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DMS cyclone separation processes for optimization of plastic wastes recycling and their implications

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Abstract

It is demonstrated that substantial reductions in plastics presently disposed of in landfills can be achieved by cyclone density media separation (DMS). In comparison with the size fraction of plastics presently processed by industrial density separations (generally 6.4 to 9.5 mm), cyclone DMS methods are demonstrated to effectively process a substantially greater range of particle sizes (from 0.5 up to 120 mm). The purities of plastic products and recoveries obtained with a single stage separation using a cylindrical cyclone are shown to attain virtually 100% purity and recoveries >99% for high-density fractions and >98% purity and recoveries were obtained for low-density products. Four alternative schemas of multi-stage separations are presented and analyzed as proposed methods to obtain total low- and high-density plastics fraction recoveries while maintaining near 100% purities. The results of preliminary tests of two of these show that the potential for processing product purities and recoveries >99.98% of both density fractions are indicated. A preliminary economic comparison of capital costs of DMS systems suggests cyclone DMS methods to be comparable with other DMS processes even if the high volume capacity for recycling operations of these is not optimized.

Keywords

Recycling technology, physical operations, density separations, plastics and rubber waste, plastics recovery

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Introduction

Reduction of the high volumes of plastics in waste materials destined to landfills presents a challenge for waste management. This situation is expected to deteriorate as the demand for disposal of such wastes is generally forecast to increase. It is estimated that within the 27 members of the European Economic Community (EEC), Norway and Czech Republic, some 12.4 million tonnes were disposed of in landfills, while 5.0 million tonnes was recycled and 7.2 million tonnes were used in energy recovery (PlasticsEurope 2008). Energy recovery from plastic waste is widely promoted in some sectors and purported to be a means of reducing fossil fuel CO_2 emissions. It is suggested that being derived from fossil fuels, the combustion of plastic wastes should not be considered as a means of reducing greenhouse gas emissions. Furthermore, the combustion of certain types, especially those containing halogens, increases the potential environmental risks of producing toxic or carcinogenic gases. When compared with its value as a manufacturing feed stock, recyclable plastics constitute a particularly high value substitute for other fossil fuels as a source of thermal energy.

As there is a vast range of plastic types (many with very similar physical properties), their recycling represents a daunting task, especially in many instances the purity of products generated is an essential parameter for their reuse. Primary sorting of solid wastes by selective collection and sources has achieved important results in simplifying the processing methods required to generate reusable products and thus reduce the volumes of municipal and manufacturing wastes. However, the composition and the ease with which waste from selective collection or sourcing can be recycled

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are highly subject to the conscientiousness or reliability of producers not including extraneous materials. This situation is complicated by the absence of Society of the Plastics Industry (SPI) identification codes on many common products. Although the authors are not aware of studies in this regard, they have noted that at least in Spain, this situation is common to low-cost consumer products imported from outside the EEC and North America. In other instances, unusual mechanical and physical properties suggest that the SPI codes of some recyclable products are probably erroneous – a situation that could counter-effect the benefits of manual sorting.

In addition to the technical complexities of separating plastics, the commercial viability of recycling processes is in large part a function of the economics of scale of operation and the value of products generated, which is largely dependent on their purity. The required purity of recycled plastics is a complex issue that is largely determined by their intended applications. Publications reporting the market value relative to purity of the various types of recycled plastics are notably limited. Dodbiba & Fujita (2004) have indicated that a 99.5% level is required for reuse of plastics in a circulating system as virgin plastics and that a 95.0% grade is acceptable for reuse of plastics in a circulating system for low-quality plastics. These values are, at least in some instances, of particularly low levels and consultations with plastics manufacturers indicate that substantially higher purities for many applications may be necessary. This is especially the case when there are other plastics present that are incompatible with those in use and which may cause serious product defects or interference in the manufacturing process.

Due to the unpredictable variation in composition of waste materials, the great variety of plastics present and the varying requirements of the different waste treatment processes in use, a number of different recycling methods may normally be required to generate a final product. The use of multiple or complex system of processing methods requires that the methods applied be of low cost and high efficiency for such recycling operations to be viable. Generation of intermediate products with an optimum purity by each method of separation is important for simplifying and optimizing subsequent separation processes so that products to be marketed are of the most advantageous purity and that there is a maximum recovery of such materials.

The first step in processing waste plastics for their recovery and recycling requires that components of differing composition be physically separated from each other, which is usually achieved by fragmentation processes. Where possible, the degree of fragmentation conducted is minimized due to the large increase in energy input required, tendency to produce untreatable ultra-fine particle sizes and the mechanical wear created that is associated with fragmenting materials to finer particle sizes. Furthermore, the reduction of particle sizes of other materials such as metals or organic wastes to only be eliminated from the recycling circuit is non-productive. Once the waste plastics have been fragmented such that the different types present have been liberated from each other, a number of different physical and chemical separation processes can be applied. As there may be a large variety of plastics present, a combination of separation processes are frequently used to separate the types present. A comprehensive review of the different plastics separation and recycling process has been reported by Jody & Daniels (2006), Delgado & Stenmark (2005) and Dodbiba & Fujita (2004). Of these, electronic sorting and selective solvent extraction recycling methods represent the optimum means of obtaining recycled products with purities matching or approximating those of virgin materials. However, electronic sorting cannot effectively treat a feedstock with a wide range of plastics types and particle sizes and solvent extraction methods require a high-grade feed to be economically viable. Virtually all automated industrial plastics recycling processes presently use density media separation (DMS) to separate particles according to their densities relative to that of the separation media used. DMS is conducted either as a cleaning or preparation and/or pre-concentration phase for subsequent processing methods. In some instances, it is used to produce a marketable product that in certain instances may consist of a mixture of compatible plastics.

Present industrial DMS of plastic wastes use saline or alcohol/water solutions under normal gravitational force, so that particles of differing density are recovered separately due to their floating or sinking in the separation media. The equipment used must be constructed of specialized materials. The effluents produced from cleaning and post-separation washing of particles treated with some separating media solutions require in-plant treatment (Santos *et al.* 2005) and in some instances may be toxic. DMS methods presently used for recycling plastics are relatively limited in tonnage throughput and particle size capacity. The rate of separation of particles with slight differences in densities is low and as such the minimum particle size that can be treated is limited. The maximum treatable particle size is limited by the equipment design limitations. The rate of plastic particle separation by floating or sinking of particles of a density in a separation media of a given density under the force of gravity is determined by the degree of difference in densities between the particle and the fluid; the force exerted on the particles moving in the fluid due to its viscous resistance; and the degree of turbulence created by the particles displacing the fluid. Numerous attempts have been made to establish the theoretical relationships of the maximum velocity of floating or sinking of solid non-spherical bodies in a fluid (e.g. Rajitha *et al.* 2006), but for the irregular shapes typical of waste plastics where both the viscous and turbulent resistances are both greater and vary according to particle shapes and their orientation within the separation fluid, these laws are only partially effective.

The only variable that can be applied to accelerate the rate of separation of particles of different densities, either to increase throughput or reduce the particle size treated is that of the force of gravity by substituting it with a centrifugal force.

Large volumes of finer particle sizes are not being recycled due to the present limitations of industrial density separations of plastic wastes to 6.4 to 9.5 mm particles. Small waste electronic equipment is composed primarily of particles finer than this particle size range due to the inherent design of such equipment. Some 720 000 tonnes of plastic waste was reportedly produced globally in 1997 from scrap cable recycling (BIR 2009). This process requires fragmentation to <3 mm in order that the metal content can be recovered effectively (de Araújo *et al.* 2007). The need to process finer particle sizes is also exemplified by automobile shredder residue (ASR) produced where the <6.4 mm particle size fraction varies from 24 to 69% by weight of the total (Ambrose *et al.* 2000, Bareel *et al.* 2004, Jody & Daniels 2006).

Gent *et al.* (2009a) have proposed that the cyclone-type DMS technologies applied in the mining industry could be applied to substantially expand the recycling capacities of both throughput and particle size capacities. DMS technology is well established in the mineral processing industry as being the most precise density separation process, especially when there are only small differences in densities between the materials to be separated. A number of cyclone-type DMS processes based on medias of fine, high-density particles suspended in water are well established in the mineral processing industry. These processes use centrifugal forces to accelerate particle separation by difference in density and constitute a means of optimizing throughput capacity with a significantly larger range of particle sizes, including those <6.4 mm.

Objectives

The present study was conducted as a preliminary demonstrative evaluation of the potential of cylindrical-type DMS cyclone technology for the recovery and recycling of plastics based on differences in densities.

As DMS cyclone technology is yet to be applied industrially for recycling of plastic waste materials, this study was conducted to indicate the precision of density separations obtainable, maximum and minimum treatable particle sizes, through-put capacity, product purities and recoveries that might reasonably be anticipated. Several potential DMS cyclone methods for optimizing product purities and recoveries were considered based on conventional theory of DMS processes. Preliminary tests were conducted to derive a reliable indication of the potential precision in density separation, and the combined purity and recovery of high- and low-density products generated of the two most basic versions of these optimizing methods.

An in-depth evaluation based on operation using optimum operating parameters was beyond the scope of this study. The efficiency and capacity of such processing is determined by a number of operating parameters including: media flow rate, pressure and viscosity; type of media used; size and design of product exit ports (vortex finder and apex); separation cylinder inclination; throughput of plastics to be processed; and effects of the plastic particles size and form that could be treated collectively. Despite these devices being used extensively in the mineral processing sector for several decades the selection of such optimum operating conditions remains to be quantified and at present defining such conditions for a given operation remains in part a process of trial and error.

Since any industrial plastics recycling operation should ideally be economically viable and DMS cyclone technology is yet to be applied in this sector, the present work includes a tentative comparative economic evaluation of the probable viability and potential industrial impact this technology relative to other DMS systems in use.

Factors limiting DMS cyclones for plastics recycling in industrial applications

Actual industrial DMS of plastics are based on the use of separation media of controlled densities such that plastics of distinct densities sink or float in a quiescent regime according to their densities. There are a number of parameters that determine the effectiveness of DMS processes. These determine the rate by which such separations can be achieved, the quality or effectiveness of such separations, and the particle size that can be treated. They include the following items.

- The hydrophobic properties and adherence of air bubbles to particles present in a separation media cause such particles to respond to densities lower than their real densities. Materials such as plastics that are hydrophobic are water repellent. This results in plastic particles tending to float on the surface of aqueous solutions even though they are of a greater density than the separating medium.
- The separation media viscosity. The rate of separation of identical particles of plastics of different densities decreases with increase in the separation media viscosity.
- Plastic densities. The velocity of floatation or settling of a particle is proportional to the contrast in density between it and the separation media.
- The effectiveness of separations in terms of recovery and purity are influenced by the proportion of low- to high-density particles to be treated. A separation by sinking of high-density particles from a feed with a high proportion of this fraction will yield a high-grade product but at a loss in recovery. Conversely, a small proportion of such particles generally yields a lower grade product but with a higher level of recovery.
- The abundance of particles with densities approximating the separation density applied increases the difficulty of the separation.

- Particle sizes to be treated. The rate of floatation or settling of particles of plastics of the same density decreases with the size of the particles. Furthermore, there is a limit to the abundance of small particles that can be present within a separation media without them interfering with the displacement of other particles within the media. The larger the variation in particle sizes to be treated, the greater the time required for the separation of particles of different densities to occur.
- The shape of a particle to be separated affects its hydrodynamic properties. Less hydrodynamic forms such as flakes can present a greater resistance to movement within a separation media and thus have a slower rate of separation. Furthermore, the more non-equidimensional the particle form to be processed in separation medias with non-laminar flows, the greater the probability that miss-classification by density may occur.
- The gravitational or centrifugal force applied to particles of a given mass within the separation media determines the capacity of the particles to displace the media and to sink as a dense product or to float as a low-density product.
- All DMS processes produce at least one 'optimized' product of very high purity with a less than total recovery of that fraction, with the other fraction(s) having less than 'optimum' purity but virtually total recovery. High-density product separations are generally 'optimized' when that fraction has to sink away from the raw feed for it to be recovered (i.e. the raw feed material is fed onto the surface of the separation media and the high-density material must sink below the surface for it to be recovered). The purity of low-density product separations is generally highest 'optimized' when that fraction has to float away from the raw feed for it to be recovered (i.e. the raw material is fed at a depth within the separation media and the low-density material must float to the surface to be recovered).

There is a minimum rate at which material must be processed by a DMS method for it to be economically viable and the value of such products is determined by their market value which is in large part a function of their purity. With all other factors being equal, the use of centrifugal forces in cyclones to accelerate DMS represents a distinct advantage over other density separation processes. The extent or limits to which cyclone DMS can be applied to the separation of plastics might best be indicated by the results actually obtained by industry and by the results of investigations specific to this application.

Technical limits of DMS cyclones for plastics recycling as indicated by industrial operations and research investigations

No such application of this technology in the plastic recycling sector is known to the authors, but present industrial applications of cyclone media density technology in the processing of low-value minerals such as coal and other minerals has proven to be applicable to the treatment of particles $>500\,\mu m$ or in some instances as fine as $200\,\mu m$ or less. The various types of DMS cyclones, their characteristics, operating parameters and potential benefits to recycling of plastics is summarized by Gent *et al.* (2009a). Based on the performance characteristics of these devices for processing a variety of types of mineral ores, it is reasonable to anticipate that cyclone-type DMS could significantly enhance the reduction of plastic wastes presently sent to landfills, especially those of fine (<6.4 mm) particle sizes such as found in ASR and waste electrical and electronic equipment (WEEE). Furthermore, reduction in operational costs could be achieved through increased plant throughput capacity.

Introduction

Results of published investigations based on DMS cyclones have been reported among others by Gent *et al.* (2009b), Pascoe (2006), Bevilacqua *et al.* (2000), Ferrara *et al.* (1999) and Pascoe & Hou (1999). Of these, the best reported results for separating plastics with slight density differences are those of Gent *et al.* (2009b) and Pascoe and Hou (1999). Both of these investigations were conducted with the LARCODEMS version of the cylindrical-type DMS cyclone. No comparable research has been published for the cylindroconical-type DMS cyclones even though used much more extensively in industry. However, a number of investigations have been conducted to attempt the separation of plastics by density (Petty *et al.* 1993, MBA Polymers 1998, Bevilacqua *et al.* 2000, Pascoe 2006) using density medias in hydrocyclones which have a form that is identical to cylindroconical-type DMS cyclones. All reported hydrocyclones have limited use due to the low product purity obtained or limited range in particle sizes that could be processed collectively. It is suggested that these investigations might have obtained significantly superior results if they had been conducted with the axis of the hydrocyclone at $\approx 30^\circ$ from the horizontal as is done with the cylindroconical-type DMS cyclones so as to minimize particle size effects.

In comparison with cylindroconical type DMS cyclones where particles to be treated must pass through the pumping circuit, this is not the case for the cylindrical version. Furthermore, when using suspensions of mineral particles in water to form the separation media, a lower density offset is produced in the cylindrical version due to the lower centrifugal forces applied. Of the cylindrical cyclone versions, this industrial design also offers the largest range of particle sizes that can be processed simultaneously (0.5 up to 120 mm) with Ecart probable (*Ep*) values of 0.006 to 0.044 (Baille *et al.* 1997, McCulloch & Baillie, 1998). The *Ep* is a standard measure used to describe the precision of such separations and is derived from the partition curve, which is defined by the percentages of the proportion of feed particles of given densities that reports to a density separation product. *Ep* is defined as half the difference in densities where 75 and 25% of a material in the feed of a specific density reports to the sinks (dense) fraction. The lower the *Ep* value, the smaller the differences in density between the 25 and the 75% partition values and thus the better the separation obtained. Although an *Ep* value of zero indicates a perfect separation, it is of limited value in applications in which the total product purities are critical since it does not indicate the density range where the <25% and >75% proportion of particles have been incompletely separated. As such, it is suggested that the use of this value should only be considered as a comparative measure of separation devices or process separations attainable and not of the purities of products that might be anticipated for recycling plastics.

Product purity and recovery

Pascoe and Hou (1999) reported especially low *Ep* values of 0.0018 to 0.0022 for their evaluation of the DMS of polyethylene terephthalate (PET) and polyvinyl chloride (PVC). Test samples consisted of processing samples of PET (1.312 and 1.328 $g\,cm^{-3}$) and PVC (1.315 and 1.317 $g\,cm^{-3}$) flakes 0.234 to 10 mm thick that had been cut into 10 mm squares. Analysis of the data presented suggests that the actual Ep values are one order of magnitude larger than those reported. It also indicates that the density range over which all particles of PET floated, decreased with particle thickness from a maximum of $\pm0.092\,g\,cm^{-3}$ for 0.234 mm thick particles to $\pm0.035\,g\,cm^{-3}$ for 10 mm cubic particles. This effect was attributed to the hydrophobic surface effect of plastics such as PET requiring a greater force to sink particles of smaller mass. Results of the treatment of PET and PVC particles with sodium lignosulfonate to reduce hydrophobic effects resulted in particles floating at densities closer to, but still less that of the real densities of these materials. Furthermore, there is no evidence of improvement in the range in densities required for the floating or sinking of all the particles of each plastic type ($\pm0.092\,g\,cm^{-3}$ for PET and $\pm0.084\,g\,cm^{-3}$ for PVC).

Tests simulating an industrial-scale operation of the LARCODEMS by Gent *et al.* (2009b) showed that cyclone separations with non-toxic suspension media could effectively separate plastic particles with a wider variety of shapes and greater range of particle sizes than DMS processes presently used for industrial recycling applications. Virtually 100% purity with >99% recovery was reported for high-density products while >98% purity and ≥97% recovery was reported for the low-density fraction. It was also demonstrated that although *Ep* values for a given DMS device are generally constant for a given particle size of any type of material to be separated at a specific density, *Ep* values do vary slightly with the suspension media particle size used.

These tests demonstrate the importance of a judicious selection of the material used to create a separation media using suspended particles. This is shown in Table 1 for a worst-case scenario in which a <2 μm media suspension with a density of 1.11 $g\,cm^{-3}$ was used to separate polystyrene (1.051 and 1.057 $g\,cm^{-3}$) from acrylonitrile butadiene styrene (1.185 and 1.190 $g\,cm^{-3}$), and polymethyl methacrylate (1.196 and 1.201 $g\,cm^{-3}$). The very fine particle size of this suspension material increases the media viscosity, resulting in the observed poorer separation efficiencies of smaller plastic particle sizes as exemplified by the mediocre separation obtained for particles <1.6 mm despite the moderate difference in density (0.07 $g\,cm^{-3}$) between the lightest of the high-density particles and the separation media density. In contrast, substantially improved separations were obtained with a water-only separation media at a density of 1.00 $g\,cm^{-3}$ (Table 2) and a difference in density of 0.05 $g\,cm^{-3}$ between the lightest of the high-density particles. However, the purity of the low-density product and the recovery of the high-density 1.0 to 1.25 mm particles were seriously reduced due to the much higher content of <2.0 mm high-density particles that were present in the initial feed used for that test. Furthermore, excessively coarse material creates a density offset between the media producing the high- and low-density products.

Limitations in separable plastic particle sizes treatable by cylindrical DMS cyclones

All separation processes for plastics such as DMS requires that plastics of different compositions be physically separated (i.e. liberated). Since automated processes apply fragmentation to reduce particles to sizes where these materials are

Table 1. Recovery and purity of high- and low-density plastic separation products by grain size obtained using a precipitated calcium carbonate media with a density of 1.11 $g\,cm^{-3}$

Product fraction	High-density		Low-density	
Particle size range (mm)	Recovery (%)	Purity (%)	Recovery (%)	Purity (%)
5.0–6.3	96.57	100	100	93.15
3.15–4.0	97.01	100	100	94.86
2.0–2.5	94.98	99.31	98.76	91.28
1.25–1.6	88.36	99.52	98.99	78.11

Table 2. Recovery and purity of high- and low-density plastic separation products by grain size obtained using a water only media with a density of 1.00 g cm^{-3}

Product fraction	High-density		Low-density	
Particle size range (mm)	Recovery (%)	Purity (%)	Recovery (%)	Purity (%)
6.3–8.0	100	100	100	100
5.0–6.3	97.83	100	100	92.60
4.0–5.0	97.97	100	100	85.72
3.15–4.0	97.64	99.97	99.93	94.19
2.5–3.15	99.49	100	100	99.60
2.0–2.5	98.52	100	100	98.63
1.25–2.0	96.90	100	100	46.47
1.0–1.25	94.75	100	100	2.46

liberated from each other, the maximum particle size to be treated depends upon the design characteristics of the waste product to be treated. All DMS cyclones are generally reported to be adequate for treating particles as fine as 0.5 mm. Of the cylindrical type, the LARCODEMS version is reported to have both the greatest tonnage throughput capacity and range of particle sizes that can be treated simultaneously. It is presently supplied in two versions of 0.3, 0.5, 0.85, 1.0, 1.2 and 1.35 m. diameters. The standard version with a single separation cylinder (Figure 1(a)) and the other in development with two separation cylinders consisting of a secondary separation cylinder fed directly from the dense product port of the primary cylinder (Figure 1(b)). The device consists of a cylindrical separating chamber inclined 30° from the horizontal into which the separation media is pumped tangentially at the lower end, forming a vortex with a central air core. Originally developed to process coal, it was designed to avoid having to pump rock or mineral fragments along with the separation media. Material to be processed is fed dry or moist at the top end so as to enter into the vortex and the dense fragments must settle through the ascending separation media circulating around the inner circumference of the cylinder. Material denser than the separation media exits through the upper port (underflow) while the lower density material floats down the surface of the vortex to exit at the bottom end (overflow). The diametrically opposing separation media flow directions as indicated for the low- and high-density products favours the separation of particles with densities approximating that of the separation media.

Maximum plastic particle sizes treatable by cylindrical DMS cyclones: Virtually all DMS cyclones are reported to be effective for processing particles as fine as 0.5 mm but the maximum particle size that can be processed in a given separation media cyclone increases with its diameter. The cylindrical DMS cyclones have the greatest particle size capacity relative to cyclone diameter, and of these, the LARCODEMS version has the largest particle size range of all. The manufacturer of this device reports (J. McCulloch, JMC Engineering (UK) Ltd, Alfreton, Derbyshire, UK, 2008, personal communication) that the maximum particle size treated in a LARCODEMS is largely dependent upon the diameter of the separation cylinder and the exit ports for the floats and sinks products. The port dimensions were originally determined from trials on coal beneficiation applications and were selected in part on the basis of the material feed size to be treated. The design objective was to maximize capacity without producing blockages and it is thought that their minimum aperture diameter should be at least 2.5 times the maximum dimension of the particles to be treated.

Based on the manufacturers (JMC Mining Services Ltd 2004) recommended maximum admissible particle size and adjusting the coal-processing capacities relative the separation cylinder diameter, (Figure 2) it is evident that these increase exponentially with the separation cylinder diameter. Modelling of these values for the models and testing of the laboratory version found the following situation.

1. A maximum treatable particle size (y_s) in millimetres relative to cylinder diameter (x) in millimetres can be expressed by Equation (1) with a correlation coefficient R^2 of 0.9926. Higher order polynomial equations such as Equation (2) have a higher correlation coefficient R^2 (0.9990) but the authors suspect that the use of such a polynomial order is unjustified for the slight improvement in correlation, especially as there may be some error or simplification in the data and since this relationship is a function of the radius or circumference of the separation cylinder.

$$y_s = (0.000006x^2) - (0.0734x) + 6.9574 \quad (1)$$

$$y_s = (0.01x^4) - (0.00007x^3) + (0.0004x^2) - (0.029x) + 10.283 \quad (2)$$

1. Proportionally adjusting the maximum coal processing (typically conducted at 1.35 to 1.60 g cm^{-3} with a value of 1.55 g cm^{-3}used) capacity to that of a mean real density of plastic waste (assumed to be 1.10 g cm^{-3}) the maximum

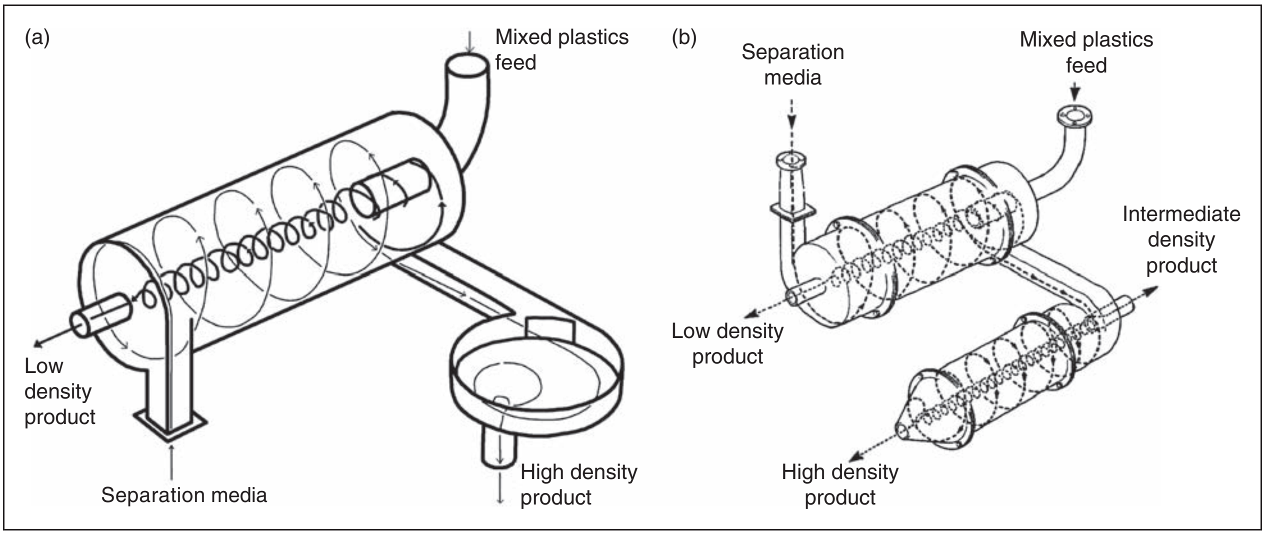

Fig. 1. Schematic diagram of the media flow patterns and product ports of the LARCODEMS (A) single separation cylinder (Gent et al., 2009b) and (b) dual separation cylinder cyclone separator (Gent et al., 2009a).

plastics processing capacity (y_c) in kg h^{-1} relative to cylinder diameter (x) in mm can be defined by Equation (3) with a correlation coefficient R^2 of 0.9938.

$$y_c = 0.00009x^{2.0869} \tag{3}$$

As the original design of this device was for use in mineral processing and is based on the concept that the material to process included the full particle size range for which it is specified, it is not known how much inter-particle interference may occur if only a narrow particle size range is treated. However, it is reasonable to anticipate that throughput capacities must be less with reduction in the size of particles processed for which the device was designed. Furthermore, it is unknown if there is any effect on the purity of separations obtained using a large diameter device to process only fine material. Due to the minimum size required to liberate the different components in the waste, the maximum treatable particle size of some of the larger models of this type of device far exceeds the requirements for most plastic recycling applications. A possible exception to this could be the separation of organic from inorganic material in municipal waste.

Minimum plastic particle sizes treatable by cylindrical DMS cyclones: Although all versions of the LARCODEMS version of cylindrical DMS cyclones are reported to be suitable for the processing of mineral particles as fine as 0.5 mm, the minimum treatable particle size in the cylindroconical versions tends to increase with the diameter of the separation cylinder. The precision in any DMS operations relative to particle size should vary to some degree due to the rates of separation for different particle sizes and effects of media viscosity. This is substantiated in the results of tests indicated previously in Tables 1 and 2 which show that slightly poorer separation recovery results were obtained for finer particle sizes. Analysis of *Ep* versus particle size data reported by McCulloch & Baillie

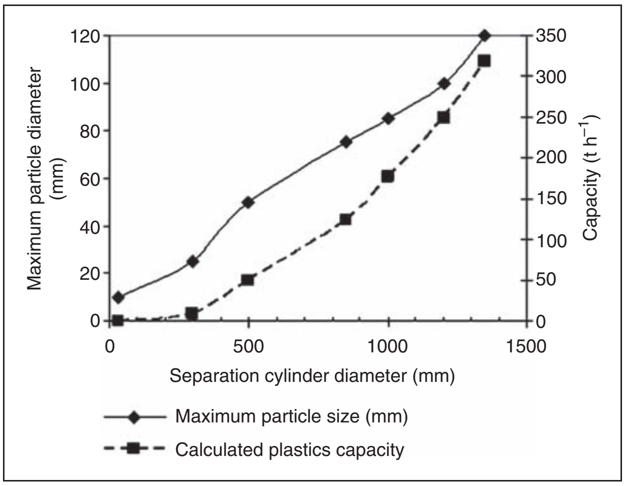

Fig. 2. Relationship between calculated plastics processing capacity relative to separation cylinder diameter of the LARCODEMS based on testing of the laboratory model and manufacturers reported performance characteristics for coal particles of industrial scale versions.

(1998) for a 1200 mm-diameter separation cylinder shows that these values increase both with an increase in separation density from 0.0069 to 0.0143 at 1.35 to 1.8 g cm^{-3} for 75 mm particles and reduction in particle size treated from 0.0069 for 75 mm particles to 0.0455 for 0.75 mm particles. It is suggested that this effect may be due to increases in media viscosity and time required for dense particle to separate out of the material being treated. Furthermore, extrapolation of this data suggests that it is reasonable to anticipate a very low *Ep* value of 0.017 for 0.5 to 1.0 mm plastic particles being separated at 1.1 g cm^{-3}.

It is suggested that to attain very high tonnage throughput of fine plastic particles and high-purity product separations, several smaller diameter devices might be preferable to one large diameter version. This solution would also facilitate maintaining plant flexibility but complicate its control.

Cylindrical DMS cyclone plastic processing capacity

In addition to being recognized as being the most precise method for conducting density separations on an industrial scale, all cyclone DMS devices are recognized as having particularly large throughput capacities. The maximum throughput capacities are related directly to the maximum particle size that may be processed (Figure 3). The significantly higher media pressures used in cylindroconical DMS cyclones relative to those of cylindrical DMS cyclones results in much larger rates of media flow through the separation cylinder in the cylindroconical type, and thus a correspondingly greater processing capacity. DMS cyclones are normally are operated at a maximum capacity (30% by weight solids to be treated relative to separation media) but even at 5% of the maximum throughput capacity, processing of particles up to 10 cm in cylindroconical and cylindrical (LARCODEMS) cyclones would be 24.6 and 15 t h^{-1}, respectively. It is thought improbable that any industrial plastics recycling operation presently operates at these rates.

Options for optimizing plastics recycling by DMS cyclone processes

Plastic separation product purities and recoveries

Purities and recoveries of plastics produced by industrial separation processes are primary factors in the viability of recycling of such waste materials. However, extremely high purities ($\gg$99%) of both low- and high-density plastics may be required to optimize product value and in many instances may be essential for such products to have any use as a manufacturing feedstock. As with any concentration process, any increase in product purity results in a decrease in recovery. In the case of the cylindrical-type DMS cyclones, feeding the materials to be treated directly into the separators vortex results in the high-density product having the highest or total purity but at a loss in recovery and total recovery of the low-density product but with a product purity inferior to that of the density fraction. With the cylindroconical-type DMS cyclones, material to be separated is fed into the cyclone along with the separation media. This results in the low-density fraction produced being of high purity but with a loss in recovery of particles corresponding to that fraction, and a total recovery of the high-density particles in the dense product fraction but with a corresponding lower purity in that separation product. However, published investigations of DMS cyclone separation of plastics are limited and the authors are unaware of any having been conducted in which the plastics to be separated have been treated in cylindroconical-type DMS cyclones. Although not practiced industrially, it is also theoretically possible to feed material to be separated into a cylindrical-type DMS cyclone along with the separation media as is done with the cylindroconical type.

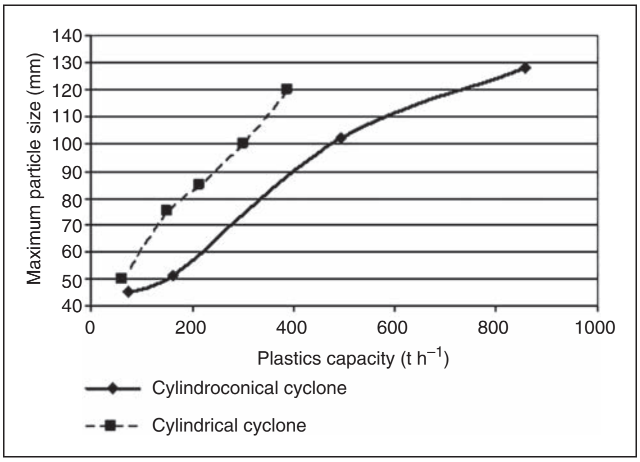

Fig. 3. Relation between maximum particle size (mm) and plastic waste throughput capacities (t h-1) of industrial cylindroconical and cylindrical (LARCODEMS) DMS cyclones.

To obtain both higher recoveries and product purities, reprocessing is frequently used in other industrial processing operations. There are a number of possible reprocessing configurations (Figure 4) that could be used to achieve optimum DMS product purities and recoveries. These include: repetitive processing under identical operating conditions; a two-stage processing at different densities with a dual cylinder separator in the second stage having a separation media that generates a slightly higher media density entering the second; and a combined cylindrical followed by a cylindro-conical-type cyclone; and a combined standard cylindrical cyclone separation followed by a cylindrical cyclone separation with the plastics pumped into the separator along with the DMS feed.

Repetitive standard cylindrical DMS cyclone processing: Since one DMS fraction is always ‘optimized’, reprocessing the other ‘un-optimized’ partially concentrated fraction once or preferably twice should result in this fraction also attaining a relatively high purity. To minimize possible defects in separations, recycling the ‘optimized’ density products from the subsequent separations should be re-circulated in closed circuit back into the initial feed of the first separation cyclone. This configuration (Figure 4(a)) of separation equipment has the advantage of minimizing the variety of devices used.

Testing of this concept based on reprocessing (Figure 5) in a LARCODEMS of a low-density product (Table 3) found that a separation of similar order of efficiency to the first separation was achieved with low-density product recovery consistently >99% but high-density product recovery declining with each subsequent separation. This is interpreted as indicating that the separation error or inefficiencies obtained are inherent to the process or to slight variations in densities of the plastics used. It is also evident that as the proportion

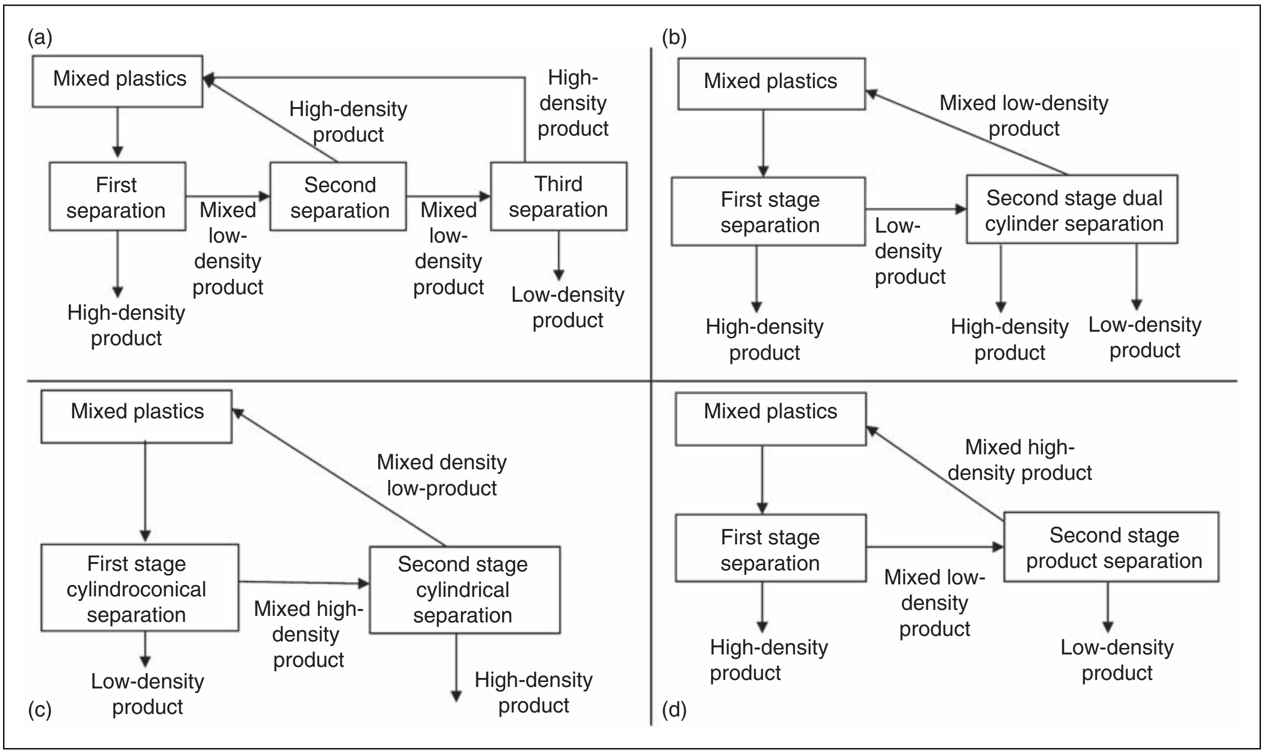

Fig. 4. Alternative proposed schemes for plastic recycling by DMS cyclones to produce high purity low and high-density products with total recoveries of both fractions. a) Repetitive processing with a cylindrical DMS cyclone. b) Two stage processing including a dual DMS cylindrical cyclone. c) Combined cylindrical and cylindroconical DMS cyclone processing. d) Combined two stage cylindrical DMS cyclone processing with plastics pumped with the media separation feed in the last stage.

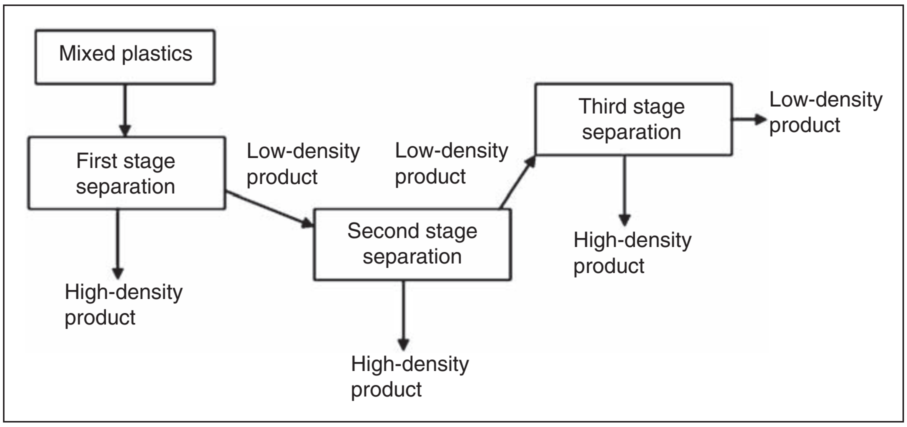

Fig. 5. Schematic diagram of DMS reprocessing conducted of the low-density product conducted with a media separation density of a 1.0 g cc-1.

of low-density to high-density plastics present in the feed increases, so does the grade of high-density fraction decrease.

The actual amounts of high-density plastics products generated in the second and third separation are extremely small relative to that of the first separation and demonstrate that such reprocessing of incompletely separated fractions by the same processing method can substantially improve purity of the low-density product as well as slightly improve recovery of the high-density material. If the high-density fractions from reprocessing are blended with that of the first separation product there is a corresponding, but small reduction in product purity. This could be avoided or minimized if the secondary sub-product were marketed separately or recycled within the processing circuit.

Two-stage cylinder DMS cyclone processing including a dual separator: The density offset of the separation media created during the separation process using suspended particles to create the separation media can be used in the dual cylinder separator to create a second density separation product of the dense fraction. If the grain size distribution of the particles used to create the separation media in a dual LARCODEMS cylinder separation is judiciously selected, duplication of the density of a

Table 3. Results of repetitive media separations at 1.00 g cm^{-3} of low-density (<1.00 g cm^{-3}) plastics (11.87% polypropylene) from an initial feed with densities of 0.96, 1.051, 1.057, 1.179, 1.187, 1.196, 1.206, 1.364 and 1.693 g cm^{-3}

	Low-density product purity (%)	Low-density product recovery (%)	High-density product purity (%)	High-density product recovery (%)
Raw mixed plastic feed	12.51	–	87.49	–
First separation pass	90.30	100	100	98.09
Second separation pass	99.26	99.77	97.78	93.12
Third separation pass	99.95	99.96	94.65	92.77

previous, higher density separation product can be achieved. This combination of processing (Figure 4(b)), would result in first an 'optimized' high-density product in the first DMS, followed by an 'optimized' low-density and an 'optimized' high-density product from the secondary cylinder of the second DMS. Recycling in closed circuit of the mixed low-density fraction from the secondary cylinder of dual separation LARCODEMS back into the initial raw feed of the first separation cyclone should minimize misclassifications. The use of this schematic requires a complex selection of the material and its grain size distribution used to create the separation media, which in most, if not all cases may be impractical.

A combined standard cylindrical and cylindroconical cyclone DMS processing: The differences in the separation process of cylindrical and cylindroconical DMS cyclones are such that their differences can be used to maximize purities and recoveries of both the low- and high-density fractions. With cylindrical type DMS cyclones, the high-density particles must settle through the separation media to exit from the underflow, resulting in a high-density product of high purity. In the cylindroconical-type DMS cyclones the opposite applies, as the low-density particles must float through the separation media to exit from the overflow, resulting in this product being 'optimized'. The optimization of this configuration (Figure 4(c)) requires that the initial feed of material to be separated be treated first in the cylindroconical-type DMS cyclone as this type has even higher throughput capacities than the cylindrical type. As such, a smaller, second-stage, cylindrical-type DMS cyclone would be sufficient. Recirculation in closed circuit of any incompletely separated material can be used to optimize recovery while producing both high-purity low- and high-density products. The higher pumping pressures and specialized pumps required for cylindroconical-type DMS cyclones is a disadvantage of this otherwise simple schema. An additional disadvantage to this process is the fact that the very large diameters of the cylindroconical-type cyclone required to process large particles have extremely high throughput capacity such as is indicated by the 1.45 m DMS cyclone from Multotec reportedly being able to treat particles up to 128 mm at a rate of 1000 t h^{-1} of coal (Bookless, Multotec, Johannesburg, South Africa, 2008, personal communication) which should be equivalent to $\approx$ 785 t h^{-1} of plastics. This capacity probably greatly exceeds the resources of most if not all recycling centres presently in operation.

A two-stage cylindrical DMS cyclone processing with plastics pumped with the media separation feed in the last stage: Theoretically, the low-density fraction should also be of maximum purity in cylindrical-type DMS cyclones if the plastics to be separated are pumped along with the separation media into the separation cylinder. The combined use of two cylindrical-type media cyclones as indicated in Figure 4(d) has the theoretical potential to produce high-purity low- and high-density products with total recoveries of both fractions. Such a process would require that the first separation have a conventional feed of material to separate directly into the vortex, producing approximately 100% high-density product and a mixed low-density product. If the mixed low-density product is then pumped along with the separation media into a second separation cylinder, the low-density product of this second separation should be of optimum purity. Any material not separated will occur in the high-density product from the second separation and could be recycled in a closed circuit back with new feed into the first separator so as to maintain total product recovery.

This method has the advantage of simplifying maintenance and operation by standardizing the equipment used. It is emphasized that although pumping of the material to be separated by density along with the separation media is essential for separations with the cylindroconical-type cyclones there does not appear to be any industrial operations or published research using this procedure. The need for pumps capable of passing large fragments is probably the only major disadvantage of this process.

A preliminary test of this hypothesis was conducted with the demonstration model of a conventional LARCODEMS type separator modified to feed plastics either directly into the vortex or along with the separation media via gravity feed. No prior investigation or experience of the operational optimization for this type of separation was available. Testing conducted with the plastics to be treated being fed separation media was based only on prior LARDODEMS operating observation of vortex form when material for

Table 4. Estimated capital costs and processing capacities of DMS systems

	DMS 0.5 and 1 m. cyclone system	Centrifuge system	Sink-float tank system
Cost (€ K)	22–43	500–720	17–55
Throughput capacity ($t\,h^{-1}$)	50–180	0.45–1.36	0.45–0.91

separation was fed into that devices vortex. A separation media of water ($1.0\,g\,cm^{-3}$) and a sample of flakes of polystyrene (PS) and high-density polyethylene (HDPE) with a maximum surface area to thickness ratio of 19 : 1 were used. The sample consisted of using equal proportions by weight of PS and HDPE with a difference in densities of 0.068 to $0.094\,g\,cm^{-3}$. The PS fragments had densities of 1.028 to $1.042\,g\,cm^{-3}$ and ranged in size from 0.7 to 8 mm. The HDPE fragments had densities of 0.948 to $0.960\,g\,cm^{-3}$ and ranged in size from 0.5 to 12 mm. The sample was washed and then fed damp, firstly into the vortex of the LARCODEMS. The high-density product was removed and the low-density port product was then fed along with the separation media into the LARCODEMS. The products were dried, manually sorted by plastic type and each product fraction weighed.

The first separation (sink from feed high-density product) consisted of PS with a purity of 99.999% and a recovery of 97.898%. The second separation (first float from feed – low-density product) consisted of HDPE with a purity of 99.990% and a recovery of 98.353%. Of the original feed, only 1.870% remained as un-separated plastics which could be re-circulated with new raw feed of plastics to be separated. The particularly high product purities and recoveries of both density fractions despite very small differences in densities suggests this procedure to be especially effective. This is emphasized by the fact that no prior process optimization tests were conducted for separations with the plastics to be treated being fed along with the separation media.

Economic considerations

In view of the market value of recycled plastics and subsequent processing methods that may be required as well as recycling plant capital and operating costs, it is probable that the scale of operations required using DMS cyclone technology must be of an order of magnitude similar to that of small-scale mineral processing operations. The potential for such large-scale operations is also indicated by the high capacities of DMS cyclones. Even the smallest industrial version of the LARCODEMS operating at the standard 30% solids (by weight) to separation media has a calculated separation capacity of plastics with a mean real density of $1.1\,g\,cm^{-3}$ of $9\,t\,h^{-1}$. This value is probably far in excess of the vast majority if not all of the present industrial operations. Under such a scenario, unless large-scale transport of wastes with the associated increased costs is used, recycling facilities could only be located near major urban centres with large volumes of wastes. The capacity of devices using this technology is such that a single recycling plant with a series of cyclones, with the largest of 1 m. diameter and operating three shifts could process in excess of 1 million tonnes per year.

DMS cyclone operations typically have a very low operating cost ($\sim$0.0241 € t^{-1}; Fernández Maguregui, Equibemin, Madrid, Spain, 2008, personal communication) and a large throughput is typically required to maintain plant operations and maximize economic viable. A preliminary analysis of the estimated of costs (Table 4) for these devices and necessary associated equipment as reported by MBA Polymers (1998) for centrifuge and sink–float tank systems and those for 0.5 and 1 m. cylindrical DMS cyclone (McCulloch 2007, personal communication). The cost of the cylindrical DMS cyclone has been increased 60% for associated systems equipment similar to those of the other systems. A conversion to euros at the international exchange rate of 0.722 € : 1US$ and 1.151 € : ₤1 GB has been applied and all values adjusted for a 4% annual inflation. This data indicates that the capital costs of DMS cyclone systems are similar or lower to that of any other DMS system and even though a recycling plant may not be able to optimize the throughput capacity of DMS cyclone systems, this may not have a significant impact on the economic viability of a plastics recycling operation.

Conclusions and recommendations

The results of investigations for separation by density of plastics indicate that cyclone DMS has the potential for substantially reducing plastic wastes such as ASR, WEEE and cable sheathing presently being disposed of in landfills. Large amounts of plastic waste materials as fine as 0.5 mm and as coarse as 120 mm and with a difference in densities of 0.068 to $0.094\,g\,cm^{-3}$ or less can be processed effectively by density into fractions with purities >99.9%. DMS cyclone separations of plastics at a several densities and the reprocessing procedures required to achieve high purities in both the low- and high-density products along with total recoveries of a broad range of waste plastic types implies a scale of operation that has yet to implicated anywhere by the recycling industry. Subject to the physical characteristics of the plastic waste types processed, these separation products may be directly marketable products or constitute high-grade feed stocks for secondary processing by other recycling methods. Even though this process can achieve density separations with $\gg$99.5% purity and very high levels of recovery, achieving even higher levels of purity should have a significant impact on the market value of such products.

Small-scale DMS cyclone operations to concentrate a specific type of plastic waste (e.g. PVC or polypropylene/polyethylene) from other types of wastes are technically feasible and are anticipated to be of a similar or superior economic viability to other DMS processes presently used. However, despite the relatively low cost to throughput capacity ratio of DMS cyclones, the application of such technology on a small scale to produce multiple recycled plastic products from wastes such as ASR is not anticipated to be practical unless such operations are conducted in a discontinuous batch mode due to the infrastructure otherwise required. As such devices are capable of treating larger volumes of plastic waste materials there is the prospect of achieving very low cost separations or concentrations of the vast majority of these materials that are presently disposed of in landfills. In addition to recovering fine particle size waste plastics, such an operation has the potential to substantially reduce the energy requirements for fragmenting large waste particles.

Although DMS cyclones are extensively used in the mineral processing industry, the absence of publicly documented use or testing of its application to waste plastic separation is noteworthy and the optimal operational conditions for such separations remains to be determined. As the tests results presented are for a laboratory-scale device and many of the operational options of an industrial version are not available, it is reasonable to anticipate that superior results should be attainable in an industrial operation. Further investigation of its application for plastics recycling is therefore strongly recommended prior to any attempt to incorporate it in any industrial-scale operation.

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