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Shredder Practice for Preparation of Nonmetallic Concentrates and Potential for Particle Sorting of these Concentrates

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1 Introduction

EU directives for end-of-life vehicles (ELVs) require recycling or “recovery” of non-metallic materials from the ELV. ELVs are collected, de-polluted and stripped of reusable parts at licensed de-pollution facilities (i.e. junkyards). The remaining hulk is flattened for transport to a shredder where, in a matter of seconds, it is reduced to fist-sized pieces. Next, steel is removed by magnets and nonmetals are separated by eddy-current rotor separators. The resulting nonmagnetic metal concentrate enables profitable shipment of that concentrate from the shredder to the metal sorter, and thus the recovery of nonmagnetic metals from the residue.

Preparation of concentrates of plastic-rubber and of precursors for residue-derived fuel (RDF) will be necessary to enable profitable shipment of these concentrates to plastic and rubber recyclers and to producers of RDF for waste-to-energy incinerators, cement kilns and metal smelters that use RDF as fuel or reducing agents. The Basel Convention bans trans-boundary shipment of wastes, but by concentrating the recyclables in the concentrate, waste can be converted to an article of commerce that is allowed to travel across boundaries and between continents. Shredded-scrap-derived Al, dense metal mix, mixed metal grain, and nonmagnetic metal concentrate (NMMC) are now routinely sold in US and Europe for export to Asia. Since industrial plastic scrap is already sold for export, there is no reason for the Basel Convention to ban transport of shredder-scrap-sourced plastic and rubber concentrates for recycling. The Convention requires local disposal of the non-recyclable residue fraction.

This paper discusses the preferred composition and size specifications for these concentrates, and preferred practices and technologies for their production. It then explores the potential for further upgrading of these concentrates by downstream recyclers by sensor-



based particle sorting to either recycle plastics or prepare intermediate fractions for further size reduction, wet cleaning and wet sorting.

The sorting of metal, plastic, rubber and RDF and how it can be accomplished using already industrially applied sensors and data processing techniques is discussed. The paper concludes with a discussion of the remaining shredder residue (SR), which is dominated by fines, and what can be done to extract the substances of concern (SOCs) and residual metals and organics.

2 Structure of the current material recycling industry and the need for production of nonmetallic concentrates

Steel scrap, together with scrap that contains other materials attached to the steel, is sent to steel shredding plants by scrap collectors (e.g. repair shops, dismantlers, de-polluters, solid waste transfer stations, scrap yards, municipal recycling facilities and demolition contractors). This scrap includes not only ELVs, but also material from other consumer durables and demolition. The scrap arrives at the shredding plant flattened or baled, with no possibility for further dismantling. The main product of the shredding plant is a consistent quality steel shred. To achieve this consistency, it is a common practice to blend scrap from various sources in the input to the shredder. Nonferrous metal and nonmetallic recyclables are a small fraction of the steel product volume. Primary steel shredders rarely segregate the feed in order to improve the recovery of non-steel feed components.

The composition of shredding plant products is defined by its feed, which is a complex mixture of materials from various sources. These sources are rarely limited to a single manufacturer or industry, or even a consumer market segment. Materials that are dismantled and/or hand sorted upstream usually bypass the primary steel shredders and can be sold directly to secondary processors, smelters, or scrap sorters, where they may be processed separately in a secondary shredder (i.e. a smaller hammer mill or slow-speed shear shredders).

Plastic bottle sorters and glass cullet colour sorters represent successful industrial applications of particle sorting to these pre-sorted scrap streams. Up until nonferrous scrap started being exported to Asia for hand sorting on a large scale, particle sorters were being successfully used on an industrial scale for sorting of nonmagnetic metal scrap (Al, Cu, brass, Zn, stainless steel and lead), using colour, shape and eddy-current coil (ECC) sensors. The use of ECC sensors is expanding industrially for the recovery of stainless steel from SR. Laser-induced breakdown spectroscopy (LIBS) sorters are currently industrially used to batch aluminium alloys. In this discussion, however, we will focus on the still-unsolved question of the recovery of nonmetallic recyclables from primary steel shredder residue and how particle sorters could be used.

2.1 Steel shredding plant processes

Shredding plants can run a dry, moist or wet process.



Dry shredding

In a dry process, the scrap is fed to the shredder without the addition of any water. An extensive dust collection system controls air emissions. This system sucks fluff from the shredder, the shred discharge and from all the transfer points in the conveyor system.

The material separated by and from the suction air stream is processed by sizing and magnetic and eddy-current separation (ECS) to recover more metal from an organic concentrate containing foam, textiles, plastic film and paper. This concentrate is usually referred to as the shredder light fraction (SLF).

The material left over after magnetic-drum separation of steel, is treated by sizing and ECS to split the residue into fines, nonmagnetic metal concentrate and a nonmetallic shredder dense fraction (SDF). ECS separation can be done on two size fractions ($>5<30$ and $>30<100$ mm) to improve metal-nonmetal separation.

Currently the SLF, SDF and the fines are usually combined for shipment to a landfill, where the operator uses this material as an alternative daily landfill cover (ADLC) – a regulation-prescribed daily cap on top of municipal solid waste to deter disease-spreading scavengers such as rats, raccoons and gulls.

As shown in Figure 1, the SDF could alternatively be separated by a combination of ballistic separators, a high-intensity magnetic separator, and an eddy-current sensor-based particle sorter to yield, separately, dense organic concentrate, inorganic rock-brick-glass, and stainless steel products.

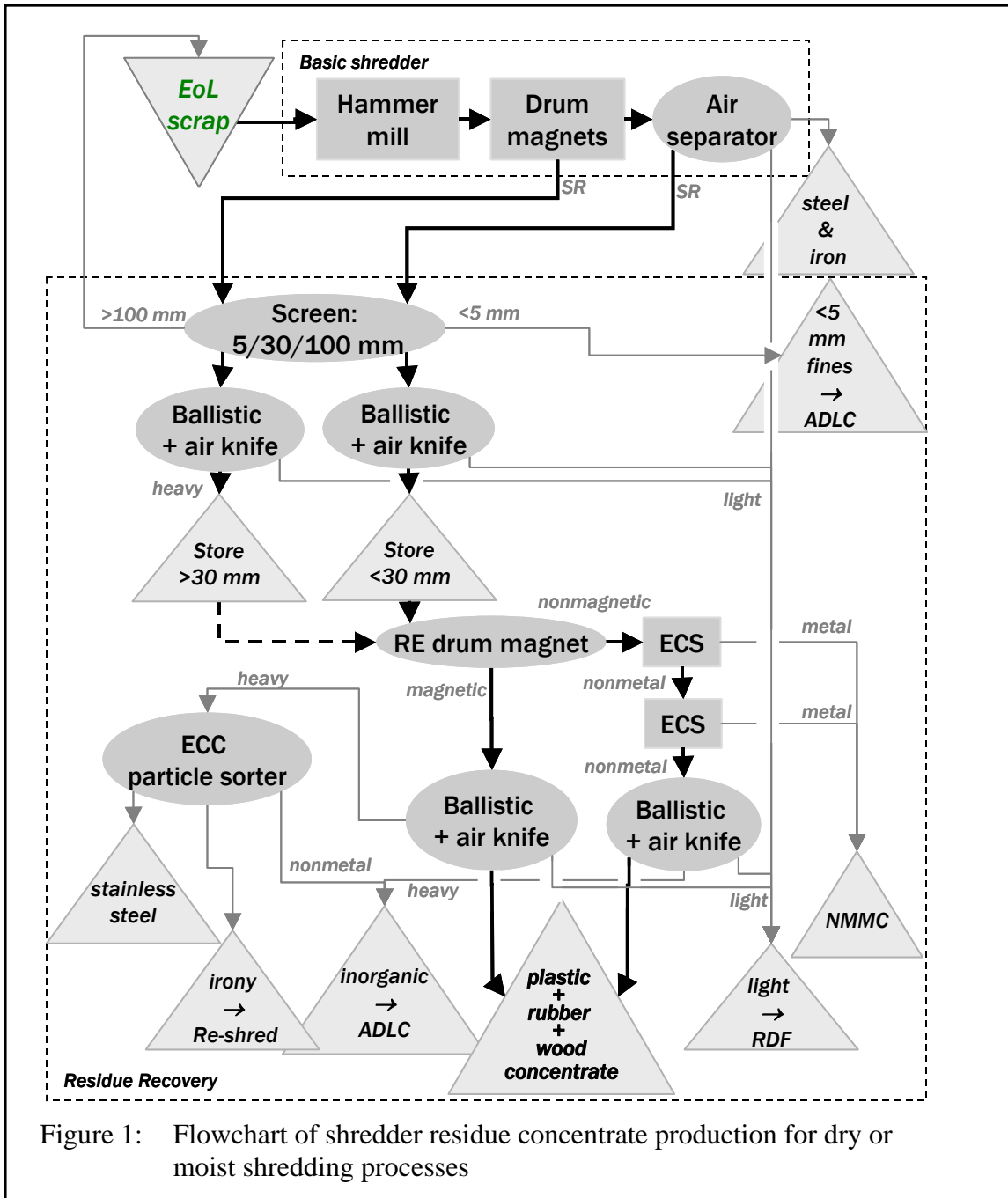
Moist shredding

In a moist process, a small amount of water is sprayed into the shredder to eliminate airborne dust emissions from the shredder and from the product transfer points without the need for other dust-control measures. The shred goes directly to drum-magnet separators that take out the iron. The iron shred is separated from the lower-density magnetic contaminants in a Z-box air elutriator. The air stream transports the light fraction to a cyclone separator.

NMMC is produced from the nonmagnetic output of the drum magnets and from the cyclone solids by screening and magnetic and eddy-current separations. ECS performance improves if done separately for large ($>30<100$ mm) and small ($>5<30$ mm) particle sizes. The >100 mm oversize is fed back to the primary shredder. Screened-out fines and ECS nonmetal products are then combined as the SR.

This moist process can be extended to additionally produce fines plus separate $>5<30$ and $>30<100$ mm size fractions of light and dense organic (textile, foam, paper, wood, plastic and rubber) concentrates, inorganic rock-brick-glass, and stainless steel products by a combination of ballistic separators and a high-intensity magnetic separator and an eddy-current sensor-based particle sorter.

The hundreds of the steel shredding plant operators throughout the world practice many variations on these basic dry and moist processes.



Wet shredding

An interesting alternative of combining shredding and wet dense-media separation in the shredding plant has been proposed. Three leading scrap recycling companies have both the shredding and the appropriate sink-float drum technology industrially implemented: CFF and Galloo in Europe and Carpenter Steel in the US. None of these companies has published their shredding plant process information, but ESR Int. (the sink-float drum manufacturer) patents suggest the following, as shown in Figure 2.



The thoroughly wet shredding, screening and sizing operations keep the dust in check, and can replace maintenance-intensive eddy-current separators with sink-float dense-media drums. The air-solid separation and dust control-system is replaced with a closed-circuit process water treatment system, and a filter press dewateres the fines. Separation up to a particle density of 1.6 g/cm^3 can be made with a fine silica sand slurry. This sand comes from the feed stream contamination. The $>1.6 \text{ g/cm}^3$ density fraction consists of rock and nonmagnetic metals, while the $<1.6 \text{ g/cm}^3$ density fraction concentrates all organics. Rust ends up with the fines in the water treatment system, and could be separated cleanly with a wet magnet used industrially for iron ore concentration.

The organic concentrates from the dry, moist or wet processes would then be transported to downstream processors for further separation of recyclables and the residue.

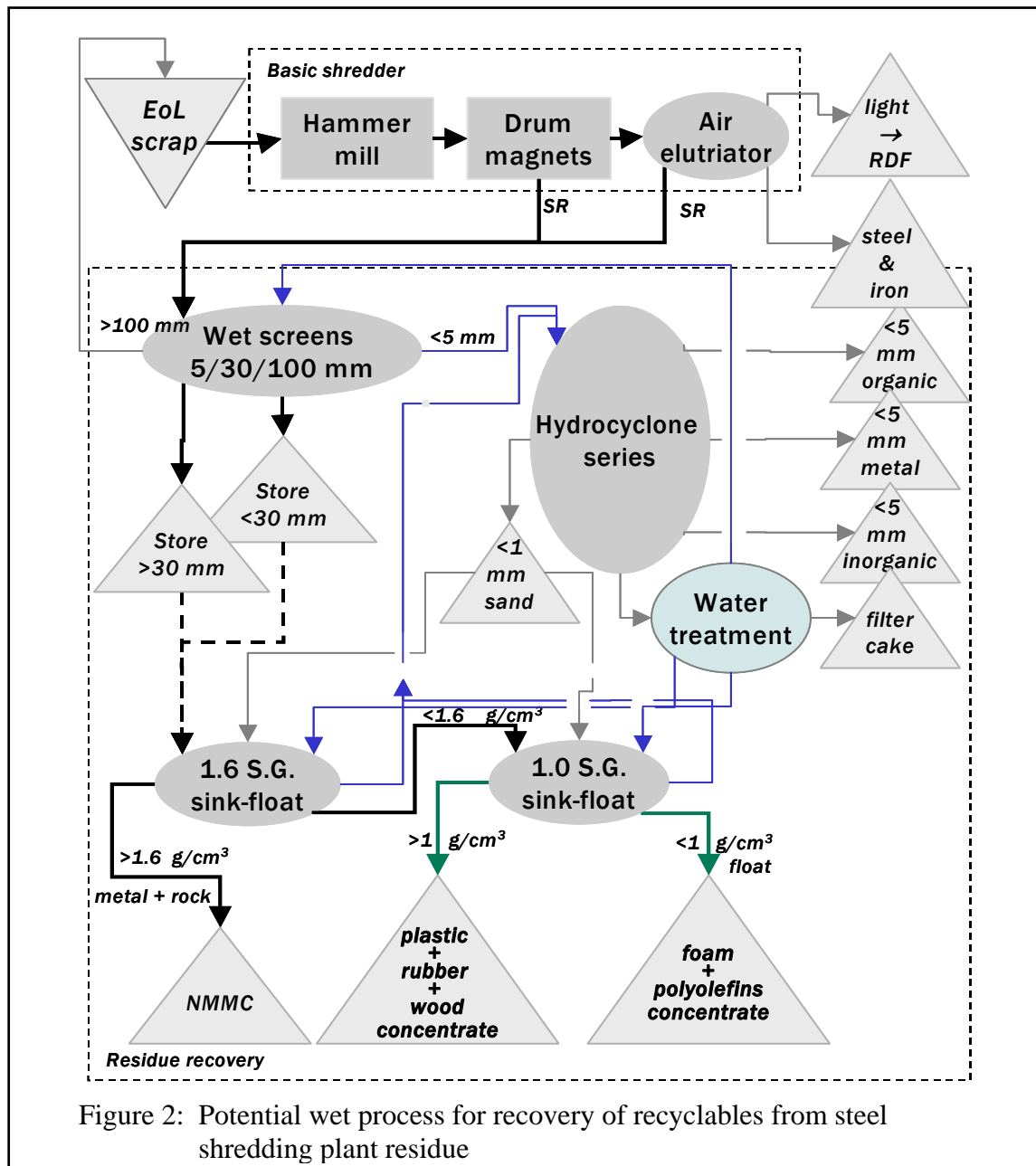


Figure 2: Potential wet process for recovery of recyclables from steel shredding plant residue



3 Steel shredding plant concentrate products

The objective in NMMC preparation is to maximize metals recovery. This is usually accomplished by accepting a considerable amount of dense organics and inorganics in the concentrate. Typically these concentrates average ~50% metal content. The NMMC is processed by sink-float separation in dense-media plants to separate organics and inorganics as separate fractions. From a global recycling system point of view, the metal content of this concentrate is less important than a high metal recovery in the NMMC. This keeps the metals out of the residue that is bound for landfill. It is also important to keep recyclable organics out of the landfill. This means maximizing organic recovery in the sum of all the intermediate product concentrates bound for downstream processing.

Depending on the next separation step in the downstream process, there can be widely differing particle size requirements. Moreover, there can be a considerable composition difference at different particle sizes. Primary shredder fines are mainly sand, glass, soil and rust. The small fraction is rich in brittle components, casting alloys, rock, and brittle plastics; the large fraction is rich in malleable wrought sheet and extrusion alloys, plus elastomeric foams, rubbers and textiles. These composition differences in the separations can be exploited to improve both recyclable component recovery and content in the shredding plant concentrates. This also helps in downstream sorting of NMMC and organic concentrates if the size fractions of the concentrates are shipped separately.

Once one accepts the capital cost of a closed-circuit process water treatment system, which can be justified for large-scale steel shredding plants, the wet process has several definite advantages. Wet material handling, and its elimination of airborne dust, improves the plant environment. Wet sizing and screening circuits have a high efficiency that is independent of the feed moisture content. Material can be effectively pre-cleaned by washing in process water.

Wet density separation is the only option that allows separation of recyclables (metals and organics and toxic basic lead sulphate) from the fines by hydrodynamic particle sorting in hydrocyclones or centrifuges. This helps make the residue fines inert and non-toxic. Table 1 summarizes the various possible combinations of shredding plant products for the three basic plant process options.

4 Suggested nonmetal concentrate specifications

The shredder concentrate and residue product specifications, which are listed in Table 2, are formulated to achieve the shredding plant process objectives, by specifying the impurity contents of these plant outputs.

4.1 Shredding plant process model

Process objectives for a shredding plant are:

1. Provide consistent quality recycled material products satisfying the minimum product purity specifications
2. Provide maximum recovery of the recyclable components in the sum of all the intermediate concentrates bound for further material recovery
3. Minimize the loss of recyclable components in the residues destined for landfill



Table 1: Shredding plant products after dry, moist and wet shredding

Process Option:	Dry shredding	Moist Shredding	Wet process
Output stream			
Steel <100 mm	Product	Product	Product
Stainless steel >5<100 mm	Product	Product	Product
Fines < 5 mm	Residue	Residue	Residue
Baghouse dust	Residue	Residue	
Iron oxide < 5 mm			Product
Filter cake < 1 mm			Residue
NMMC >5<30 mm	Concentrate	Concentrate	Concentrate
NMMC >30<100 mm	Concentrate	Concentrate	Concentrate
Inorganic >5<100 mm	Residue	Residue	Residue
Polyurethane (PUR) foam	Product	Product	Product
SLF >5<100 mm	RDF		
SDF organic >5<30 mm	Concentrate		
SDF organic >30<100 mm	Concentrate		
Organic < 5 mm			RDF
Organic < 100 mm			Concentrate
Organic >5<30 mm		Concentrate	
Organic >30<100 mm		Concentrate	
Magnetic attachments	Concentrate	Concentrate	Concentrate

4. Minimize the recovery of the non-recyclable components in either products or intermediate concentrates
5. Maximize the recovery of the recyclable component in its own concentrate: metal in metal concentrate and plastic + rubber in the organic concentrate

In this context “recovery” is a process engineering term used to mean the fraction of the weight of a given component of the feed stream mixture that ends up in the output stream of interest.

Process modelling of a shredding plant operation, using industrially achievable unit operation component recovery estimates, suggests that for a dry process shredding plant being fed a mixture of 50% ELVs, 30% construction and demolition waste and 20% consumer durables, one can expect the output product distribution to be:

- 66% metal (steel and NMMC)
With the process tuned to a high metal recovery, one can get ~99% recovery of iron and steel, and ~93% recovery of nonmagnetic metals in the NMMC. To achieve that, one needs to also accept contamination of the NMMC with other components at the following recoveries: plastics and rubber (15%), tires (18%), rock (20%) and glass (10%).
- 17% residue
Shredder residue can recover 78% of the inorganics and can account for losses of 10% of the organics and 1.5% of the metals. Downstream processing at the dense-media plants provides a chance to recover an additional 0.3% of shredder metal



Table 2: Suggested shredding plant intermediate concentrate and residue impurity specifications

Process Option	Dry shredding	Moist Shredding	Wet process	Destination
NMMC >5<30 mm		> 50% metal <10% inorganic <10% <5 mm		Metal dense-media plant
NMMC >30<100 mm		> 50% metal < 10% inorganic <10% <30 mm		Metal dense-media plant
Inorganic >5<100 mm		<5% organic < 5% metal <10% <5 mm		ADLC
SLF organic >5<100 mm	<5% inorganic <5% metal <10% <5 mm			RDF preparation PUR recycle
SDF organic >5<30 mm	<5% inorganic <10% metal <10% <5 mm			Plastic dense-media plant
SDF organic >30<100 mm	<5% inorganic <10% metal <10% <30 mm			Plastic particle sort
Inorganic fines < 5 mm	<5% organic <5% metal	< 3% organic <3% metal	ADLC	
Metal fines< 5 mm			>50% metal	Metal jig sort
Organic fines < 5 mm			<10% inorganic <5% metal	Plastic dense-media plant
Organic < 100 mm			<10% inorganic <5% metal	Plastic particle sort
Organic >5<30 mm		<10% inorganic <5% metal <10% <5 mm		Plastic dense-media plant
Organic >30<100 mm		<10% inorganic <5% metal <10% <30 mm		Plastic particle sort
Magnetic attachments		<10% nonmagnetic		Metal dense-media plant
Organic = plastic, rubber, wood, paper, textile, foam, plastic foil SLF organic = paper, textile, foam, plastic foil SDF organic = plastic, rubber, wood				

input from the organic fractions and 14% of shredder organic input from NMMC, and adds 10% of the shredder inorganic input to the ADLC.

- 13% dense organics (SDF)
In the SDF, one can recover ~70% of the plastics and rubber including tires, and ~50% of the wood. Important SDF contaminants include inorganics (~10% recovery) and attached metals and wire (~2% recovery of nonmagnetic metals).
- 4% light organics (SLF)
In the SLF, one can recover ~90% of the PUR foam and textiles and ~15% of the wood from the shredder feed – but this concentrate is likely to be contaminated with soil, rust and insulated wire.



5 Sensor-based particle sorting

The most successful industrial particle sorters distribute and separate a moving stream of particles randomly in a plane. They use either a scanning or line array sensor or sensors to identify and locate individual particles. A linear array of blowholes, known as a blowbar, is then used to divert the selected particles in freefall from their ballistic trajectory. Up to three blowbars have been industrially implemented on one sorter, enabling four output streams. As underlined by presentations at this conference, sensor-based sorting is an exciting, rapidly developing field driven by exponential growth in the computing power of process controllers and of sensor capabilities. Industrially implemented non-contact sensors of interest to SR particle sorting can identify and sometimes image:

1. Light spectral line intensity over the hyperspectral range of ultraviolet (UV: 150-400 nm) through visible (VIS: 400-900 nm) into the near infrared (NIR: 900 nm - 5 μ m) and infrared (IR: 5-15 μ m)
2. X-ray absorption in two selected energy bands
3. Disruption of the varying magnetic field amplitude and phase by the passage of the particle

From this basic information, the controlling computer can infer colour, shape, size, average atomic number, thickness, metal/nonmetal, metal type, absorption/remission IR or NIR (near infrared) spectra correlated with polymer type, and finally, UV-VIS emission line intensity, which is correlated to the concentration of a particular element. Particle sorters can certainly have the performance required for sorting scrap, and are already industrially applied to sorting:

1. Glass by colour and transparency
2. Plastic bottles by polymer resin type
3. Stainless steel by the ECC magnetic field signature
4. Nonmagnetic metals by colour size and shape
5. Al alloys by elemental concentration

Particle sorters have some inherent limitations; the most basic one is throughput-particle size correlation. Since the sort is done particle by particle for a given sensor-blowbar combination, there is a limit to the rate at which individual particles can be either identified or diverted. Hence, the weight/time measure of throughput scales as a cube of the particle size for equiaxed particles and as a square of the size for flat ones. Throughput for a given particle size can be increased first by increasing the belt loading and then the belt width until the limiting blowbar and sensor number rates are equal. Further increase in the throughput is done by cloning the sorters and placing them in parallel, which gives no further economies of scale because the capital and operating costs then tend to scale proportionally to the number of sorters in the plant.

Blowbar technology contributes additional basic limitations on the achievable precision of a diversion. There is a practical minimum cycle time required to open and close a high-pressure valve to deliver the air pulse. Typical times for industrial blowbars range between 10 and 20 ms. For particles travelling at 3 mm/ms, that corresponds to a distance of 30-60 mm – the minimum gap required between particles in the direction of belt motion so the air pulse does not affect the neighbouring particles. There is also a statistical con-



sideration which states that for particles placed randomly on a surface, the probability of having two or more particles in contact increases very quickly above 15% surface loading for disks and even at lower loadings for high-aspect-ratio and non-convex particle shapes. While increasing particle velocity can increase particle spacing, this velocity is limited by particle aerodynamics that cause particles to either move on the belt or deviate from the ballistic trajectory once in freefall. A typical industrial bottle sorter belt speed of 3 m/s is near the upper limit for plastic particles with a flattened bottle aspect ratio.

Random particle shape, their random distribution on a belt, particle aerodynamics plus probe beam and sensor “noise” all contribute to random error in either particle identification or particle diversion. Adding to the random noise is systematic error in particle identification due to insufficient sensor signal content or computation time to solve the inverse particle identification problem (see below). Given the combination of these random and systematic errors, an industrial particle sorter at commercial throughput can never give a perfect sort. Sort quality is defined by a combination of product composition and component recovery achieved at a commercial throughput. Reduction of both systematic and random sort errors can improve the sort quality.

Systematic errors can be minimized by process development, for example:

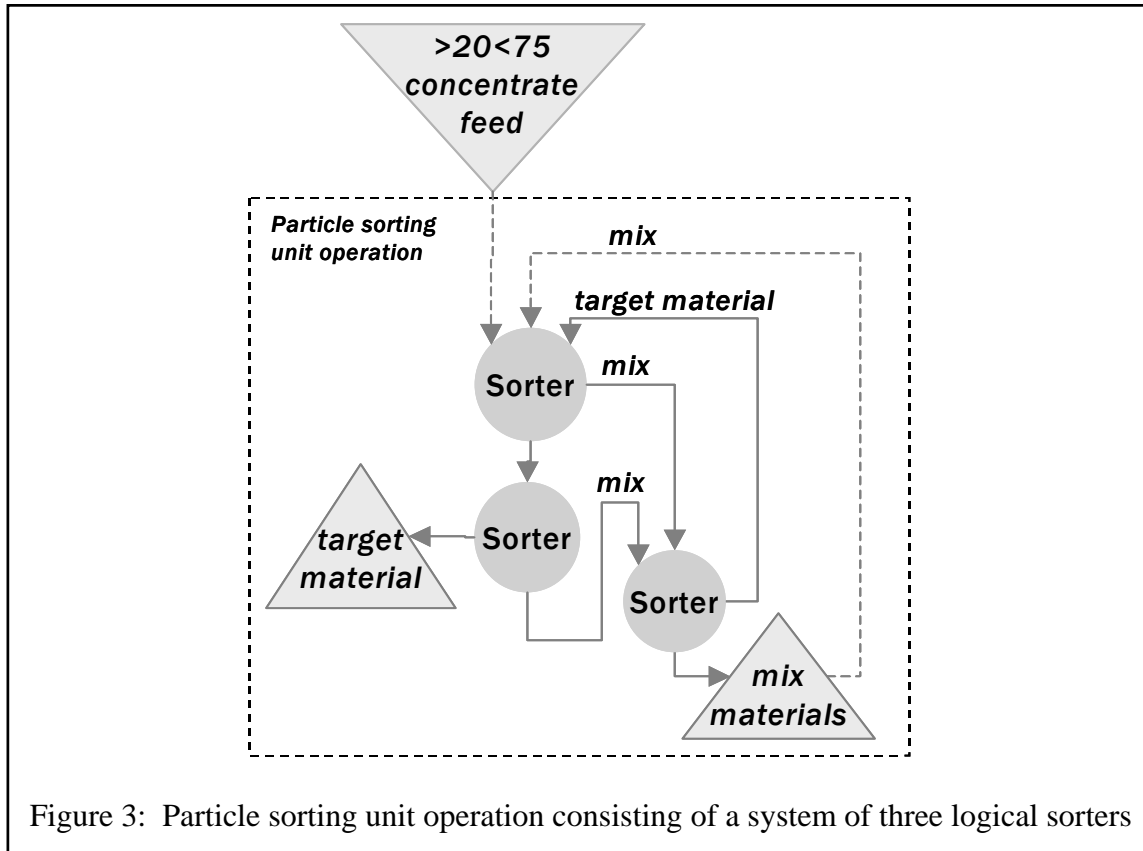
1. Selection and tuning of appropriate combination of sensors
2. Sensor, blowbar and sorter alignment
3. Calibration and training of the sort algorithm on a sample representative of feed components

Random errors can be addressed by:

1. Narrowly sizing and pre-sorting the particles by shape
2. Limiting the particle velocity
3. Limiting the belt area loading with particles, and
4. Passing the material through the sorter more than once
5. Passing the material through a system of more than one the sorter

A typical system of three logical sorters, each with one blowbar, that could overcome random errors is illustrated in Figure 3. Assuming that the target component does not make up the majority of the feed, the first of the sorters would identify the target component particles and divert them out of the non-diverted “other” mix. The diverted particles would be fed to a second sorter, with the target component now as a majority of the feed stream. The second sorter would again identify the target component, but this time divert any “other” particles at a sorter setting that would deliver the required product purity. The “other” particles from a first and second sorter would be combined to be fed to a third logical sorter to identify and divert the target component at a sorter setting that would maximize target component recovery. Depending on the composition of the target component product from the third sorter, this product could be blended with the target component product of the second sorter, or fed back with the system feed stream into the first sorter. With such a system, it is possible to deliver higher product purity and higher component recovery than in a single pass though a single sorter.

Each of the three logical sorters in such a system can correspond to an individual physical machine. In this case improved sorter system performance is paid for with added capital and power. Alternatively, output streams of the sorter can pass, one by one, through the



same physical machine with modified settings to achieve a similar improvement. This time improvements in quality and recovery come at a cost of reduced system throughput.

Some new particle sorters now come equipped with two and sometimes even three blowbars. This enables simultaneous sorting of a number of target components equal to the number of blowbars, plus a mix fraction. This requires more sophisticated non-binary sort algorithms that can identify more than one target volume in the multidimensional sensor parameter space and decide what to do with the overlap portions of the target volumes. Such a system allows much more efficient use of the available sensor information, reduces the required number of sorters and potentially leads to significant simplification in the sorter plant circuit with significant capital and operating cost savings. However, random diversion errors typically increase with multiple blowbars, making the sorter system approach to counteracting these random errors described above even more important for multiple-blowbar sorter systems.

5.1 Sorting as an inverse problem

Sorting is basically an inverse problem. It is trivial to sort between a limited number of known materials; it is a much more difficult problem to sort within a large number of materials of unknown composition. Sensor signal attributes (amplitude, phase, time or wavelength distribution) are correlated with some property of the material, which in turn is determined by the material composition, microstructure and macrostructure. This composition-property mapping is not unique; different materials can produce the same type of



signal. This inverse sorting problem is not limited to sensor output. In density-based bulk sink-float separation, the same particle density can be obtained for a porous dense material and a low-density material with inorganic filler. To arrive at an unambiguous sort decision for a set of known materials, one increases the number of sensor channels or sorting steps, until an unambiguous mapping of sensor signal with particle type is obtained. Each set of desired products and of feed components defines a different, time-consuming sorting process development problem.

How do you deal with such an issue for a feed stream as complex as shredder-residue concentrate, which can contain any polymer/elastomer material or composite that has been produced in the last century? Clearly, sorting out all material grades is not practical.

The first step is to focus on products with established markets for post-consumer recycled content that retain the energy value of the material production, but have most tolerant composition specifications. An example for polypropylene (PP) would be a dark-grey coloured PP filled with 20-30% talc. This is a widely used PP formulation that can accept any talc-filled PP scrap, from pure transparent PP to black with 40-50% filler. Such an additional sorting step would be justified only if there were a significant price premium for the PP over a mixed polyolefin product.

The next step is to recognize that a particular plant draws its feed from a limited range of suppliers, and that locally there usually is a smaller range of material grades in the feed. One tracks the inbound feed composition by supplier and learns about the nature of the local plant feed and thus slowly converts the intractable “unknown feed” sort problem to a little more tractable “fuzzy knowledge” problem.

Let us consider how such a fuzzy knowledge problem is approached for an industrial particle sorter with a sensor based on NIR spectroscopy. While the particles are illuminated by a continuum “white light,” absorption or remission of NIR light is measured at a discrete set of wavelengths. The sorting decision is then based on an algorithm that takes this discrete set of measurements as input. However, in an NIR region, the spectral signature is dominated by harmonics (multiples) of the fundamental IR molecular vibration frequencies. These harmonic bands are broad and overlapping. Usually a set of NIR wavelengths can be determined that gives sufficient data to differentiate between known plastics. This enables bottle sorting, which deals with a small number of known resin and plastic compositions. However, with the unknown plastics in SR, the absorption or remission signal strength of the basic resin can be affected by fillers, additives, plasticizers, fire retardants, and reinforcing fibres. There are reports that an NIR sort of types of plastics found in SR is possible with a neural network sort decision algorithm trained with a sample set specific to a particular feed. It remains to be proven whether such a fuzzy sort can be successful industrially. Success will depend on learning as much as possible about the feed and narrowing the range of possible variations by adequate pre-sorting.

One possible strategy would be to select a region in the NIR spectrum parameter space that corresponds to an acceptable product composition with no overlap with other unwanted plastics. In such a batching approach, one could expand this region to account for composition averaging and diluting effects by particles that are purer than the product target composition.



6 Particle sorting of SR organic concentrates

The combination of the above-mentioned constraints on sensor-based particle sorting leads to four types of potential applications where this technology can be practical and economic:

1. Particle sorting of very high-value ores: diamonds, precious metals and coins
2. Particle sorting of individually diverted large particles
3. Product cleanup: removal of a low fraction of contaminants from a small particle-size stream. In this case each contaminant particle is diverted with a number of surrounding particles
4. Product inspection: particles are not diverted and the sensor is used for quality-control inspection of the product

What can such a technology contribute to sorting of organic concentrates produced by shredding plants? These are low-value materials and the value added by sorting is also limited by the value of the source-segregated scrap, which in most cases is sold at significant discount to virgin plastic or rubber. Sorting of valuable particles does not apply here.

The concentrates produced by the shredder will inevitably have a high concentration of both the particles of interest and of contaminants, so at this stage the product cleanup mode is not of interest to the shredding plant organic concentrates.

The second application, individually diverted large particles, can apply to SR organic concentrates. Of particular interest is the $>30<100$ mm size fraction of the shredder output. For grate sizes typical of large hammer mills, without further size reduction, this size fraction recovers ~50 % of the more brittle plastics, and a significantly larger proportion of tough elastomers (flexible PUR foam and tire rubber) from the shredder feed.

Particle sorters in product cleanup mode and sensors in product inspection mode can be applied to sink-float density-separated plastic outputs. Here, a minor volume fraction of harmful residual contaminants can be eliminated. Sorting of polyolefin product, for example, could eliminate inorganic, metal and fire-retardant particles. The quality of the product could be certified by an automated inspection of each particle (100%) by an appropriate sensor.

Table 1 shows three $>30<100$ mm SR organic concentrates that could potentially be sorted as individual particles. They correspond to the three basic shredding plant process options:

1. Dry SDF >30 mm organic concentrate
2. Moist organic >30 mm concentrate
3. Wet organic > 5 mm concentrate

The dry SDF organic concentrate has few low-density/high-aspect-ratio components such as foam, textiles, film and paper, and consists mainly of plastics and rubber contaminated with wood, insulated wire and residual inorganic. Moist and wet organic concentrates contain all the organic components of the shredder feed. Such concentrates can be economically transported from several shredders to one plastic and rubber sorting plant.

Further pre-grouping of these concentrates prior to particle sorting is a necessity for the complex unknown mixture of polymers present in SR. The sorting plant feed should be



re-sized on a secondary shredder to limit the top particle size to less than the 100 mm nominally produced by the primary shredder; a good top size would be 75-80 mm. The feed can be wet screened to eliminate the <30 mm fraction. The sized >30<75 mm fraction can be sink-float separated at various media densities to yield concentrates of:

1. Polyolefins (<1.0 g/cm³)
2. Unfilled low-density sink polymers (>1.0 <1.15-1.20 g/cm³)
3. Dense plastics, filled or reinforced plastics and those containing fire retardants (>1.15-1.20 <1.6 g/cm³)
4. Inorganics and metals (>1.6 g/cm³)

Hydrodynamic separation of polyolefins and low-density sink plastic can eliminate high-aspect-ratio particles such as plastic films and textiles. These are impossible to uniformly distribute and to divert in particle sorters.

For a sensor that depends on surface inspection, additional washing of the sorter feed may be necessary to remove paint, labels, oils, etc. Industrial friction washers have impellers that generate high shear between particles and actually mechanically heat the liquid. Abrasive grit and caustic or surfactants can enhance the cleaning action. After rinsing and grit separation, the particle mix can be fed wet to the particle sorter or be dewatered by spinning. Depending on the sensor, additional drying of the feed may be necessary. Colour is actually enhanced by a water film on the particle; magnetic fields and NIR and x-rays look into the particles and can ignore surface moisture. For a LIBS chemical analysis sensor, however, evaporation of water film from the particle surface dominates composition of the plasma in the ablation spark and the required correlation between the spectral emission from the plasma spark and the particle bulk composition is lost for wet particles.

After such preparation for particle sorting, we have low-aspect-ratio particles – thick sheet/plate and chunks – in three feed streams ready for sorting:

1. Polyolefins with low-density rubber contamination

The polyolefin feed would benefit from separation of contaminants and possibly separation of polyethylene (PE) from polypropylene (PP).

2. Low-density sink plastics dominated by filled PP, ABS and HIPS content

From the low-density sink plastics one would like to sort out the most abundant and highest value particles: acrylonitrile butadiene styrene (ABS), filled PP and PS+HIPS (high-impact polystyrene). Two out of these three could be separated on the first pass; the third one would be concentrated in the residue mix and could be targeted separately. In this case particle sorting would have an advantage over a density-based sort, where the densities of filled PP and other filled plastics and rubbers can overlap those of ABS and PS.

3. Dense and filled organics

Dense organics, the most varied feed stream, encompass composite materials with significant volume fractions of fillers and reinforcements, plus dense additives containing high atomic weight chlorine and bromine atoms. It is unlikely that value added to a small fraction of any two polymers that could be sorted out in one pass through a particle sorter could justify the sorting costs. A more likely use for this fraction is for mixed-polymer filler in a composite product such as plastic lumber, for the core of spiral wound pipe or



for coastal pilings. Such a fraction can be converted to oil feedstock through hydrocracking or used in preparation of solid RDF for combustion in a cement kiln, metal smelter, or a power plant.

How would particle-sorting lines look for these three feed streams? A suggested flow-sheet for a plastic particle sorting plant is shown in Figure 4.

1. Polyolefins

A particle-sorting line for polyolefins would first sort by colour and shape. The sorter would separate the feed into three streams: light shades, dark shades and black plus contaminants. The contaminants would be recognized by shape or a particular colour hue.

In the next step one could attempt to recognize the polyolefin type in the light-coloured and the dark-coloured fractions separately: sequentially on one sorter or in parallel on two. This step would separate “other” plastics from the polyolefins, and maybe PP or PE from the polyolefins, again giving three output streams.

For the light-coloured fraction, one could use a bottle sorter type NIR sensor. In bottle sorters, the illumination and NIR collection optics are located ~50 cm above the belt surface. For the dark-coloured fraction there is insufficient light reflected back to the bottle sorter type sensor for a good signal. A dark-plastic NIR sorter attempts to resolve this by delivering the light through optic fibres and collecting the remitted light into a sensor fibre, which are both placed directly behind the particle slide chute. The signal strength of the dark-plastic sensor is increased by minimizing the source-particle-sensor distance.

This type of sorter is required for the dark fraction, but would also improve the signal-to-noise ratio for light plastics. Standardizing on the dark-plastic type sensor for all SR NIR sorting would be a good choice. Pre-sorting the NIR sorter feed by colour is still preferred, as the available dynamic range of the dark-plastic sensor would be matched to a narrower range of signal strengths, allowing higher sensor sensitivity. Additionally, a separate light colour product might be in demand at a significant price premium.

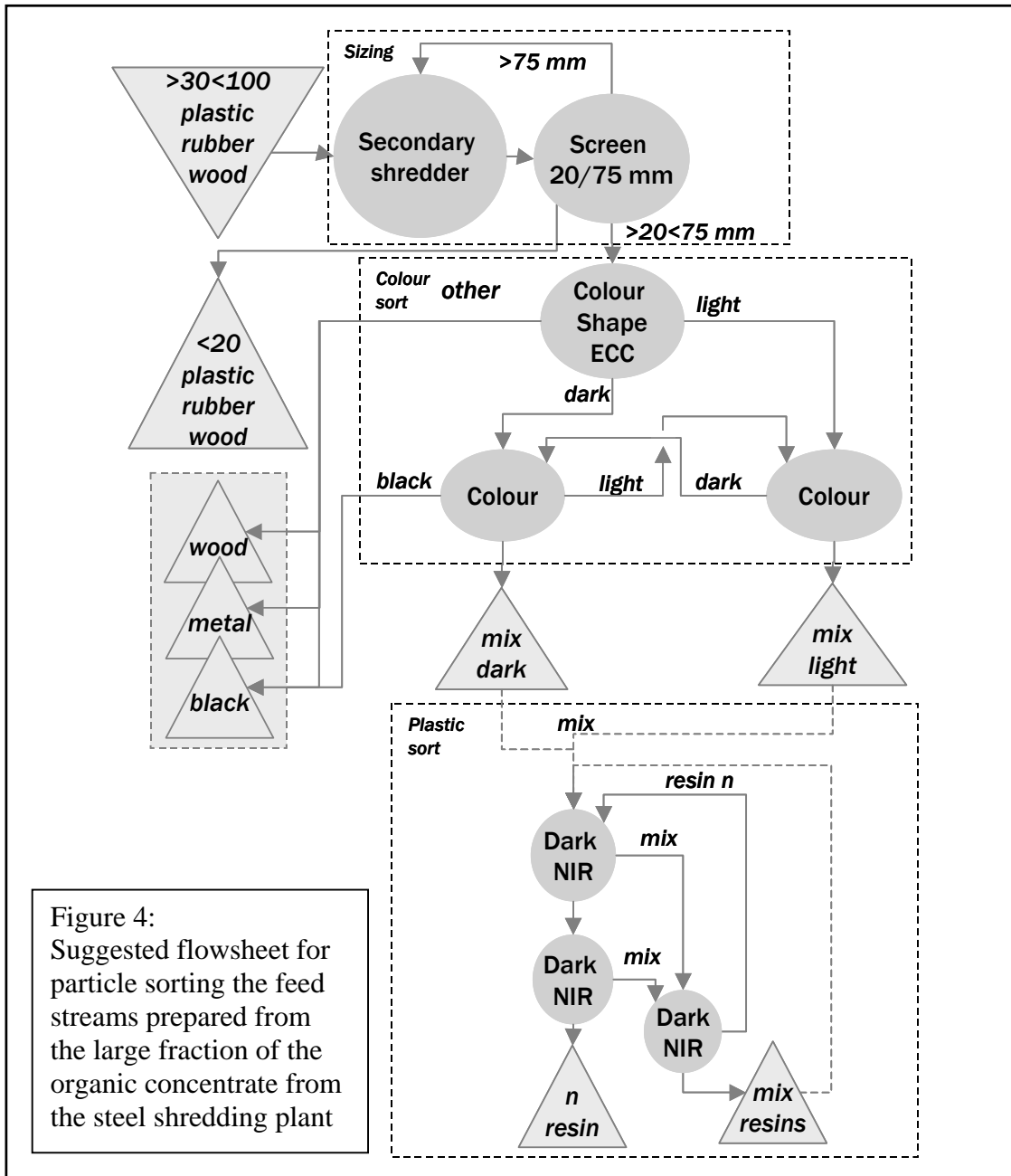
2. Low-density sink polymers

The sort logic for this fraction follows the pattern established for polyolefins, in this case, colour sorting out light and dark plastics and colour/shape rejecting wood, wire and other contaminants, then sequentially using dark plastic NIR sorters to sort out the target polymer types from the light and dark fractions.

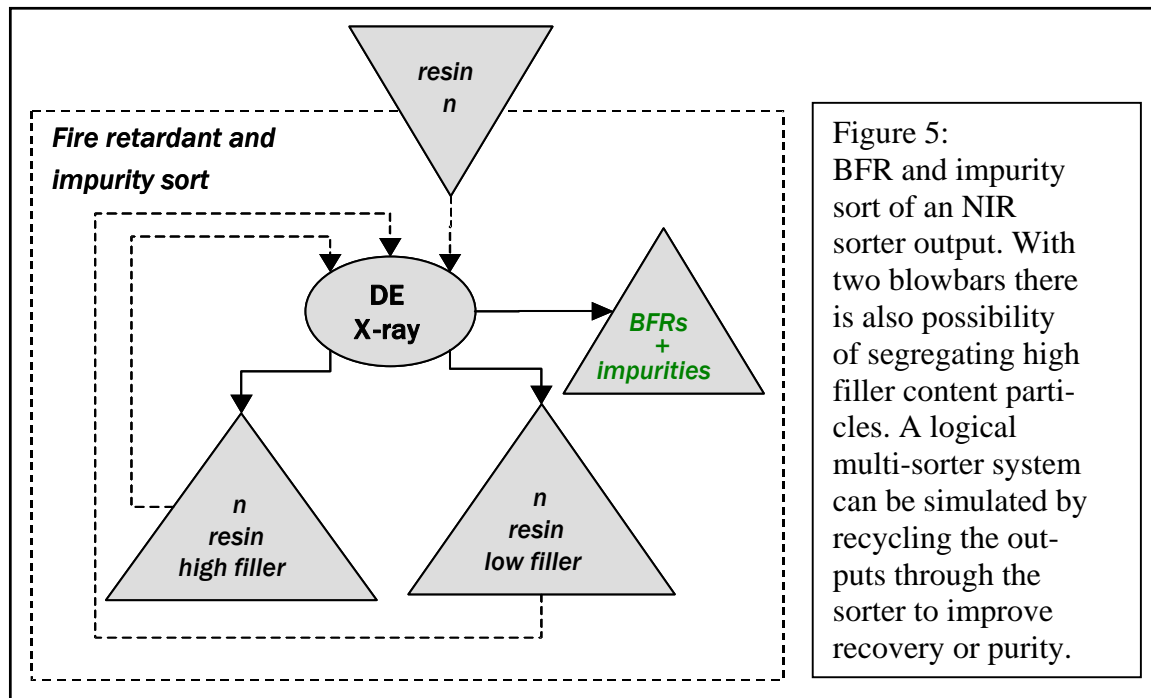
The ban on the pentabromodiphenylether (pentaBDE) type of fire retardant in recycled products may require an additional sorting step for each final product. A dual energy (DE) x-ray sensor could be used to identify Cl- and Br-containing particles and to eliminate them from the product. In the same sorting step one could also eliminate non-liberated particles and, if necessary, those with high filler content.

3. Dense organics

In the case of RDF-bound dense organics, the ECC sensor is well suited to the task of detecting and removal of, for example, residual copper wire buried in polyvinyl chloride (PVC) insulation, steel wire under a tire tread, or a hose clamp on a rubber hose.



Dense organic fractions contain a large proportion of fire-retardant-containing particles. Even though some users may specify Cl- and Br-free RDF, they are not willing to pay for the cost of sorting them out as long as regulations allow fire retardants in RDF. Even if Cl- and Br-containing particles are sorted out, there still remains a problem of dealing with what is now considered hazardous waste, or the need to develop an economic process for Cl and Br recovery. At this point, there is no business case for sorting fire-retardant-containing particles out of RDF, even though DE x-ray sensor sorters are technically capable of accomplishing this task, as illustrated in Figure 5.



6.1 Small particle sink-float product cleanup option

With the notable exception of plastic bottles, industrial sorting of plastic scrap from industrial or post-consumer packaging and electrical/electronic equipment is currently done through wet sink-float or hydrodynamic separation. This approach is also being proposed for SR organic concentrate. Organic concentrate feed material is reduced and sized to $\sim 5 < 10$ mm particle diameter range, hence all the shredder organic concentrates listed in Table 1 are suitable as feed material in this product cleanup option. The sized material is friction washed, pre-wetted, surfactant treated and sequentially separated at a number of density cut points. Control of surface tension and pH allows attachment of gas bubbles to selected types of particles, giving another measure of control over the separation process.

In the end, for mixed post-consumer scrap of unknown composition, one cannot achieve uncontaminated products through wet sink-float or hydrodynamic separation because of density overlap between different polymeric materials. There may be a potential for cleaning up these products using sensor-based particle sorters. To maintain economic throughput for small particle sizes, a high area concentration of particles would have to be used in a particle sorter. The blowbar then diverts some of the product particles with each contaminant particle, resulting in a reduced product recovery. This makes such a process economically feasible only for low levels of contamination. Suitable sensors would be vision, ECC, NIR and DE x-ray. They would be used either in a sequence of sorters or in a sorter using a combination of sensors.



7 Substances of environmental concern: Conflicting regulations affecting organic concentrate preparation and sensor-based particle sorting

In theory there is complete de-pollution prior to shredding; in practice it is rarely so. As recyclable metals are separated from the shred, substances of concern concentrate in the residue. These substances include toxic heavy metals (mainly mercury from switches and basic lead sulphate from battery paste). Key organic SOCs are the persistent organic pollutants (POPs) that bioaccumulate in the food chain and can be acutely toxic, teratogenic, mutagenic or carcinogenic. POPs of concern include a very closely structurally related family of halogen- (Cl and Br) substituted aromatic hydrocarbon compound groups:

1. poly(chlorinated/brominated)-biphenyls (PCB and PBB)
2. poly(chlorinated/brominated)-diphenylethers (PCDE and PBDE)
3. poly(chlorinated/brominated)-dibenzodioxins (PCDD and PBDD)
4. poly(chlorinated/brominated)-dibenzofurans (PCDF and PBDF)

This family is composed of hundreds of congeners that differ in the type, number and location of the halogen atoms substituting for hydrogen atoms around two linked 6-atom carbon rings. These compounds are stable in-vivo, lipophilic and hence tend to bioaccumulate in fatty tissues all along the food chain. The structural similarity in this family suggests particular ease of conversion from one compound group to another by chemical reaction. Biphenyls can oxidize to furans and then to dioxins, and ethers can oxidize to dioxins with few structural changes. Tetra- and penta-halogen congeners of these compounds are particularly bioaccumulating, bioactive and toxic. The more halogen-saturated congeners tend to be less bioreactive and less toxic, but are more prone to de-halogenation by photodegradation activated by sunlight to more bioactive congeners. Long-range atmospheric transport of these compounds, adsorbed onto the surface of dust particles, has been shown to take place. This provides the opportunity for exposure to intense sunlight and photodegradation to unsaturated PBDEs. Acutely toxic dioxins and furans can also be formed during low-temperature combustion of aromatic hydrocarbons in the presence of halogens. In SR, these halogens come mainly from PVC, PCB dielectric oil additives from transformers and capacitors, and PBDE fire-retardant additives in plastics, foams, carpets and textiles. There is increasing awareness among environmental scientists that the bromine-substituted analogues of PCBs, PCDDs and PCDFs, while they may not have quite as high a toxic equivalent (TEQ) rating as the Cl-containing compounds, they exhibit all the unwanted characteristics of POPs.

Compared with nearly a billion tonnes of municipal solid waste and a trillion tonnes of mine tailings and industrial waste, the annual 17 million tonnes of SR is a small fraction of the total global solid waste problem. The EU ELV directive has focused attention on SR by requiring nearly complete recycling of materials from vehicles, even though SR already serves a useful function as ADLC, and even though diversion of SR from the landfill to RDF for energy-recovery power plants, cement kilns and metal smelters is likely to increase generation of POPs.



7.1 Conventions and directives affecting SR

The Basel Convention forbids transboundary transport of waste except for recycling or for closely monitored, environmentally responsible destruction or decontamination. This dictates local disposal of SR. Nonmagnetic metal SR concentrate is an approved article of international commerce under this convention, and once downstream sorting, recycling and recovery processes are industrially implemented, organic SR concentrate should also be able to obtain the necessary international trade permits. This requires development of additional standards and organic concentrate product specifications for shredding plants.

The United Nations Stockholm Convention on POPs specifically targets nine man-made POP chemicals (including hexachlorobenzene (HCB) and PCBs) listed in the Annex A for elimination. PentaBDE is in the process of being added to the POPs Annex-A list. Annex B deals with restriction on production and uses of DDT. Annex C deals with elimination of unintended production of POPs, and its target list includes HCB, PCBs, PCDDs and PCDFs.

Article 5 of the UN Stockholm Convention specifically requires the use of best available techniques and best environmental practices for elimination of unintended production of Annex-C POPs from any new sources.

Article 6.1 of the UN Stockholm Convention specifically states:

"In order to ensure that ... wastes, including products and articles upon becoming wastes, consisting of, containing or contaminated with a chemical listed in Annex A, ... are managed in a manner protective of human health and the environment, each Party shall:

(d) Take appropriate measures so that such wastes ... are:

(iii) Disposed of in such a way that the persistent organic pollutant content is destroyed or irreversibly transformed so that they do not exhibit the characteristics of persistent organic pollutants...

(iii) Not permitted to be subjected to disposal operations that may lead to recovery, recycling, reclamation, direct reuse or alternative uses of persistent organic pollutants."

Once the Stockholm Convention is ratified, regulations based on article 6.1 will either eliminate recycling of plastics from SR, or justify removal of halogenated plastics from SR-sourced recycled plastic products by sensor-based sorting and more aggressive cleaning technology for removal of other POP precursors (PCBs).

Penta- and octa-BDE fire-retardant compounds are already banned since August 2004 from inclusion in new products in EU by the Directive on Hazardous Wastes, and a California ban is scheduled to become effective in 2008. The world has a legacy pool of these compounds in use that arrive at the shredder with end-of-life scrap in electrical and electronic equipment waste, construction and demolition waste, and in ELVs, and will continue to do so for many decades. The notable exception to the marketplace ban is decabromodiphenyl ether (decaBDE) fire retardant, an especially bioinert, completely Br-saturated PBDE with a low tendency to bioaccumulate. However, long-range atmospheric transport of decaBDE on dust particles and susceptibility to photodegradation by sunlight to more bioactive penta- and octa-BDE has been already firmly established. DecaBDE can act as precursor to the formation of dioxins and furans during combustion. Calls for banning all precursors that can degrade to pentaBDE, including decaBDE, are like to continue and intensify.



7.2 Chlorine and bromine and recycling of plastics from SR

The legacy pool plus continued production and use of decaBDE assures that both chlorine from PVCs and bromine from decaBDE will continue to dictate the nature of plastic recycling, complicating it for many future decades.

Once halogenated organics are segregated from polymers bound for recycling, the POP-containing residue will need to be destroyed or transformed. There is now a considerable body of knowledge on the destruction of hazardous wastes contaminated with PCBs, defoliants or pesticides. These wastes can be remediated by:

1. Solvent extraction
2. Supercritical water oxidation
3. Reductive hydrogenation thermal treatment
4. Base catalyzed decomposition
5. Reaction with metallic sodium dissolved in an organic hydrogen donor solvent

Brominated diphenyl ethers are structurally very similar to chlorinated biphenyls. Destruction of the PBDEs through these hazardous waste remediation processes is technically feasible, but it is likely to be expensive, as demonstrated by current industrially implemented processes for destruction of PCB-contaminated oils and cleanup of PCB-contaminated soils. If regulations do require such treatment, this cost may provide a financial incentive for the use of sensor-based particle sorters to sort out any plastics that do not contain BFRs, as such plastics can either be recycled or converted to an RDF that is suitable for non-hazardous-waste combustion systems.

A more likely outcome is that the regulators will continue to permit combustion of waste with BFRs and contaminated with low concentrations of PCBs as RDF in power plants, municipal solid waste (MSW) incinerators, metal smelters and cement kilns, while tightening and monitoring air, water and ash emission standards for plants using RDF. Such combustion can destroy most of the POPs present in the feed. Installation of special combustion controls and pyroscrubbers on MSW incinerators in 1980-90s in US and EU converted these incinerators from the largest single source of dioxins and furans to a minor source, with a 3% contribution to total dioxin and furan generation. This “minor” emission still contaminates local surroundings of a combustion site with a variety of harmful POPs. However, as long as regulations continue to allow BFRs and PCBs in RDF, there will be no incentive for sensor-based sorting of BFRs from RDF-bound material.

Components that contaminate the products (steel belts from tires for cement kilns, and copper wire in steel plant reductant) should be sorted out from the RDF for cement kilns and metal smelters. This is especially helpful because transition metals have been identified as effective catalysts for dioxin and furan formation.

Bans on PCBs and pentaBDE in plastics in commerce will require removal of these substances from the recycled materials compounded directly into plastics. This will either involve chemical processing during conversion of the recycled plastic into a chemical feedstock, or particle-by-particle sorting of Cl- and Br-containing particles. Feedstock recycling expends energy to break down the material chemically into monomers, oils or other precursor chemicals, and in doing so also gives up the energy that has been expended in polymerization and in compounding the plastic. Retaining the plastics’ identity



in mechanical recycling keeps these energy contributions and is usually less energy- and capital-intensive.

Sensor-based sorting is the only way of identifying and mechanically sorting out particles of PVC and those with fire-retardant additives from the output destined for direct compounding into plastics. It would be of commercial interest to identify the allowed decaBDE-containing plastic particles and sort them out for recycling. DE x-ray sensors can detect particles with elevated chlorine and bromine contents, but total halogen content is not indicative of the BFR type, because a given average bromine concentration in two materials can be due to a lower concentration of allowed decaBDE or a higher concentration of banned pentaBDE. Since the bromine-carbon bonds are similar in both congeners, NIR absorption is also not likely to be able to identify PBDE congeners diluted to various extents in a plastic matrix. Analytically, discrimination between PBDE congeners is done through an expensive and time-consuming combination of chromatography and mass spectroscopy. These techniques are not amenable to conversion into a high-speed industrial sensor for particle sorters.

Since there is no technically viable way to identify and mechanically separate particles containing pentaBDE from the still-allowed decaBDE fire retardants, then separation of these materials to comply with the pentaBDE ban will necessarily result in a loss of yield of all BFR-containing materials that might otherwise be recycled.

7.3 SOCs in SR fines

SOCs, including mercury, basic lead sulphate, and PCB-containing oils, remain in the fines. Shredder residue, after segregation of metals, typically has a low enough concentration of SOCs to pass leachability tests and be approved for use as ADLC. Landfill operators sometimes charge lower tipping fees for ADLC. Once the recyclable organic components are removed, the fines, with their high concentration of SOCs, now make up a major portion of the shredder residue. If this new residue fails leachability tests, it will be relegated to hazardous waste landfill at much higher tipping fees. The higher unit disposal costs outweigh the reduction in volume of the SR and more than eat up any value created by separation of the organic concentrate.

A wet shredding plant process has an advantage when dealing with shredder fines. The fines are washed off the larger particles in the concentrates preventing transport of SOCs to downstream concentrate processors. The fines are washed and leached in the process, and the residue can be conveniently treated to ensure non-leachability.

Although sensor-based particle sorting has no role in processing SR fines, unless the disposal of residue fines is adequately and economically addressed, it will make no economic sense to recover plastic and rubber concentrates from SR as feed to downstream sensor-based sorters.

Sensor-based output stream inspection can, on the other hand, demonstrate compliance with environmental regulations. LIBS has been successfully applied to monitoring elemental concentrations of heavy metals, arsenic and other toxic elements in liquid effluents, and Raman and IR spectroscopic sensors can monitor concentrations of organic SOC molecules.



8 Summary and conclusions

The organic fraction of shredder residue (plastics and rubbers) is among the most challenging of post-consumer materials sources for recycling. Distributed worldwide among nearly 1,000 shredding plants, this SR fraction contains a mixture of materials from vehicles and demolition and consumer durables, making it a very complex mixture of unknown compositions that is contaminated with SOCs from various industries.

Individual shredding plants are usually too small and do not have adequate technical sophistication to invest in a sorting system for SR organics. Downstream processors would be better equipped than shredding plants to recover the recyclables. There is a tradeoff between plastic and rubber recovery from the residue at the shredder, and transportation, waste-disposal and sorting costs at the downstream processor. Collaboration will be required between shredder operators and downstream processors of the organic SR concentrates to develop suitable recycling, decontamination and recovery systems.

It is the SOCs and their environmentally responsible handling that will dictate which products can utilize recycled plastics, and which processes and technologies will produce them. Production of plastics for the transportation sector can tap into the available supply of recycled packaging plastics that are relatively pure and can be compounded to vehicle plastic specifications. There are few automotive applications that can utilize SR-sourced recycled plastic scrap directly, and these will not be sufficient to provide a sufficient market. Production of plastics for the construction sector has more applications that can consume the type and volume of recycled plastics available from SR. Additional effort is required for the development of specific large-volume, recycled-content-friendly products for this market.

The SR market and potential profit from recycling of organics is not sufficient to justify independent development of sensors and particle sorters for this application. It is more likely that sensors and sorters developed for metal scrap, glass, ores, coal and plastic packaging will be adopted and modified for SR sorting.

Sensors are likely to find use in automated inspection of recycled plastic particles and of compounded plastics with recycled content. If high-value-added applications for SR-sourced recycled plastics are specified, sensor-based sorters are likely to be necessary to sort out contaminants. If costly, complete destruction of BFRs is mandated by regulations, sensor-based sorting of BFR-containing particles would be economically justified to reduce BFR treatment costs.

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