SR into energy and mineral rich streams may facilitate the use of a sizable fraction of SR by this industry. Due to the large scale of the cement industry in the US, a significant amount of SR is recoverable.

The goal of this study was to identify the feedstock quality parameters needed to satisfy kiln operators and then to assess the mechanical means necessary to process SR into material acceptable as coal and mineral substitutes. To test this concept, the USEPA and the California Department of Toxic Substances Control (DTSC) funded this study to investigate inexpensive separation systems capable of producing acceptable fractions.

Initial physical and chemical test results allowed kiln operators to assess limitations of SR as a fuel or mineral substitute. Analyses included the moisture, volatile matter and mineral content, the calorific value, and elemental concentrations. Beneficial mineral content (namely silicon) was found to be much lower than expected, but not surprising since low glass content was seen in the fines. After discussions with shredder operators, it is clear that appreciable removal of glass occurs at the dismantling yards before autos reach the shredding facility. As a result, recovery of SR for mineral content was not studied further.

In general, the fuel characteristics of SR as generated were found to be poor due to high ash, heavy metals, and chloride content. A literature review and discussions with shredder operators offered great insight into the equipment needed to upgrade SR to valued fuel. Technologies that have been used or could be used to recover valued sub-streams from SR include heavy media separation, froth flotation, vibrating tables, optical

sorting and air classification. With these technologies in mind, discussions with shredder and kiln operators lead to a conceptual system design to recover a fuel rich fraction from SR.

To test this concept, field tests were conducted to separate and further beneficiate the SR waste stream. Flotation/density separation techniques commonly used by shredders in the past were tested to separate rubber and plastics from non-combustibles and contaminants (e.g., PVC and copper wire). A fraction constituting about 30 wt% of the total SR was found to have fuel characteristics mirroring those of coal. However, levels of potentially problematic constituents (e.g., total chlorine and heavy metals) may limit use to a low relative addition rate.

An economic review of a full scale separation system was compiled. Processing SR appears to be economically marginal considering avoided landfilling costs alone. However, significant economic benefits would result from additional non-ferrous metals recovery (namely copper). Full scale demonstration of separation systems is the next step. Some development of techniques to reduce the contaminant levels may be needed, followed by testing to show that no significant increases in emissions at kilns would occur. The presence of mercury lowers the value of SR derived fuel. Other contaminants may be of concern as well.

Reducing the contamination of SR from components in the shredder feedstocks (e.g., PCB laden capacitors, lead wheel weights, and mercury switches) may be the most significant barrier to overcome. If PCB and other contaminant concerns cannot be overcome for use of SR, few if any other options exist other than landfilling. Residual PCBs present a barrier for any recovery alternative but actually promote landfilling over resource recovery, contrary to the principles of RCRA.

BACKGROUND

Shredder Residue
Shredder residue (SR) is generated by businesses that recover ferrous and non-ferrous metals from waste automobiles, appliances and other light scrap. The metallic feedstocks are collected from automotive parts reclaiming and dismantling yards, metal recyclers as well as appliance dealers and landfills. About 12 million tons per year of steel and nonferrous metals are recycled at over 200 dedicated shredding operations nationwide (USEPA 2004c, Fisher 1999, ISRI 2004, Staudinger 2001). Roughly 20% of the feedstock becomes shredder residue comprised primarily of glass, plastics, textiles, rubber, and fines. Over three million tons of SR generated in the U.S. each year are landfilled (USEPA 2004c, ISRI 2004).

Typical shredder residue

The heterogeneity of shredder feed material makes it very difficult to quantify the composition of the shredder residue waste stream (Ambrose 2000). Additionally, the physical nature of SR (photo), cross contamination, weak markets for major recoverable materials (such as polyurethane foam, rubber and plastics) and significant processing needed to meet market specifications hampers recovery of specific materials from SR.

The directive for end-of-life vehicles in Europe has generated numerous efforts to increase dismantling, and to recover plastics, other materials or energy value from SR (European Commission 2005, CARE 2005, Forton 2005, WERG 2002, Schut 2004, Schut 2001). As a result, many different recovery systems have been studied (Zevenhoven 2003). Similar efforts are also underway in the U.S., Japan, and Australia (Gallmeyer 2003, Kusaka 2000, USCAR 2002, Toyota 2005, Recycling Today 2005, Nissan 2004, APC 2005, CWT 2005, Environment Australia 2002). Recovering of plastics for recycling and limited testing of SR as a pyrolysis feedstock or as a fuel for waste combustors and cement manufacture have also been performed (CARE 2005, Day1993a, Winslow 1998, 1999, and 2004, Plastics 2005, Keller 2003, Redin 2001). Systems to process SR to meet specifications (low ash and low sulfur) for blast furnace fuel or for secondary material recovery are expensive and a significant residual waste volume remains (SALYP 2004, ANL 2004, American Plastics 2005, Das 1995).

Recovery of gross fuel value from wastes can provide a significant economic benefit to large energy consuming industries. Dry SR is about 50% combustible and 50% non-combustible (metals, glass, dirt, and residual ash). Others have studied the energy value of SR and energy recovery in various systems (Mark 1999, CAC 1998, Zevenhoven 2003, USDOE 1987, CMP 1990, Automotive Engineering 1994, Saxena 1995). Some

separation of the SR components was required to improve the energy value, as well as to reduce residual ash or remove problematic constituents such as PVC. As a result, co-combustion of SR with municipal solid waste for energy recovery or as a blast furnace fuel was only be viable for half the SR waste stream (plastics and rubber) with highest energy and lowest ash content. The residual fraction of the SR would need to be landfilled or managed in another way.

Cement Manufacturing
Cement kilns can use a wide variety of different fuels without compromising cement product quality, plant operations or emissions. Kiln operator experience with substitute fuels such as waste plastics, tires, paint, used oil and other solid and liquid wastes is widespread. The portland cement product quality and kiln air emissions are not impacted by contaminants in the commonly used alternative fuels even at up to 30% fuel supplement (USEPA 1995, Gabel 2005, Choate 2003). The most commonly used supplemental fuel, waste tires (which contain significant amounts of zinc) has contaminant levels similar to that of SR (USEPA 1991).

Numerous studies discuss the very successful use of alternative fuels and minerals in cement manufacturing, the resulting benefits of energy and raw materials savings, the incorporation of residual ash into the cement product, and the destruction of organic constituents in the fuel (PCA 2004, Prisciandaro 2003, Taiheiyo cement 2004, RRF 1992, Cembureau 2004, WBCSD 2005, Lanoir 1997, Dyckerhoff 2005, Holcim 2005, USEPA 2004, Heart 1996, Denis 2000). Most of the low and medium volatility heavy metal contents in mineral and fuel feedstocks are incorporated into the cement product. In contrast, air pollution control systems capture only about 50% of the highly volatile metals such as mercury (Seyler 2005, PCA 2005). Additionally, the large amount of limestone in the feed minerals effectively controls acid gas emissions.

Cement producers are also successfully using many different materials for mineral feed substitutes (Holcim 2005, van Oss 2002, van Oss 2003, Taiheiyo cement 2004, CIF 2003). These include spent catalysts, aluminum production wastes, glass, industrial ashes, filter cake and mill scale. Considering the alternative feedstocks that kiln operators currently use and the volume of SR generated each year, SR should be reviewed for its potential as both a fuel and mineral supplement. Plastics and rubber make up the majority of SR combustible content. But compared to the alternative fuels used at cement kilns today, SR is a heterogeneous mixture of many different materials with comparatively low BTU value and high ash content. Others have shown that SR has about 5000 BTU per pound (40% that of coal) and may consist of up to 40% of mineral equivalent to that used in cement production (silicates, calcium, aluminum and iron). Separating SR into high BTU and high mineral content fractions for recovery in cement kilns could result in considerable coal and minerals conservation.

The avoided landfill fees for shredder operators, as well as fuel cost savings at kilns would need to offset the SR processing costs. Use of SR in kilns would also lead to reduced environmental impacts from less mining, transporting and preparation of coal and mineral ores. The potential impacts of landfill leachate contaminated with SR

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constituents would be avoided and landfill space would also be conserved. As a secondary benefit some emissions reductions may occur with substitute fuels such as waste tires, plastics and used oil (e.g., a lower carbon, nitrogen and sulfur content per unit of energy than coal yields lower carbon dioxide, nitrogen oxide and sulfur dioxide emissions (EPA 1995, Gabel 2005)). All these issues should be considered when evaluating resource recovery options (Boughton 2005).

Project Goal and Description
Discussions with cement manufacturing industry representatives indicate that the main barriers to the use of SR is the perception that it is too contaminated, too heterogeneous and of insufficient energy value for use as fuel (Bennett 2005, Meinen 2005, Shumway 2005, Hawkins 2005, Mayes 2005). These became the key considerations to address in this study. The plastic, rubber and textile components of SR exceed the BTU value of coal. The inert content (namely glass, iron, calcium and aluminum) in SR can substitute for mineral feed-stock. The goal of this study was to assess the mechanical means necessary to separate and process SR into material acceptable for substitution for coal and mineral feedstocks. The USEPA and DTSC funded this study to determine if an economical separation system appears capable of producing material acceptable for kiln use.

The project was developed in phases. The first phase was to characterize the SR as generated. Samples of SR were taken at the Hugo Neu-Proler shredder facility in Los Angeles, California. Laboratory tests were conducted to assess SR characteristics including physical parameters, fuel characteristics (proximate and ultimate analyses), as well as beneficial elements and contaminant concentrations. Two contract laboratories were chosen, Hazen Research of Colorado to do the sample preparation and proximate/ultimate analyses, and American Scientific Laboratories of California to do the elemental analyses. We discussed the results with kiln operators to determine the considerations for supplemental fuel and mineral additives. In the second phase, we demonstrated separation techniques to recover valued streams. The final phase included the estimation of operating costs for a full scale separation system and comparison to the costs of SR landfilling.

INITIAL SAMPLING RESULTS

Waste Sampling
SR sampling was conducted at Hugo Neu-Proler over two days (February 10-11, 2005). The non-ferrous metals recovery system produces <½", ½-1½", and 1½-4" size sub-streams of SR material by trommelling. (A small volume stream of >4 inch oversized material passed through the trommel and was noted to contain significant amounts of rubber and metallic material. This material was not sampled because it is returned to the shredder for size reduction, but it could be separately sorted to obtain the energy rich materials.) The trommelling and nonferrous metal recovery systems act to homogenize each sub-stream (helping to meet one of the identified barriers to SR use) and to separate fines from the larger materials. These processes result in relatively clean and uniform sub-streams; hence small sample sizes should be adequate.

After sufficient time for the non-ferrous recovery system operation to stabilize, sampling was conducted after shutting down the entire system three times on February 10, 2005. Two separate nonferrous metals recovery systems operate in series for the fines and midsize streams, and one system for the coarse material. Samples were taken from each of the five nonferrous recovery system discharge conveyance belts. In general, material from a one foot wide swath across each two foot wide discharge belt filled 1-gallon plastic bags. Larger cross sections were taken from the sparsely loaded belts (secondary discharge belts). For the >1½-4 inch coarse material, two or three bags were filled to adequately characterize the waste.

In addition to three samples from each of the sampling points described above, three samples were also taken from the recombined <1½ inch materials (the <½ inch and >½ inch to <1½ inch sub-streams) on February 11, 2005. Sampling both the <1½" recombined sub-streams and the >1½" sub-stream will help to characterize the total SR waste since the weight proportions of the individual sub-streams are not well known. A total of 33 samples were collected over the two days. All sample bags were sealed to retain moisture and sent for processing and analysis. Also, the laboratories reanalyzed 16 samples to gather information on the heterogeneity of the samples and reproducibility of laboratory analyses.

Field observations showed that the fines appeared very uniform, consisting mostly of fiber and dirt, and free of material larger than ½ inch. A portion of the fines material were sieved with several trays to examine the ability to further size separate the material (screen sizes included 19mm, 4.75mm, 2mm, and 0.85mm openings). In general the fines contain a significant amount of fibers that obstructed the 4.75mm screen. Very small amounts of glass were seen in the fines samples, meaning glass recovery would likely not be feasible. All samples of SR larger than ½ inch size were relatively free of fines, and well mixed and fairly uniform in composition despite the diversity of materials within. Ferrous and nonferrous metal recovery seems to be complete with the exception of small amounts of metals attached to plastic or rubber pieces (such as a hose clamp on a rubber hose or a small screw within a plastic piece), short lengths of copper wire entangled with other materials, as well as steel cord wire imbedded in tire shreds.

Laboratory Results
The laboratory processed the total volume of each sample, with the exception of some metal fragments and rocks that were removed during milling. Materials were cryogenically milled to pass a 2mm screen (which preserved the volatile components such as mercury). After through mixing, proximate and ultimate tests as well as elemental mercury and total chlorine determinations were completed. Elemental analyses were then done on the ash resulting from the proximate analyses. Duplicate analyses for 16 of the 33 samples gathered information on the homogeneity of the processed sample material as well as the reproducibility of the laboratory analyses. Standard laboratory QA/QC procedures were also performed.

The laboratories reported the proximate, ultimate and elemental test results for all samples as well as duplicates. The nature of rubber and plastics makes it very difficult to analyze for elemental concentrations because of the resistance to digestion. Tests on the recovered ash should reflect the raw material elemental concentrations except for volatile metals such as mercury, lead and cadmium. With the exception of mercury, analyses for total metals from other samples of SR material were gathered to fill this gap.

The moisture content of the samples varied due to dust control sprays in the shredder and the non-ferrous separation system and may also be significantly different depending on the season. Hence, all results are presented on a dry-weight basis to provide consistency and for comparison to other fuels. The results are presented as an average of the six samples for each sampling point (note that only three samples of the <½-1½ inch combined material were taken). In general the variation between the six samples in each size fraction was small. Duplicates showed only slight variation in results. Statistical confidence intervals were not determined, but the samples appear representative of each size fraction.

Table 1 shows that the larger the material size, the lower the residual ash content and the higher the BTU value (as expected, BTU values inversely correlate with the residual ash content). The fines, which constitute about 30% of the total SR wastestream, had the highest ash content of 50-60% and the lowest BTU content of about 5000 BTU/lb. The ½ -1½ inch mid-size fraction, also about 30% of the total SR wastestream, has marginal energy content. The coarse material, which constitutes about 40% of the total SR stream, had a BTU value comparable to coal. However, none of the size fractions yielded a chlorine content low enough to be valued. Chlorine levels were found to trend higher with larger material size. The net chlorine levels correlate with the PVC content in automobiles and appliances. For example, autos typically contain 20 lb of PVC and yield 350 lb of SR after metals recovery. PVC is typically 50% chlorine by weight; hence the PVC should contribute up to 3 wt % of chlorine to the total SR, consistent with the results in Table 1.

Laboratory data for the ash concentrations of elements were converted to equivalent raw material concentrations using the residual ash wt % determined for each sample. The tables that follow present averaged results for each size fraction and each sampling point.

Table 1 -Averaged proximate/ultimate results for SR by size fraction sampled
(dry weight basis, n=6)

Material fraction	BTU/lb	Ash wt%	Chlorine wt%	Sulfur wt%
Fines <½ inch	5880	54.4	1.0	0.24
Fines <½ inch	4650	61.4	0.6	0.30
½ -1½ inch	8670	40.8	1.8	0.31
½ -1½ inch	9420	33.4	2.3	0.31
**<½-1½ (n=3)	7170	46.3	1.1	0.25
Coarse 1½-4 inch	12900	20.5	3.2	0.49

** samples of facility recombined stream

Table 2 presents the average values for several elements in SR that could substitute for mineral feedstock for cement manufacture, namely silicon, aluminum, calcium and iron. Generally, the levels of beneficial constituents decreased with larger material size as expected, but are lower in the fines based on reports of others (cited in the Background section). Overall, none of the size fractions would be valued as kiln mineral feed substitute. The fines could be beneficial as a mineral substitute if the silicate levels were higher. Others have found silicon levels of over 5 wt % in SR mostly due to the presence of glass. These results showed silicon concentrations below 0.5 wt %, which was not surprising after visual inspection of the fines showed little glass. After discussions with shredder operators, it is clear that a majority of auto glass is removed or broken at the dismantling yards before reaching the shredder facility.

High levels of deleterious elements reduce the value of SR as a mineral or fuel supplement for kilns. Excessive alkali content (namely potassium and sodium) will lead to cement kiln dust (CKD) generation or operating problems if not removed. In general, the smallest sized materials contain the highest levels of potassium and sodium (Table 2). These levels are too high for kiln fuel supplement at most kilns (the exception being kilns with low alkali containing mineral feed stocks or kilns which can manage increased CKD generation).

As shown in Table 3, with the exception of volatile metals shown, the elements generally were at the same levels as previous studies have found for SR. Mercury, beryllium, cadmium, selenium and thallium were non-detectable in every ashed sample. The high levels found for copper are unacceptable for kiln use of any fraction as a fuel. Considerable amounts of copper wire fragments, many connected to or intertwined with other materials, were seen in the samples and are likely a major contributor to the copper levels. As expected, no mercury was found in the ashed materials. Mercury content before ashing was measured in the 1-2 ppm range and appeared to be higher in the smaller size material. The results for lead, vanadium, cadmium, arsenic, and zinc are underreported due to volatilization during ashing from the proximate/ultimate analyses. Table 4 shows losses due to volatilization during ashing range from 35% to 100% depending on the metal compared to SR as disposed (DTSC 2002).

Table 2 - Averaged concentration of beneficial and deleterious elements in SR fractions
(ppm dry weight basis, n=6)

Material fraction	Aluminum	Calcium	Silicon	Iron	Potassium	Sodium
<½ inch	11016	31094	2428	15218	740	5332
<½ inch	12655	31162	6379	24798	941	6162
½ -1½ inch	8425	23363	4015	18701	517	3515
½ -1½ inch	9214	25495	1584	6579	557	1377
**<½-1½ inch	9120	27733	3779	22685	639	3423
1½-4 inch	3549	17384	1092	14166	171	760

** 3 samples of facility recombined material

Table 3 - Averaged elemental concentration in SR fractions
(ppm sample dry weight basis, n=6)

Element	<½ inch	<½ inch	½ -1½ inch	½ -1½ inch	<½-1½ inch**	1½-4 inch
Antimony	101	98	113	165	117	125
Arsenic	8	9	5	3	5	4
Barium	828	987	636	376	676	110
Chromium	171	89	95	38	134	101
Cobalt	13	22	18	10	17	14
Copper	15333	16345	24461	29454	29560	15735
Lead	784	692	148	560	233	64
Molybdenum	17	30	30	103	21	23
Nickel	212	235	190	133	338	148
Magnesium	5008	4808	3385	2994	4156	1744
Silver	6	25	3	3	5	1.0
Titanium	538	643	706	704	639	386
Vanadium	9	15	15	11	12	7
Zinc	7092	6482	8868	9793	5089	3415

** 3 samples of facility recombined material

The presence of PCBs is a concern for any material returned to market or used as a fuel.
Despite efforts to eliminate PCBs from metallic discards before shredding, low levels of
PCBs continue to be found in SR. Tests for PCBs were not conducted on the size
separated SR. PCB tests of disposed SR generated by several California facilities average
total levels ranging from 16 to 82 ppm (DTSC 2002 and DTSC files). Levels above 50
ppm trigger TSCA requirements for hazardous waste management. SR with levels below
50 ppm can be landfilled or managed at TSCA permitted facilities. SR derived fuels may
or may not be allowed to be used if PCB's are present depending on many factors
(Tokiwa 2005).

Duplicate analyses of 16 samples showed that the laboratory preparation methods lead to
well homogenized material for analysis and that the laboratory analytical methods were
consistent (good reproducibility). The laboratories met all quality objectives via
laboratory QA/QC including duplicates, matrix spikes and blanks.

Table 4 - Metal concentrations from other SR samples* and estimated loss from ashing

Metal	Average ppm*	Estimated % loss**
Cadmium	18	100%
Lead	3120	95%
Zinc	6890	35%
Arsenic	6	85%
Vanadium	29	65%
Mercury*	2	100%

*Except for mercury, values for landfilled SR from numerous facilities (DTSC 2002);
mercury results are for material before ashing
** % loss from ashing (present study results versus other SR as disposed)

SR SEPARATION AND ANALYSIS RESULTS

SR Materials Separation
Based on the results for the size-segregated SR materials, further separation is needed to yield material with acceptable energy, metals and chloride content. A literature review and discussions with shredder operators offered great insight into the equipment needed to reduce the contaminant levels. Technologies that have been used or could be used to recover valued sub-streams from SR include heavy media separation, froth flotation, vibrating tables, optical sorting and air classification. In the past, shredders used density separation systems with heavy media baths to recover and separate non-ferrous metals from other SR constituents. This technique can also be used to recover a high energy content plastics and rubber fraction from SR. The density of metals, glass, and dirt are two to three times that of most plastics and rubber materials. Additionally, density separation of PVC from less dense plastics and rubber has been demonstrated (TXI 2005, MBA 2005, Galloo 2005, Salyp 2004, Schut 2004). This technique looks to be the least expensive and most well developed to affect a separation of SR to yield a low ash, low chlorine, and high BTU content material.

Five gallon containers of the <1½ inch (the combined <1/2 inch and >1/2 to <11/2 inch material) and of the >1½-<4 inch sub-streams were separately collected on August 2, 2005. The 26.5 lb of <1 ½ inch material was found to be highly fibrous with some plastic, rubber and copper wire pieces interspersed. Hand sorting showed that only 3.5 lb of small plastic and rubber pieces were in the total sample. The material was sampled for lab analyses, but there was not enough plastic and rubber content to test density separation.

The total 14 pounds of >1½ inch coarse material was separated by hand to remove materials from the plastics and rubber materials of interest. Seven different recovered fractions resulted; copper wire, polyurethanes, polystyrenes, carpet/textiles, mixed plastic/rubber, tire rubber, and a residual fibrous mix. The plastic/rubber fraction weighed about 8 pounds, the fibrous material weighed about 4 pounds, and the remaining materials collectively weighted about 2 pounds. The plastic/rubber fraction was retained for density separation, and the other materials were separately bagged for laboratory analysis.

Small scale tests with salt water baths are commonly used to test density separations. A laboratory scale experiment was designed to test separations using Epson salts ($MgSO_4$) in hot water. The plastic/rubber materials were first placed into a hot water bath to separate floaters. A significant amount of material floated including plastics, wood, textiles, and paper as well as polyurethane and styrofoam. The floaters were collected, bagged for laboratory analysis and labled as <1.0 specific gravity (sg). A set of salt water baths were then used to sink/float the remaining >1.0 sg plastics and rubber materials. Bath densities were chosen based on those successfully used by others to separate mixed plastic wastes. The premise was that PVC should be separated by sinking at densities near 1.3 sg (depending on specific plastic product formulation) while the bulk of the less dense plastics and rubber will float. Mixed plastics and fillers used in specific plastics

formulations may lead to different specific material densities however. Hence, a range of bath density levels should separate the plastics/rubber sample into fractions with the purpose of removing a majority of the overall chlorine content.

Actual bath densities achieved were >1.3, >1.275, <1.225, and <1.125 specific gravity. The material that sank in the initial water bath was transferred to the highest density bath (>1.3 sg). Sinkers, the material with a density above 1.3sg (observed to be mostly vinyl backing for floor mats), were collected and washed in hot water to remove residual salts and then bagged for analysis. The materials that floated at 1.3sg were transferred to the next lower density bath. This sequential procedure was followed until the final 1.125 sg bath where both the sinking and the floating materials were collected. Relatively small amounts of materials were recovered at the mid range density splits and a majority of the rubber separated at 1.1 sg, while plastics appeared to be more distributed. The separation by density experiment lead to seven separated components which in addition to the six hand separated materials gave a total of thirteen separate components sent for lab analyses.

Laboratory Results
Table 5 shows the fuel value testing results for each of the 13 components on a dry weight basis. In general the results were as expected. The heating values were highest in plastic and rubber materials with the lowest residual ash weight. The materials below 1.1 sg had the lowest chlorine content. And the material above 1.3 sg including copper wire had a high relative chlorine content which supports the concept of density bath sink-float techniques separation from the other materials. Fibers were the major component by weight but not of high energy value. A large amount of material was found to have a density less than water.

Table 5- Proximate/ultimate analysis results for coarse SR components
(dry weight basis)

Component	Weight -grams	Wt % ash	Wt % Cl	BTU/lb
carpet	283.9	41.0	2.1	6660
fiber	1557	45.8	1.6	6650
copper wire	282.5	71.0	12.0	8110
>1.35 sg	263.6	37.6	4.7	7730
>1.3 sg	163.6	25.9	12.5	10680
>1.2 sg	137.2	18.4	1.3	12330
>1.1 sg	425.7	8.2	3.7	13250
>1 sg plastic	291.2	5.0	1.2	15890
>1 sg rubber	616.4	4.1	0.10	15950
tire rubber	272.2	22.6	0.10	14900
<1.0 sg	1087	9.2	1.2	15750
polyurethane	119.6	21.3	0.35	10350
polystyrene	39.6	10.7	0.44	12460
Weighted Total *	**5540**	**26.4**	**2.4**	**11380**

* based on individual component contributions to total sample

The sample total values were calculated by adding the individual component contributions. The net 26% ash, 2.4% chlorine and 11,380 BTU/lb are in line with prior results for this size fraction of SR (see Table 1).

The goal of the project is to recover a significant volume of material with the most energy value and the least chlorine content. The proposed separation system design (as discussed later) includes a fiber separation system as a first step, followed by density separation of the remaining materials. The ordering of the sub-fractions in Table 5 mirrors the proposed sequence of separation steps. For simplicity, the components shown in Table 5 were consolidated by grouping as follows: fibers and carpet, >1.3 sg includes the >1.3 sg and the >1.35 sg components, >1.0 sg includes the tire rubber as well as the separated plastics and rubber, and <1.0 sg includes the polyurethane and polystyrene. The values presented in Table 6 are the cumulative contributions to the total sample for each of the groups. For example, the components of <1 sg contributed 22 % of the total sample weight of 5540 grams, 10% of the total chlorine, 9% of total ash, etc.

Table 6 - Fuel value contributions by component groups of coarse SR material

Component Group	Percent cumulative contribution to the sample total			
	Weight	Chlorine	Ash	BTU
<1 sg	22.5	10.3	8.8	29.9
>1 sg	43.8	13.1	15.8	59.3
>1.1 sg	**51.5**	**25.0**	**18.1**	**68.2**
>1.2 sg	54.0	26.4	19.9	70.9
>1.3 sg	61.7	51.0	29.5	76.9
Copper wire	66.8	76.6	43.3	80.6
Fiber/carpet	100.0	100.0	100.0	100.0

Choosing the media bath density leads to a trade-off between recovering the most heating value while retaining the least chlorine content. As shown in bold, a 1.2 sg density bath would result in recovery of two thirds of the initial heating value while only retaining 25% of the total chlorine and less than 20% of the ash content. The component contributions shown in Table 6 were further consolidated into two sub-streams at the 1.2 sg density cut-off. Two fractions result, half the mass as an energy rich material and half as a residual. The fuel rich sub-stream comprised of all materials under 1.2 sg, labeled *fuel* in Table 7, has characteristics comparable to coal. The remaining material, labeled *residual,* would be burdened with a majority of the ash and chlorine content.

Table 7- Key fuel characteristics for separated coarse SR at 1.2 sg

Characteristic	Sub-fractions (1½ - 4 inch)	
	Fuel	Residual
BTU/lb	13240	6560
Chlorine	1.2 wt %	3.7 wt %
Ash	9.3 wt %	44 wt %
Sulfur	0.59 wt%	0.44 wt %

Other elements in SR are of concern including heavy metals as well as the beneficial elements such as silicon, aluminum, iron and calcium. The elemental analyses results were compiled and shown in Table 8 for the same 1.2 sg separation cut-off discussed above. Low levels for nearly every element are found in the in the *fuel* fraction. Most of these levels fall into acceptable levels for supplemental fuel. However, about 1 ppm of mercury was found in the *fuel* fraction (measured before ashing), a level several times that of coal (Federal Register 2005).

As a benefit of the separation system, some of the copper (wire fragments) should be recoverable from the residuals sub-stream. The *residual* fraction showed only a 7.5 wt % net content of beneficial minerals (bottom four elements shown in Table 8), not high enough for further recovery for use as a kiln mineral feed substitute.

Table 8 –Elemental analysis for separated coarse SR at 1.2 sg
(ppm dry weight basis)

| Element | **Sub- fractions (1½ - 4 inch)** | |
	Fuel	Residual
Mercury	1	4.73
Antimony	130	371
Arsenic*	1.2	4
Barium	59	1170
Cadmium*	2	9
Chromium	17	123
Cobalt	24	23
Copper	914	56291
Lead*	94	1186
Magnesium	1203	4119
Molybdenum	9	37
Nickel	98	133
Silver	0.9	11
Vanadium*	6	15
Zinc	4954	5925
Potassium	244	802
Sodium	523	2810
Phosphorus	169	219
Tin	26	465
Strontium	22	244
Titanium	237	455
Tungsten	86	109
Aluminum	1101	9503
Calcium	7622	29892
Iron	5080	31559
Silicon	853	4299

* Concentrations shown are significantly lower than the actual concentrations due to volatilization, see Table 4

DISCUSSION

Full Scale Considerations
A list of specific requirements or contaminant limitations for cement kiln operators was not compiled. Because each kiln has mineral feedstocks with different characteristics, has different operating designs and has different environmental limitations, little guidance on common limitations for supplemental fuels or minerals was gathered from discussions with operators. What became clear was that some facilities could accept materials with certain characteristics while others could not. There also is considerable flexibility at some facilities depending on many factors. Some cement manufacturers will accept poor quality fuels based on the amount of payment offered for disposal, others have strict limits on specific constituents such as total alkali because of CKD generation.

Discussions with shredder operators lead to a conceptual system design to recover a fuel rich fraction from SR (Andrusyshyn 2005, Neu 2005). A full scale system would likely need to first break up and separate entangled fiber material from the valued rubber and plastic pieces. Air classification could remove the very low density materials such as expanded polystyrene and polyurethane (much of this material may already be recoverable at the shredder). Following some cutting of fibers to disentangle the SR and further separation, density sink/float techniques will effectively recover a valued plastics/rubber stream.

Density separation at 1.2 sg appears to remove the majority of the chlorinated plastics and high ash bearing materials. However, resulting chlorine levels of 1 wt % may mean that the final recovered fuel fraction (see Table 7) would be marginally valued and perhaps only useable at a few facilities or at low substitution rates. Reducing the media bath density cut-off to closer to 1.1 sg should result in a chlorine content of 0.7 wt%, while still leading to significant recovery of BTU content (60% from Table 6). Alternatively, additional separations to further reduce the chlorine levels may be needed. Such separations have been demonstrated with mixtures of plastics and with SR (Galloo 2005, MBA 2005, Salyp 2004, WERG 2002). Texas Industries (TXI) apparently demonstrated such a system with SR but no information is available (TXI 2005, Schut 2004). However, it is notable that the reconstituted fuel material results from this study (shown in Table 6) are lower than the supplemental fuel requirements of less than 4% total chlorides stated by TXI for their cement facilities.

The presence of PCBs may impede the use of SR supplemental fuel in kilns. Creating a system oriented towards efficient use of resources could require fundamental changes in the waste versus non-waste regulatory construct embedded in RCRA (USEPA 2003). One such change may be needed in the federal scrap metal exemption rules so that non-metallic materials recovery at shredders is allowed.   Alternatively, SR could be considered a mixed waste under RCRA to allow the SR derived fuel to be used despite traces of PCBs below TSCA limits (50 ppm).

Conceptual full-scale design
Some of the technologies that have been used or can be potentially used to recover valued sub-streams from SR include heavy media separation, froth flotation, cryogenic grinding, vibrating tables, air classification, and optic sensors (Jody 1994, Buchan 1995, de Jong 1997, Scheirs 1998, Trouve 1998, Day 1999, Fraunholcz 2000, Singh 2001, Shen 2002, MBA 2005, SALYP 2004). With these technologies in mind, discussions with shredder and with kiln operators lead to a system concept to recover a valued fuel fraction (Andrusyshyn 2005, Osuscha 2006, Neu 2005) as described below.

A full-scale separation plant design assumes that a shredder operates a nonferrous recovery system that produces several size separated streams. Excluding the fines (< ½ inch SR material) leaves about 66% of the total SR waste stream to be initially processed by cutting, vibrating tables and air classification to separate fibrous and entangled materials. The resulting plastics and rubber rich stream (with copper wire and other dense materials) would then be placed in a water bath to separate the low density materials. The remaining material would be sent to a heavy media bath system with a density controlled between 1.1 and 1.2 sg This would lead to removal of the residual metal and PVC, with some tolerable loss of valued materials. An economic review of the entire process requires sizing each processing unit. A mass flow assessment includes the following assumptions based on the results in Table 6 and conversations with shredder operators:
- 66% of the total SR residue is over ½ inch
- 64% of that is recoverable plastics and rubber
- 70% of that is less than 1.2 sg and recoverable
- Ferrous and nonferrous metals are recovered from the sink fraction

The process steps outlined in Figure 1 would initially involve processing 33 tons/hour of fines free material to remove fibers and free entangled pieces (based on 50 t/hr SR generation). Separation by several air classification steps leads to recovery of 21 tons/hour of relatively fiber free plastics and rubber pieces (with copper wire and PVC). An initial water bath would recover about 6 tons/hour of <1s.g materials from the mixed stream. A media bath processing the remaining 15 tons per hour of >1sg residual from the water bath would result in flotation of 9 tons/hour of materials and reject about 6 tons/hour of >1.2 sg materials (including copper and PVC with some carryover loss of desired materials). Further recovery of 0.2 ton/hour of copper from the rejected fraction (conservatively assumed to be only one third of the total copper content) would be the final step. From the assumptions above, a net 15 tons per hour is recoverable and a total 35 tons per hour of waste for disposal would result.

All the systems proposed are low technology processes that are familiar to shredder operators. Simple design and low labor operations are desired even at the expense of some loss of valued material. As the key piece of equipment, several media separation systems were investigated. One design is a cone shaped settling tank with a rotating skimming device at the surface and a screw conveyor system to remove rejected material from the bottom. This will work well for the initial water bath separation system, but there are important considerations for the 1.2 sg media system. A rotating drum design

would provide the best throughput, recovery and separation quality. Density separation systems are most effective if the materials introduced are of the same size and shape. Chopping and shredding the recovered SR materials to pass a ½ inch screen would help the separation efficiency, but would add significant processing costs. However this may be the chosen method if the cement kiln operator requires the supplemental fuel materials to be small enough for pneumatic transfer into the kiln.

 For efficiency and cost considerations the media material chosen should be a ferro-silicate like magnetite. This natural ore is easy to magnetically recover from spent bath liquids and rinse waters, and inexpensive enough that drag-out losses in the separated materials are tolerable. A washing step will maximize the recovery of the media and the recovered water should make up for losses to the SR materials and evaporation, etc. Periodic bleeding of the bath water will be required to remove suspended solids that may build up and cause a shift in bath density. Any waste water can likely be discharged directly to the storm water collection and treatment system at a shredder facility.

```
            ┌─────────────────────────────────────────────┐
            │   Shredder residue generation 50 t/hr        │
            │                                              │
            │  fines                    >1/2 inch materials│
            └─────────────────────────────────────────────┘
               ↓34%                      ↓66%
┌──────────────────┐
│ 17 t/hr waste    │
└──────────────────┘
            ┌─────────────────────────────────────────────┐
            │   33 t/hr SR to air separation system        │
            └─────────────────────────────────────────────┘
               ↓36%                      ↓64%
┌────────────────────────┐
│ 12 t/hr fiber waste    │
└────────────────────────┘
            ┌─────────────────────────────────────────────┐
            │   21 t/hr to water bath separator            │
            └─────────────────────────────────────────────┘
               ↓70% sinkers              ↓30% floaters
                                  ┌──────────────────────────┐
                                  │  recover 6 t/hr <1sg     │
                                  └──────────────────────────┘
            ┌─────────────────────────────────────────────┐
            │   15 t/hr >1sg to media bath                 │
            └─────────────────────────────────────────────┘
               ↓40% sinkers              ↓60% floaters
                                  ┌──────────────────────────┐
                                  │  recover 9 t/hr <1.2sg   │
                                  └──────────────────────────┘
            ┌─────────────────────────────────────────────┐
            │   6 t/hr <1.2 sg to copper                   │
            │   recovery                                   │
            └─────────────────────────────────────────────┘
               ↓                         ↓
┌──────────────────────────┐
│  6 t/hr waste            │
└──────────────────────────┘
                                  ┌──────────────────────────┐
                                  │   0.2 t/hr copper        │
                                  └──────────────────────────┘
```
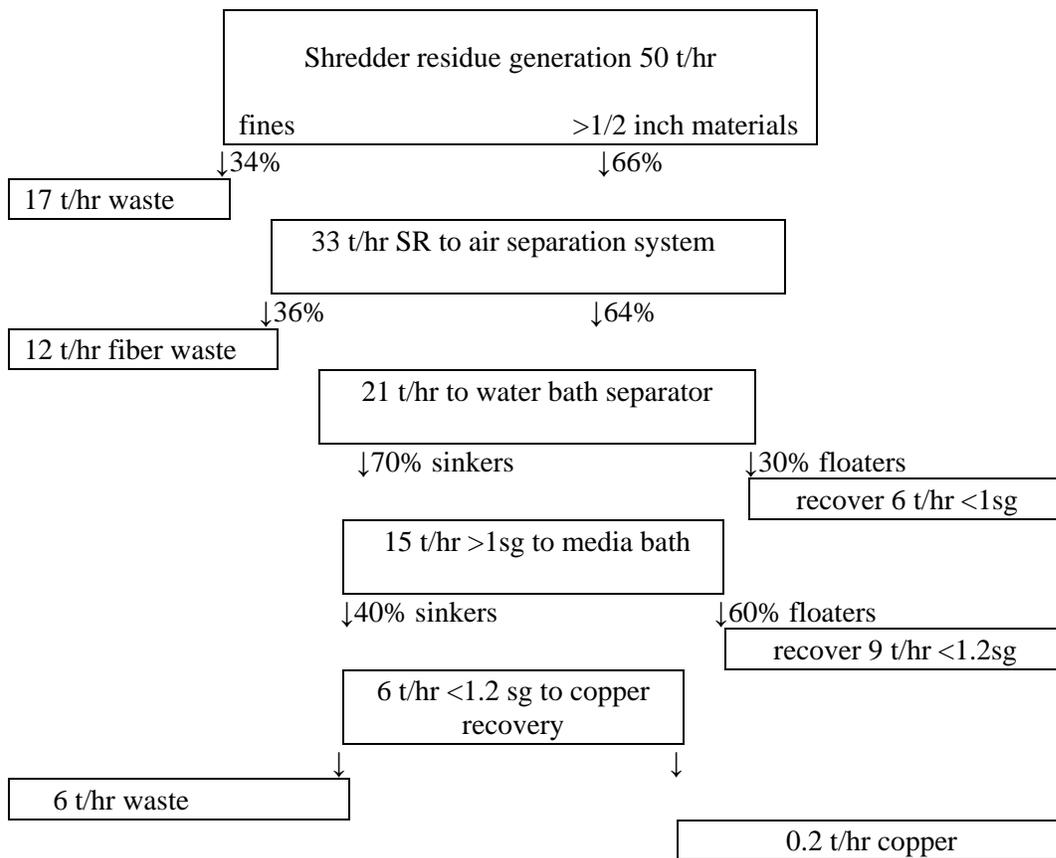
Figure 1 Processing steps and material partitioning for a conceptual separation system

The media bath is sized to process 15 tons/hour of feed. The 1.2 sg separation cut-off value is flexible. The results in Table 6 show that there is minimal mass fraction in the 1.1-1.2 density range; hence a system can be optimized to maximize recovery and reduce chlorine content, without substantial losses of valued materials. Both streams recovered from the density bath should be washed to recover magnetite. Some retention of magnetite will not reduce the value of the final product to kiln operators because the iron content is beneficial. Recovery of the low density fluff (predominately polyurethane and polystyrene) at the shredder or with an air classifier will also reduce media losses. However, certain shapes of material will retain water. A shaker table or rotating screens will help remove retained water. Magnetic separation would then recover magnetite from wash waters. If needed, the recovered SR product can be cut and shredded for efficient transportation and to facilitate the use of the material as fuel at a kiln.

Economic Assessment
A low technology processing system using commercially available equipment and minimal labor was envisioned. Air separation and shaker table systems are commonly used equipment by shredders. Many shredder operators have experience with density baths to recover and separate non-ferrous metals from SR. Table 9 summarizes the capital and operating costs and resource recovery economic benefits as described below.

Air classifiers and cutting systems and all conveyor systems are estimated to cost $350,000 (Andrusyshyn 2005, Perry 1997). An initial water bath of simple design is estimated to cost $200,000 (Andrusyshyn 2005, Osucha 2006, Perry 1997). The heavy media separation process is based on the design presented by the Bureau of International Recycling (BIR 2005) using a Protec drum separator (Protec 2005). Capital costs for a 15t/hr media bath unit are $750,000 including all ancillary equipment (Osucha 2006, BIR 2005, Protec 2005)). Assuming a 20 year operating term for all equipment (with a 10% interest rate) leads to total capital costs (P&I) of $150,000 per year (assuming complete depreciation over a 20 year period, taxes not included). Permitting fees, site acquisition and site preparation costs were not included. It is assumed that the operation would take place at a shredder facility and that those costs would be minimal.

Operations and maintenance costs include electricity to power a total of 300 hp for electric motors, 2 full time operator and maintenance personnel, and materials (including 300lb/hr media loss, and $50,000/yr in general maintenance materials). Trucking costs are based on a 50 mile round trip to a landfill, or a 100 mile round trip to a cement manufacturing facility and $2 per mile averaged cost (noting that significant savings could be found with rail transportation for long distances compared to trucks). Operating costs total $550,000/yr. The total cost of $700,000 per year will lead to recovery of 15t/hr of material (30,000 t/yr, based on 2000 hours per year) or $23/t recovered material.

Current national landfill tipping fees range from $24-$70 per ton (depending on region) with an average of $34 in 2004 (Wastec 2005). The current cost to dispose SR by landfilling may be lower if a discount is given for SR used as alternative daily cover. For the analysis to be conservative, $17 per ton was chosen. The avoided cost of trucking the recovered SR to landfills is $100,000/yr.

Table 9 Estimated economic cost/benefits for recovering 15t/hr SR derived fuel
(thousands of dollars)

	Annual Costs	Annual Benefits
Capital investment costs (20 yr term)		
Pretreatment (33t/hr), $350K	$18	
Initial water separation, $200K	$10	
Media bath (15t/hr), $750K	$37	
Non-ferrous recovery, $100K	$5	
Interest (10%)	$85	
Operating costs		
Personnel (4000 hours, 45% benefits)	$100	
Electricity (300hp total, $0.08/kwh)	$35	
Media (loss of 20 lb/t SR processed)	$120	
Other (general maintenance materials)	$50	
Transportation (30,000 t/yr, 100 miles)	$240	
Benefits		
Landfill offset (30,000 t/yr at $17/t)		$510
Transportation offset (30,000 t/yr, 40 miles)		$100
Copper recovery (400t/yr at $1.85/lb)		$680
TOTAL	**$700**	**$1,300**

Assuming that a kiln operator will take the supplemental material for free leads to a near economic balance at his point. Revenues from additional recovered copper should be included as well. The >1/2 inch SR sub-stream contains about 2 wt% total copper (see Table 3 and Table 5) mostly as insulated copper wire. Conservatively assuming that only one third of the copper content (in the residual fraction shown in Table 8) is recovered gives 0.2 t/hr or 400 t/yr. The value of recovered copper wiring is lower than the copper scrap price of about $2/lb. Assuming $0.85/lb scrap value yields $680,000/yr revenue. Obviously, by generating revenues equal to total costs, the recovery of copper alone could become the focus of a shredder residue processing system. The greatest uncertainties are for the capital cost estimates and the landfill savings. Table 9 shows that a doubling the capital investment would still give an ultimate benefit of $400,000 per year (or over $13 per ton recovered material). Higher landfilling costs lead to favorable economics.

It is useful to provide context for resource recovery savings potential for the US considering that the total generation of SR is over 3 million tons per year. Projecting the results of this study to the US would give about 1 million tons of shredder residue recovered for fuel. This amount would comprise about 6% of the US cement manufacturing industry's energy consumption (Choate 2003) and save $50 million annually (assuming $50/ton coal). The 1 million tons of avoided landfilling would amount to over $20 million savings annually. Further nonferrous metal recovery could yield revenues of over $20 million (based on 13,000 tons of copper alone). The costs to process the SR would be about $20 million annually. Considering the many conservative assumptions made for the economic analysis, the recovery of some portion of SR looks to be economically viable even if the shredder operator needs to pay transportation to far away kilns and pay a fee at the kiln.

CONCLUSIONS

The study showed that size separation alone is likely not enough to provide usable SR fractions; however, commonly available separation systems should produce an acceptable fuel supplement. Considering the large scale and the number of cement plants in the US, a significant amount of SR is recoverable. Information on the equipment needed and the costs to process SR fractions to meet kiln operator specifications is critical to the acceptance, adoption, and implementation of this resource recovery option. Kiln operators will embrace lower cost clean fuels, and shredder operators will favor avoiding the costs of landfilling while recovering more salable metals. An economic review of a full scale separation system shows that processing SR appears to be economically marginal considering avoided landfilling costs alone. However, significant economic benefits would result from additional non-ferrous metals recovery (principally copper). Remaining barriers to acceptance includes demonstration that a full-scale system will consistently produce high valued fuel with low concentrations of deleterious materials.

Recovery of a mineral rich fraction of SR was not completed. There is less economic incentive for mineral substitute compared to landfilling because of the transportation costs for dense materials like glass. For many shredders, it is possible that collection of a glass rich stream from dismantling yards located close to cement kilns could be cost effective. Some shredders may produce SR with significant glass content to be attractive.

Shredder residue was found to have substantial recoverable energy value. Following industrial ecology and sustainability themes, materials now considered wastes should be viewed as commodities. The environmental benefits of SR recovery as fuel in cement kilns look very favourable compared to other management options (Boughton 2005). Policy makers could use the results herein to support the recovery of SR as well as the facilities interested in using these materials. Financial and environmental benefits would be realized by providing incentives for SR recovery, and by supporting markets for SR derived products.

Barriers inhibiting viable recycling alternatives may need to be addressed. If PCB and other contaminant concerns cannot be overcome for use of SR, few if any other options exist other than landfilling. Residual PCBs present a barrier for any recovery alternative but actually promote landfilling over resource recovery, contrary to the principles of RCRA. The presence of mercury also lowers the value of SR derived fuel. Other contaminants may be of concern as well. Reducing the contamination of SR from components in the shredder feedstocks (e.g., PCB laden capacitors, lead wheel weights, and mercury switches) may be the most significant barrier to overcome. Full scale demonstration of separation and use is the next step. Some development of techniques to reduce the contaminant levels may be needed, followed by testing to show that no significant increases in emissions at kilns would occur.

REFERENCES

Ambrose (2000), Ambrose, C., Singh, M., Harder, M., *The material composition of shredder waste in the UK*, IWM Scientific & Technical Review, November, p 27-35

American Plastics 2005, www.americanplasticscouncil.org, accessed July 2005

Andrusyshyn (2005), Personal communications, Nick Andrusyshyn, Schnitzer Steel, www.schnitzersteel.com

ANL (2004), Argonne National Laboratory, accessed January 4, 2004, www.transportation.anl.gov/recycling/plastics.html
http://pe.es.anl.gov/What%27s%20New/FOAM.pdf,
http://pe.es.anl.gov/What's%20New/FROTH.pdf
http://www.techtransfer.anl.gov/techtour/autoshredder.html

APC (2005), American Plastics Council, www.americanplasticscouncil.org, accessed June 6, 2005

Automotive Engineering (1994), *Automotive shredder residue: three recovery choices*, Automotive Engineering 102(8), 29-31.

Bennett (2005), personal communication, John Bennett, Cal Portland Cement, www.calportland.com

BIR (2005), Bureau of International Recycling, *Shredding and Media Separation,* www.bir.org/aboutrecycling/EOLV/shred8.htm accessed December 2005

Boughton (2005), Boughton, B., Horvath, A., *Environmental assessment of shredder residue management,* Resources Conservation and Recycling, in press www.elsevier.com/locate/resconrec, accessed December 2005

Buchan (1995), Buchan, R., Yarar, B., *Recovering of plastics for recycling by mineral processing techniques,* J Met, 47 (2) 52-55

CAC (1998), Competitive Analysis Center Inc., *Automotive shredder residue; its application in steel mill blast furnaces*, Study for the American Plastics Council, www.americanplasticscouncil.org

CARE (2005), Consortium for Automotive Recycling, www.caregroup.org.uk, accessed December 2005

Cembureau (2004), European Cement Industry Association, *Environmental benefits of using alternative fuels in cement production; Alternative fuels in cement manufacture*, www.cembureau.be, accessed October 4, 2004

CIF (2003), Cement Industry Federation, *Cement industry environmental report*, www.cement.org.au/environment/case_studies/alternative_fuels_at_bcsc.pdf, accessed October 2003

CMP (1990), Center for Materials Production, *Automobile shredder residue – The problem and potential solutions*, CMP report #90-1

CWT (2004), Changing World Technologies, *Small scale processing of shredder residue using the thermal conversion process*, www.changingworldtech.com, accessed January 7, 2005

Das (1995), Das, S., Curlee, T. R., Rizy, C. G., Schexnayder, S. M., *Automobile recycling in the United States: energy impacts and waste generation,* Resources, Conservation and Recycling 14, 265-284

Day (1993a), Day, M., *Auto shredder residues- A waste or a valuable resource?*, SAE 930562, p73

Day (1993b), Day, M., *Characterization of auto shredder residue*, Resources, Conservation and Recycling, 9, p255-279

Day (1999), Day, M., et al, *Pyrolysis of auto shredder residues*, J Anal Appl Pyrol 51(1-2), p181-200

De Jong (1997), de Jong, T., Dalmijn, W., *Improving jigging results on non-ferrous car scrap by application of an intermediate layer*, Int J Miner Process 49, p 59-72

Denis (2000), Denis, S., et al., *Experimental Evaluation of Emission Factors of Cement Kilns Burning Hazardous Wastes,* Toxicological and Environmental Chemistry, 74, p155-163

DTSC (2002), *California's Automobile Shredder Waste Initiative*, accessed January, 2006, www.dtsc.ca.gov/HazardousWaste/upload/HWMP_REP_ASW_draft.pdf

Dyckerhoff (2005), Dyckerhoff Company- Environmental Protection- Secondary Fuels www.dyckerhoff.com/_english/_firma/firma04.htm accessed December 2005

Choate (2003), Choate, W., *Energy and Emission Reduction Opportunities for the Cement Industry*, USDOE, www.eere.energy.gov/industry/imf/pdfs/eeroci_dec03a.pdf

Environment Australia (2002), *Environmental impact of end-of-life vehicles: An Information paper*, www.deh.gov.au/industry/waste/elv/chapter11.html, accessed April 10, 2004.

European Commission (2005), *Management of end-of-life vehicles,* http://europa.eu.int/scadplus/leg/en/lvb/l21225.htm and *End-of-life vehicles*, http://europa.eu.int/comm/environment/waste/elv_index.htm, accessed June 14, 2005

Federal Register (2005), Vol 70, No 231, page 72333, National Emission Standards for Hazardous Air Pollutants from the Portland Cement Manufacturing industry, http://www.gpoaccess.gov/fr/retrieve.html, accessed March 2006

Fisher (1999), Fisher, M., *The role of plastics in automotive shredder residue*, SAE Technical Study Series 1999-01-0664, Society of Automotive Engineers: Detroit, MI

Forton (2005), Forton, O., Harder, M., Moles, N., *Value from shredder waste: Ongoing limitations in the UK*, Resources Conservation and Recycling, Vol 46, #1, in press doi:10.1016/j.resconrec.2005.06.007www.elsevier.com/locate/resconrec, accessed December 2005

Fraunholcz (2000), Fraunholcz, N., et al, *A novel approach to the mechanical processing of ASR* in Proceedings of the 4th international symposium on recycling of metals and engineering materials, The Minerals, Metals & Materials Society, p1303-1314

Gallmeyer (2003), Gallmeyer, W., et al, *USCAR U.S. Field Trial for Automotive Polymers Recycling*, SAE 2003-01-0645

Galloo 2005, www.galloo.com/html/engels/groupgalloo_en.htm, accessed December 2005

Gabel (2005), Gabel, K., Tillman, A., Simulating operational alternatives for future cement production, Journal of Cleaner Production, 13 (13-14) p1246-1257

Hawkins (2005), Hawkins, G., Personal contact April 2005, Portland Cement Association, www.cement.org

Herat (1996), Herat, S., *Energy recovery from solid and hazardous wastes using cement kilns*, Journal of Waste Management and Resource Recovery, v. 3(3) p 111-115.

Holcim (2005), Holcim Ltd, Alternative fuels and raw materials, www.holcim.com/CORP/EN/oid/46240/module/gnm50/jsp/templates/editorial/editorial.html accessed June 2005

ISRI (2004), Institute of Scrap Recycling Industries, *End-of-life vehicles: A proven path to recycling,* www.isri.org/industryinfo/Elv.pdf, accessed March 3, 2004

Jody (2994), Jody, B., et al, *Recovering recyclable materials from shredder residue*, J Met 46 (2) p 40-43

Keller, C., "Optimized disposal of automotive shredder residue" in Municipal Solid Waste Management- Strategies and Technologies for Sustainable Solutions, Ludwig, C., Hellweg, s., Stucki, S. (eds), Springer-Verlag, Heidelberg, Germany 2003, p 294-307

Kusaka (2000), Kusaka, K., Iida, S., *Sorting, compaction and solidification technologies for automobile shredder residue*, JSAE Review 21 (2000) 549-554

Lanoir (1997), Lanoir, D., *Physical and chemical characterization of automotive shredder residues*, Waste Management & Research, 15, 267-276

Mark (1999), Mark, F., *Environmentally sound energy recovery from automotive shredder residue*, SAE Technical Study Series, 1999-01-0990, Society of Automotive Engineers: Detroit, MI.

Mayes (2005), Mayes, G., Personal contact May 2005, TXI, www.txi.com

MBA (2005), MBA Polymers, www.mbapolymers.com/whatwedo.htm, accessed December 15, 2005

Meinen (2005), personal contact M. Meinen, April 2005, Lehigh Cement, www.Lehighcement.com

Neu (2005), Personal contact, Jeffrey Neu, Sims- Hugo Neu, www.HNP.com

Nissan (2004), *Eight carmakers form new alliance for shredder residue recycling*, www.nissan-global.com/EN/NEWS/2004/_STORY/040109-01.html accessed March 3, 2004

PCA (2004), Portland Cement Association, *Manufacturing fact sheet*, www.cement.org/concretethinking/manu_facts.asp, accessed January 5, 2005

PCA (2005), Portland Cement Association, *Behaviour and Measurement of Mercury in Cement Kilns,* www.cement.org/manufacture/mtc_milldb_detail.asp?id=941, accessed December 2005

Perry (1997), Perry, R., Green, D, *Perry's Chemical Engineers Handbook*, seventh edition, McGraw Hill

Prisciandaro (2003), M. Prisciandaro, G. Mazziotti and F. Veglió, *Effect of burning supplementary waste fuels on the pollutant emissions by cement plants* Resources, Conservation and Recycling Volume 39, (2) , p161-184

Protec (2005), *Heavy media separation plants,* www.protec-srl.com/PDF/2029%20e.pdf and www.protec-srl.com/ING/FRAMES/homeING.html accessed December 2005

Plastics (2005), *Plastics in End-of-Life Vehicles*, www.plastics-in-elv.org, accessed January 7, 2005

Recycling Today (2005), *Recycling Opportunities in Auto Shredder Residue* and *Newer and Better*, www.recyclingtoday.com accessed October 2005

Redin (2001), Redin, L., et al, *Co-combustion of shredder residues and municipal solid waste in a Swedish municipal solid waste incinerator*, Waste Manage Res 19, p518-525

RRF (1992), Recycling Research Foundation, *Shredder residue: Environmental information and characterization under RCRA*, Washington, DC

SALYP (2004), www.salypnet.com and www.salypnet.com/environmentalimpact.htm, accessed October 5, 2004

Saxena (1995), Saxena, S, Rao, N, Rehmat, A, Mensinger, M, Combustion and Co-combustion of Auto Fluff, Energy 20 (9), p 877-887

Scheirs (1998), Scheirs, J., Polymer recycling: science, technology and applications. Chichester, UK, John Wiley & Sons

Schut (2001), Schut, J., *Commingled plastic waste: new gold mine for automotive processors*, Plastics Technology, accessed February 2006, www.plasticstechnology.com/articles/article_print1.cfm#

Schut (2004), Schut, J., *Close-Up On Recycling: How to Turn Auto Shredder Waste Into 60 Million Lb of Plastic Pellets* - www.plasticstechnology.com/articles/200410cu3.html accessed December 2005

Seyler (2005), Seyler, C., et al, *Life cycle inventory for use of waste solvent as fuel substitute in the cement industry,* Int. J. LCA, 10(2) 120-130.

Shen (2002), Shen, H., et al, *Selective flotation of plastics by chemical conditioning with methyl cellulose*, Resource Conservation and Recycling 35(4) p229-241

Shumway (2005), Personal communications, Douglas Shumway, Mitsubishi Cement

Singh (2001) Singh, M., et al, *Proving the principle- recovery of plastics form shredder ELV's,* Institute of Mechanical Engineers 6th international conference on engineering for profit from waste, p181-189

Staudinger (2001), Staudinger, J., Keoleian, G. A., *Management of end-of-life vehicles (ELVs) in the U.S.*, Center for Sustainable Systems, University of Michigan, Report # CSS01-01.

Sullivan (1998), Sullivan, J. L., et al., *Life Cycle Inventory of a Generic U.S. Family – Sedan Overview of Results USCAR AMP Project*, SAE Paper #982160, Society of Automotive Engineers: Detroit, MI

Taiheiyo Cement (2004), *Environmental report 2004*, www.taiheiyo-cement.co.jp/english/envrpt2004/pdf/allenv2004.pdf accessed December 2005

Tokiwa (2005), Personal Communications, Yoshiro Tokiwa, Toxics Program Officer, EPA Region IX Toxics Office

Toyota (2005), *Toyota and Volkswagen cooperate in recycling and other areas*, www.toyota.com/about/environment/partnerships/volkswagon_cooperate.html, accessed January 7, 2005

Trouve (1998) Trouve, G., et al, *Comparative thermodynamic and experimental study of some heavy metal behavior during automotive shredder residues incineration*, Waste Management 8(5), p301-307

TXI (2005), *Company Profile*, www.txi.com/company_overview/environment.html and *Waste Management Methods* www.facilityreview.com/Site%20Profiles%20m-z/TXI.htm accessed December 15, 2005.

USCAR (2002), United States Council for Automotive Research, *USCAR celebrates a decade of automotive progress*, www.uscar.org/Media/2002issue1/p1_celebrates.htm, accessed January 7, 2005

USCAR (2000), *U.S. Field Trial for automobile polymers recycling: Interim findings*, Study 2000-01-0735, Society of Automotive Engineers: Detroit, MI

USDOE (1987), U.S. Department of Energy, *Power generation from automobile shredder waste fuel*, Report DE-Pro7-871012704

USEPA (1991), US Environmental Protection Agency , *PCB, Lead, Cadmium levels in shredder waste materials*, Report EPA 560/5-90-008A

USEPA (1995), US environmental Protection Agency, *Air pollution emission factors – Portland cement manufacturing* www.epa.gov/ttn/chief/ap42/ch11/final/c11s06.pdf, accessed January 5, 2004

USEPA (2004), US Environmental Protection Agency, *Hazardous waste combustors – Maximum achievable control technology standards*, accessed January 4, 2004, www.epa.gov/epaoswer/hazwaste/combust/

USEPA (2003), US Environmental Protection Agency, *Beyond RCRA- Waste and material management in the year 2020*, EPA530-R-02-009

USEPA (2004c), US Environmental Protection Agency, *Municipal solid waste, Automotive parts*, www.epa.gov/garbage/auto.htm, accessed March 3, 2004

van Oss (2002), van Oss, H., *Cement manufacture and the environment, Part I: Chemistry and technology*, Journal of Industrial Ecology, 6(1)

van Oss (2003), van Oss, H., *Cement manufacture and the environment, Part II: Environmental challenges and opportunities*, Journal of Industrial Ecology, 7(1)

Wastec 2005, NSWMA's 2005 Tip Fee Survey, accessed February 2006, http://wastec.isproductions.net/webmodules/webarticles/articlefiles/478-Tipping%20Fee%20Bulletin%202005.pdf

WBCSD (2005), World Business Council for Sustainable Development, *Cement sustainability initiative*, www.wbcsdcement.org, and Fuels and Raw Materials report http://www.wbcsdcement.org/pdf/tf2/tf2_guidelines.pdf accessed January 4, 2006

WERG (2002), Waste and Energy Research Group, *Towards processing polymers from ASR*, www.bton.ac.uk/environment/research/sustainability/werg/reports.htm, accessed December 2005

Winslow (1998), Winslow, G., et al, *Study of Plastic Material Recovery form Automotive Shredder Residue,* SAE 980093

Winslow (1999), Winslow, G., et al, *Recovery of Selected Engineering Plastics from Automotive Shredder Residue Using Skin Flotation Technology*, SAE 1999-01-0663

Winslow (2004), Winslow, G., et al, *Advanced Separation of Plastics from Shredder residue*, SAE 2004-01-0469

Zevenhoven (2003), Zevenhoven R., Saeed, L., *Automotive shredder residue (ASR) and compact disk (CD) waste: options for recovery of materials and energy*, Report TKK-ENY-14, Helsinki University of Technology, Energy Engineering and Environmental Protection: Finland, http://eny.hut.fi/library/publications/tkk-eny/tkk-eny-14.pdf, accessed January 7, 2005