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Recycling of flame retardant plastics from WEEE, technical and environmental challenges

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ABSTRACT

The European Flame Retardant Association (EFRA) combines leading companies offering the largest spectrum of flame retardants (FRs). EFRA conducted many studies on the recycling of FRplastics. This study concerns the recycling of plastics from liquid crystal displays (LCDs) and addresses the RoHS and WEEE directives (Restriction on Hazardous Substances and Waste Electrical and Electronic Equipment), requiring a higher tonnage of recycled plastics. Recycling standards are developed within the committee IEC TC111. A new technical report IEC/TR 62635 Ed1.0: "Guidelines for End-of-Life information provision from manufacturers and recyclers, and for recyclability rate calculation of Electrical and Electronic Equipment", aims for better and higher quality of recycled materials. EFRA cooperated with REWARD, a project in the ECO-INNOVATION program of FP7, with partners Recycling Consult, Coolrec/PHB and BRGM. Due to higher external fire safety requirements for TV housings in Europe, more FR-plastics need to be recycled following the recast of the WEEE directive. As a consequence WEEE plastics need to be processed by mechanical recycling instead of energy recovery. The EFRA and REWARD study describe composition, characterization, identification, size reduction and separation techniques. This article provides guidance to achieve the required plastic qualities and its limitations due to separation constraints and miscibility problems of the different plastics. A separation route on paper is developed for plastics from back covers of LCDs. It is found that a combination of mild size reduction, density separation and sensor based sorting gives the best results. Fractions are tested for their miscibility with virgin plastics by producers. The findings are of importance since presently solutions for FR-plastic separation are hardly offered.

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1. Introduction

EFRA combines leading companies that manufacture and market FRs in Europe [1, 2]. EFRA activities are committed to improve the level of fire safety. EFRA is a Sector Group of Cefic, the European Chemical Industry Council. EFRA aims to align itself with the industry it serves, and covers all types of flame retardants: substances based on bromine, chlorine, phosphorus, nitrogen and inorganic compounds. EFRA organisation is centered around four application Forums: Upholstered Furniture & Textiles (UF&T), Electrical and Electronic Devices (E&E), Building, Construction and Transportation. These Application Forums are complemented with ad-hoc working groups, addressing regulatory or substance-specific issues as they arise, as well as a Product Stewardship (PST) group. Recent examples of activities include: advocacy on the revision of the EU RoHS directive revision [3], VECAP (Voluntary Emissions Control Action Program) and studies about the End-of-Life phase of products containing FRs such as the recycling of FPDs. By bringing together the different players in the relevant value chains, the EFRA working groups allow to look for improved and sustainable fire safety solutions and to protect the public and the environment. EFRA is seeking for science based decisions from its members and from other stakeholders like regulatory bodies or NGOs, to maintain or improve the level of fire safety which is needed with current modern materials used in our day to day life. More information can be found in reference [4] or contact the authors.

Recycling Consult is a consulting company founded in 2005 specialized in recycling and energy. Its director (second author of the article) has a background in mining, mineral processing, recycling and metallurgy. He has been a consultant for Philips Mirec, the waste handling section for WEEE, for the European Aluminum Association (EAA) and for a range of recycling companies. Currently various projects are running in Europe and in the USA. REWARD [5] is a project in the Eco-Innovation program with the partners Dolphin Metals, Coolrec and Bureau de Recherche Gologiques et Minières (BRGM) in Orléans investigating smart size reduction and separation methods for WEEE. The LCD recycling project is running in cooperation with EFRA and its experts on flame retardants in plastics and the plastic manufacturers. PRIME is a similar project on LCD recycling running concurrently in Belgium but with focus on the business model disassembly including the economics.

2. RoHS and WEEE recast

The European Union has adopted legislation that establishes the framework for the management of electronic and electrical waste. The legislation has been subject to a recast or revision with a view to update and clarifies the legal provisions.

2.1 RoHS recast

In order to avoid the uncontrolled or diffused release into the environment of dangerous substances during recycling, the European Union adopted the directive on the restriction of certain hazardous substances in electrical and electronic equipment, better known as the RoHS Directive. The RoHS Directive restricts the use of lead, mercury, cadmium, hexavalent chromium, PBBs, and PBDEs in electronic and electrical equipment. The revised RoHS Directive was adopted on June 8, 2011 and it repeals the original RoHS Directive which has regulated hazardous substances in electrical and electronic equipment since June 2006. No changes were made to the list of restricted substances, so that substances used in electrical and electronic equipment today, such as brominated flame retardants, can continue to be used.

The revised RoHS introduces a methodology for substance restrictions and opens the scope now covering all electrical and electronic equipment except for equipment that is specifically excluded.

The European Commission is currently working with Member States to develop implementation guidelines and a methodology for restricting substances. The Commission has indicated that HexaBromoCycloDodecane (HBCD) (minor used in Polystyrene for making for example electrical switch boxes) will be one of the substances that will be evaluated first under this methodology. A link to the Commission website on RoHS can be found in reference [3].

2.2 WEEE recast

The directive on the waste of electrical and electronic equipment (WEEE directive) aims to prevent the production and disposal of WEEE through reuse and recycling targets. Moreover, it is set up to improve the environmental performance of all operators involved in the life cycle of electrical and electronic equipment.

The WEEE requires Member States to ensure that producer-financed systems are set up to separately collect, treat, recover and dispose of WEEE.

In June 2012 the revised WEEE directive was adopted. Under the new directive, member states must collect annually 45 % of the average weight of electrical and electronic equipment placed on their national markets four years after its entry into force.

Three years later, member states are to achieve a 65 % collection rate. Some EU states where consumers use fewer electronic devices may achieve the targets with some flexibility. In 2010 plastics from WEEE were recycled around 13 % as communicated by Plastics Europe. Moreover, the directive establishes the producer responsibility, as a means of encouraging design and production of EEE which take into full account and facilitate its repair, up-grading, re-use, disassembly and recycling. A link to the Commission website on WEEE can be found in reference [6].

2.3 Recycling standards

A recycling standard is approved within the global International Electrotechnical Commission (IEC) TC111 in the form of a technical report (TR) IEC/TR 62635 Ed. 1.0: Guidelines for End of Life information provision from manufacturers and recyclers, and for recyclability rate calculation of Electrical and Electronic Equipment. It is important that for plastics recycling standards are produced because the plastics recycling will become more trustfully and can produce higher qualities of plastics for higher end applications which is difficult to do today.

3. Recycling plastics from LCDs

The cooperation between EFRA and REWARD has resulted into a joint project which started in 2011 to investigate and define the plastic composition in flat panel displays and present solutions for mechanical recycling with best available technology (BAT).

Due to higher fire safety requirements for TV set housings sold in the EU, they need to be made out of materials such as plastics containing FRs in addition to the WEEE Directive recast imposing higher recycling rates. Therefore WEEE plastics need to be separated with mechanical recycling techniques as opposed to energy recovery. It is the intention of the EFRA recycling study for plastics containing flame retardants from LCDs to give guidance on achieving the desired results and to communicate possible limitations.

In order to set up a scheme for size reduction and separation a comprehensive data collection is organized comprising the brands of FPDs, serial numbers, weight and diameter of a full LCD, colour and density of the back cover plastics, a NIR and XRF scan of the back cover plastic to determine type and FR presence, for black plastics a FTIR scan, this from different equipment suppliers with various libraries (Table 3). The information is matched with information from original equipment suppliers and plastic manufacturers. Additional information is used in the study from the concurrently running project PRIME.

3.1 Main issues and challenges for plastics recycling

The main issues today in plastics recycling are:

- The small scale of economy of recycling facilities which is in the range of 5000 tons/yr to a maximum of 20.000 tons/yr of recycled plastics as output. Where plastics manufacturers produce in the range of 200.000–500.000 tons/yr of plastics. This is a ratio of 40–100 times more. Markets will develop better with higher end-of-life volumes.
- The complexity of mixtures and of the many different types of plastics used in WEEE. The main barrier is in the black colour combined with the lack of sorting techniques to be able to separate every plastic type into the individual plastic stream for a high end application. If techniques do exist at all, then high investments are needed compared to the relatively small yield of recyclate produced. Better sorting techniques are necessary.
- Lack of understanding on the type of plastics and flame retardants used and in various applications which quantities do they appear at the recycle facility. More analyses are needed.
- The lack of understanding of the effects of mixing of the different plastics and the consequences on the physical properties after recycling. A miscibility chart is necessary.

3.2 Current situation in Europe

FPDs are collected separately from other WEEE categories. In a total batch of 623 FPDs we found 500 LCDs, 94 laptops and 29 plasma screens. TVs are kept separate. The LCDs that are contained in this batch have mercury lamps, a RoHS substance to be kept and processed separately. A photo (Fig. 1) is showing the collected stacks of LCDs on pallets ready for transport. Selective collection is widely practiced in recycling activities, well known examples are bottle banks, paper, batteries etc. and is highly beneficial to recycling and the material recovery. The required collection procedure provides the advantage for separation options to sort the relatively less complex mix of plastics after shredding. A similar situation is found for polystyrene from selectively collected refrigerators. Another example is the separate processing of toner cartridges from printers.

Fig. 1 Selectively collected FPDs from NW-France and Flanders

Selective collection systems are beneficial to recycling and facilitate the relative clean collection of these batches of LCDs.

The LCDs are prepared for treatment, the plasma displays and TVs containing a cathode ray tube are treated separately. The pedestal and electrical cords are disconnected. Current practice consists of two principal ways of treatment: disassembly or shredding. In this par-ticular case of study the LCDs are shredded. A typical sequence is given in Table 1 with magnetic and eddy current fractions.

The plastic mix is analyzed for its contents with a lab sink and float test and the expected sink and float fractions are in Table 1. After magnetic and eddy current separation a plastic mix remains untreated. This mix currently is the subject for this study. The produced particle size distribution with a d_{50} of 45 mm is the starting point.

Table 1 Example of fraction composition after shredding LCDs

Category	Fraction (%)	Separator
Ferrous metals	27.6	1st magnet
Non-ferrous metals	11.2	eddy current
Printed circuits	15.8	2nd magnet
PS	8.0	sink/float
ABS+FR	25.9	sink/float
PP+PE	0.5	sink/float
Mercury	< 0.05	filter
Waste	11.0	bag filter
Total product	99.95	

4. Sampling LCDs including the FR-plastics

Part of the study is the analysis of a total sample of 623 FPDs taken in the area North West of France and Flanders in Belgium. This batch contains 500 LCDs, 94 laptops and 29 plasma displays. The volume of the sample is arbitrary. From each LCD a photo is taken of the front with the brand name (Table 2) and of the back with the tag numbers. A material sample is taken from the back cover for type analyses and material density. A list of the collected data is composed consisting of brand, diagonal width, weight of full LCD, density and plastic type of back cover plastic and additive (FR based on bromine, Br, or phosphor, P). Relations between brands and other features are documented. Information from plastic producers and original equipment manufacturers (OEMs) is collected; the data is used for cross checking and control.

5. Measurements

Some LCD's are examined for their full composition in plastics, metals, printed circuits and other components and materials. A typical composition is given by Salhofer [7].

The sample of 500 LCD back covers is analyzed with a focus on its separation after granulation. The physical properties like density, plastic type, and additives are determined. The density is determined with an air pycnometer. Plastic types are determined with a NIR device. Black plastic types are determined with an FTIR device [8]. Different plastic library scans are used. It appears that analytical equipment such as NIR and FTIR have to be stored with the known plastics examined in order to give the device a closer range of recognition; however, this is not always possible as complete libraries are not always available. The additive Br-FR is determined with a calibrated XRF device but sometimes also found via FTIR or NIR. Other additives such as phosphor sometimes are determined with NIR and FTIR depending on their libraries contained. Different analytical laboratories and companies are involved in the analyses making cross control possible.

From these collected data a strategy for separation is determined. A description of how to analyze WEEE with a focus on shredding and separation is given in Menad [9].

It appears that manufacturers have produced LCDs with certain preferred plastics and additives for the back covers. These data are helpful in the full interpretation of the 500 LCD sample. For the LCD back cover the brands Grandin, Samsung, Toshiba and LG predominantly use high impact polystyrene (HIPS) (sometimes with Br-FR), and Philips and Sony use HIPS/PPE or PC-ABS (with P-FR). Producers of these plastics are Bayer, SABIC and Styron and they contributed to important product data generation within this project.

Table 2 Brands in descending frequency in a batch of 500 LCDs

Brand	(%)
Samsung	17.8
Philips	17.6
LG	7.6
Toshiba	5.8
Sony	4.6
Grandin	4.4
Thomson	4.2
Sharp	4.0
Funai	2.4
Sum	68.4
Other	31.6
Total	100.0

5.1 Results and interpretation

The plastics of the back covers are analyzed with FTIR, sliding spark and a pyknometer. A typical result is shown in Table 3. It depends on the library contained in the FTIR device what type of plastic is given. P and Br often are recognized. A triple check of the results gives assurance, this correlated with information given by manufacturers of LCDs and plastic producers.

The LCD brands found are listed in Table 2. In total 75 different brands are found. Samsung is the most frequent with 17.8 % and Philips is second with 17.6 % in Northern-France and Flanders. In total 9 brands have a frequency of more than 2 % with a total of 68.4 %. The other brands (66 in total) have a lower frequency than 2 % and represent a total of 31.6 %.

The weight of one full LCD varies from 1.5 kg to 46 kg (without pedestal). The density for the plastics for the back cover range from 1.03 g/cm^3 to 1.25 g/cm^3. Sorting the excel list of 500 back cover samples to density results in a split or separation in HIPS-PPE and PC-ABS with phosphor FRs. Both fractions of HIPS and ABS can contain brominated FRs.

Further sorting into brominated and non-brominated plastics results in an almost perfect split in HIPS (no Br-FR), HIPS (with Br-FR) and PC-ABS (with or without P-FR). Due to analytical reasons with the FTIR so far no guaranteed HIPS/PPE differentiating from HIPS could be defined. This offers the possibility to set a scheme of sorting starting either with density or with XRF sensor sorting. The latter with the advantage of creating a batch of HIPS with Br-FR. Density sorting after that gives the split in HIPS (no Br-FR) and PC-ABS. The HIPS-PPE with P ends in the lower density range.

The basic mixture of plastics consists of 2 types: HIPS (w/o Br-FR), PC-ABS (w/o Br-FR). Other plastics found are in one brand ABS/PMMA plus PMMA from the front panel (seems not evident), ABS, SAN, HIPS/PPE and variations of HIPS and PC-ABS. NIR sorting can be used to scalp coloured plastic contaminants in one step prior to further sorting. However, colours are mostly black (444, i. e., > 93 %), other colours (32, i. e., < 7 %) found are white, blue and grey. NIR sensor sorting has the disadvantage of detecting only coloured plastics; black plastics can be recognized, this is depending on the soot level. Recent developments are promising for the fast and automatic detection of black plastics with SWIR (Short Wave Infra-Red). Presently a project is running by RTT, EVK and Pyral [11] in the Eco-Innovation program of EACI.

The approach of separation therefore is twofold based on the properties density and additives. The sequence XRF (for the HIPS with Br-FR – blue in Fig. 2) followed by density as second separation gives the fractions PC-ABS and HIPS (w/o Br-FR). Separations are never perfect. Imperfections are the cross contamination of other plastics in either fraction. Nevertheless density separation tests show a good separation between HIPS and PC-ABS for the back covers.

Table 3 Extract of table of 500 LCD back covers. The columns give the brand name, sample nr, density (g/cm^3), Br content (nd = not detected), P content, FTIR lab 1, FTIR lab 2, conclusion authors, lab 3 (sliding spark) and the last column with the measured P content in ppm.

Bluesky	324	1.204	nd	P	Polycarbonaat/Triphenylphosphate (80/20)	PC/ABS	PC/ABS	PC/ABS	10000
Philips	329	1.199	nd	P	Polycarbonaat/Triphenylphosphate (80/20)	PS	?	PC/ABS	10000
Philips	338	1.197	nd	P	Polycarbonaat/Triphenylphosphate (80/20)	PC	PC/ABS	PC/ABS	6000
Sony	367	1.100	nd	P	PPO (possibly with PS)	HIPS	HIPS	PC/ABS	7000
Grundig	368	1.217	nd	P	Polycarbonaat/Triphenylphosphate (80/20)	PC/ABS	PC/ABS	PET	8000
Sony	374	1.200	nd	P	Polycarbonaat/Triphenylphosphate (80/20)	PC/ABS	PC/ABS	PC/ABS	7000
Sony	377	1.130	nd	P	PPO (possibly with PS)	HIPS	HIPS	PC/ABS	8000
Sony	392	1.220	nd	P	Polycarbonaat/Triphenylphosphate (80/20)	PC/ABS	PC/ABS	not measured	
Philips	394	1.223	nd	P	Polycarbonaat/Triphenylphosphate (80/20)	PC/ABS	PC/ABS	not measured	

5.2 Sorting and separation

The plastic material mix from shredded LCDs contains more than the two predominant types of main plastics. This mixture needs to be classified before separation. The material typically has a particle size of 45 mm. The mixture contains beside the plastics still some metals that were missed by the magnets and eddy current. Other metals like stainless steel must be removed. Foils, dust, printed circuits (and its plastics) and the Indium-Tin-Oxide (ITO) bearing laminate layer need to be removed. A possibility is air classification and metal detection, this can be combined with density sorting [12]. In a second step the plastics PS and PC-ABS can be separated (Fig. 2) [13]. A typical break down after density separation of an intermediate fraction is given in Table 4.

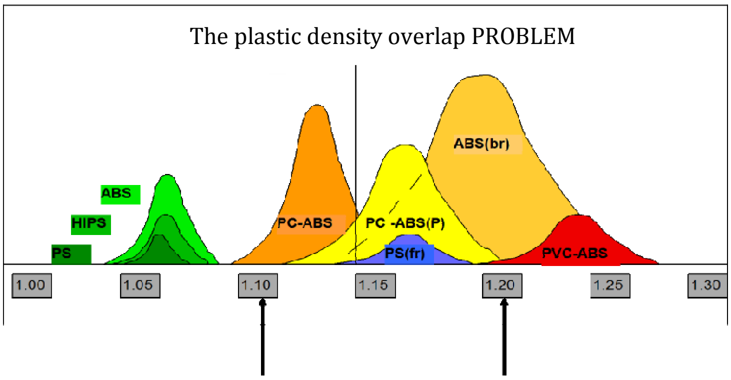


Fig. 2 Density distribution most common plastics [12]

Recent developments in electronic sorting open a range of possibilities for sorting plastics. Properties like colour, type and additive are the criteria for sorting. Even different types of wood, fibers, cartons like tetrapack and some brominated plastics are recognized. Combined with traditional sorting techniques as sink-float, electrostatic and others, acceptable grades can be produced.

For this study separation tests have been performed with a selected batch of black particles from back covers with known properties with an XRF sensor separator. Results are shown in Fig. 3. NIR sorting on coloured plastics provides information of the full composition of the input mix (Table 6). The separator offers different options for sorting whether to sort 1 polymer in 1 run, or 2 different polymers in 1 run. The preset library recognizes qualitatively the full content of the input mix, thus offering the option for control and sampling.

Systems are implemented, e. g., at the Veolia plant in Angers (F). Applications are also possible to separate a group of 2 or more foreign polymers from the targeted HIPS and PC-ABS in one step (scalping). One run through the separator often is not sufficient for the full recovery of one type of plastic. More runs are necessary until the targeted type is fully depleted and the separator is switched to the next type. The strategy is to reach for a high grade of the targeted plastic and increase recovery in successive runs. The composition is measured with each run, the first type is for the most abundant, via a decision algorithm the separator switches to the next type.

Table 4 Typical separation with density salts

LCD plastic fraction	Density (g/l)		(%)
Fraction	1030	1170	24.0
Fraction	1170	1350	40.6
Fraction	+1350		9.4
Dust			2.5
Float			6.7
Screen – 1 mm			16.9
Total			100.0

Fig. 3 Separation of black plastics labeled red (bromine) and white (no bromine) with XRT sensor based sorting

Table 5 Performance X-Ray sensor sorter (wt %)

XRF Sensor	Accept	Reject	Input
Brominated	2.2	86.7	16.5
Non - Br	97.8	13.3	83.5
Recovery Br	11.0	89.0	100.0
Rec Non - Br	97.3	2.7	100.0
Balance	83.0	17.0	100.0

A test run was made with a XRF sorter. Black plastic particles are labeled brominated and non-brominated. The results of the separation are in Table 5 and represent the number of particles in the accepted and rejected fraction. The threshold in this case is 1 % Br in plastic.

The collection of data offers a strategy for separation. It appears from analyses that HIPS can be either brominated or not and PC-ABS contains phosphor offering a perfect set for separation.

The additives Br and P are separated preferably; cross contamination is a disadvantage for granulation and re-moulding. The sequence is determined partly by economic requirements.

Table 6 Input arbitrary plastic mix NIR sorter (Courtesy RTT-Zittau)

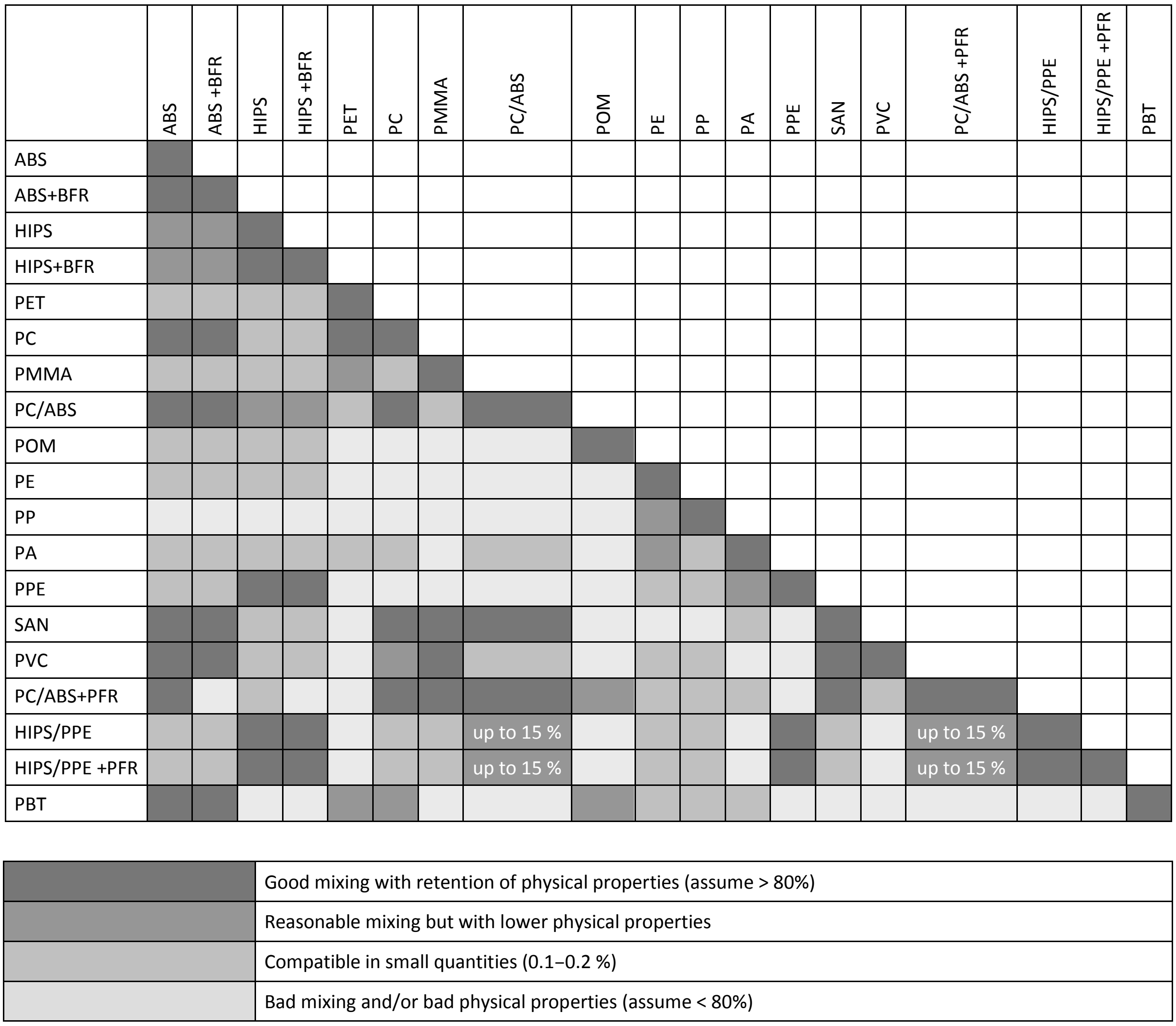
Type	Counts	(%)
ABS	52246	65.15
PA	129	0.16
PBT	39	0.05
PC	276	0.34
PE	142	0.18
PET	308	0.38
PMMA	66	0.08
POM	277	0.35
PP	66	0.08
HIPS	10080	12.57
PC+ABS	15159	18.90
PVC	161	0.20
PUR	1	0.00
PPE+SB	1144	1.43
PVC+ABS	51	0.06
TETRA	34	0.04
PAPER	20	0.02
Total	80199	100.0

5.3 Final grades and miscibility

Fractions of produced plastics from separation tests and from disassembly can be tested for their grade, physical properties and applicability in new products. The tests show good results for the final quality of pre-sorted, re-granulated and re-moulded disassembled back covers [14].

Since mechanical separations are never perfect the produced fractions of plastics do not have the optimal grade that virgin plastics have. Therefore they are mixed with virgin in low ratio's to dilute the recycled plastic and to dilute the contaminant in the recycled plastic. The authors have developed a miscibility preference scheme for mixing. An example is given in Fig. 4.

In recycling practice it is often useful to analyze the composition of the fractions produced in order to establish a chart of grades and recoveries for each material. Products show cross contamination of materials or so called false positives. A separator is never perfect and fractions therefore show impurities. These impurities are allowed to a certain level which differs for each material. For plastics the level of impurity is low, some impurities are allowed some are not. A separation scheme is developed that addressed these requirements. Optimal grades are achieved at the cost of recovery and a high recovery is reached at the cost of quality (Fig. 5). In order to improve both quality (grade) and recovery (less losses) endless separations have to be performed generating high costs. It is clear that an optimum of pro-cessing depth and costs is to be respected.



	ABS	ABS +BFR	HIPS	HIPS +BFR	PET	PC	PMMA	PC/ABS	POM	PE	PP	PA	PPE	SAN	PVC	PC/ABS +PFR	HIPS/PPE	HIPS/PPE +PFR	PBT
ABS	█																		
ABS+BFR	█	█																	
HIPS	▓	▓	█																
HIPS+BFR	▓	▓	█	█															
PET	▒	▒	▒	▒	█														
PC	█	█	▒	▒	█	█													
PMMA	▒	▒	▒	▒	▓	▒	█												
PC/ABS	█	█	▓	▓	▒	█	▒	█											
POM	▒	▒	▒	▒	░	░	░	░	█										
PE	▒	▒	▒	▒	░	░	░	░	░	█									
PP	░	░	░	░	░	░	░	░	░	▓	█								
PA	▒	▒	▒	▒	▒	▒	░	▒	░	▓	▒	█							
PPE	▒	▒	█	█	░	░	░	░	░	▒	▒	▓	█						
SAN	█	█	▒	▒	░	█	█	█	░	░	░	▒	░	█					
PVC	█	█	▒	▒	░	▓	█	▒	░	▒	▒	░	░	█	█				
PC/ABS+PFR	█	░	▒	░	░	█	█	█	▓	▒	▒	▒	░	█	▒	█			
HIPS/PPE	▒	▒	█	█	░	▒	▒	▓ up to 15 %	░	▒	▒	░	█	▒	░	▓ up to 15 %	█		
HIPS/PPE +PFR	▒	▒	█	█	░	▒	▒	▓ up to 15 %	░	▒	▒	░	█	▒	░	▓ up to 15 %	█	█	
PBT	█	█	░	░	▓	▓	░	░	▓	▒	▒	▒	░	░	░	░	░	░	█

█	Good mixing with retention of physical properties (assume > 80%)
▓	Reasonable mixing but with lower physical properties
▒	Compatible in small quantities (0.1–0.2 %)
░	Bad mixing and/or bad physical properties (assume < 80%)

Fig. 4 Example of a miscibility chart for common plastics

The miscibility chart (Fig. 4) shows the influence of small quantities of plastics of semi-pure separated batches into virgin stock. For recycled plastic material after shredding and separation the procedure is to mix it with virgin plastics at a ratio of, e. g., 90 % to 10 %, causing the simultaneous dilution of contaminants from assumed 1 % to 0.1 %. The miscibility chart shows that most of the plastics with their contaminants in LCDs are in the yellow or orange range and not harmful to final quality. Additional testing is planned to define the real quality in the range of 1-3 and 10 % contamination of the different plastics (Fig. 6).

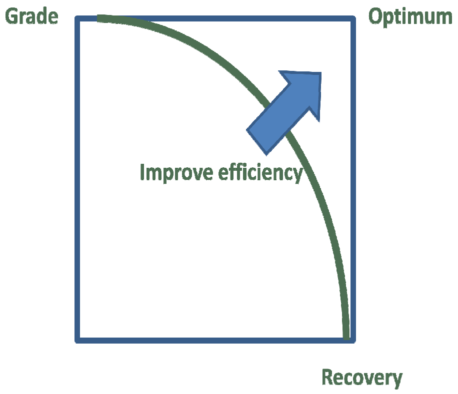
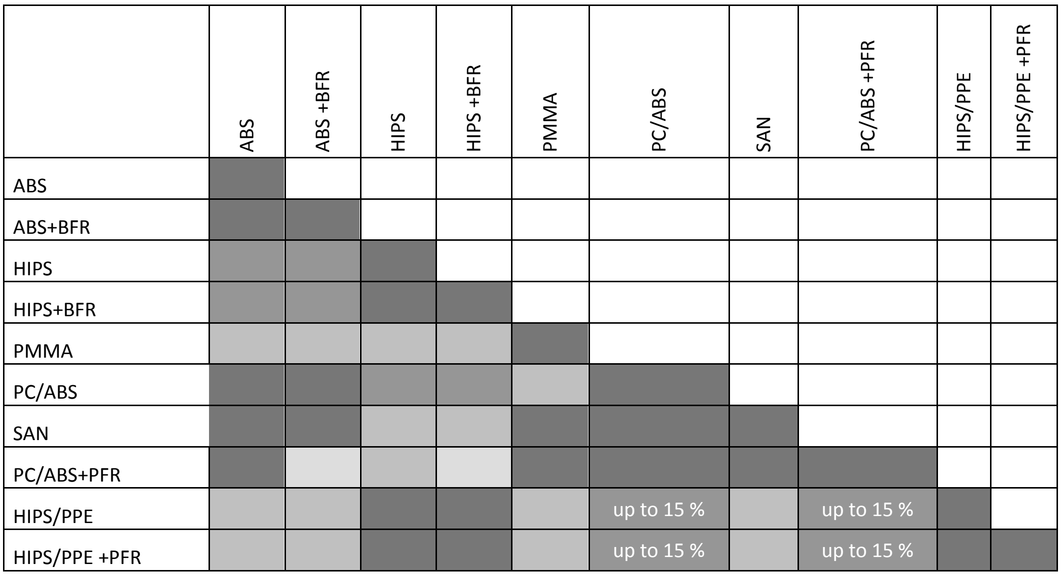


Fig. 5 Relationship of grade and recovery in separation processes



	ABS	ABS +BFR	HIPS	HIPS +BFR	PMMA	PC/ABS	SAN	PC/ABS +PFR	HIPS/PPE	HIPS/PPE +PFR
ABS	█									
ABS+BFR	█	█								
HIPS	▓	▓	█							
HIPS+BFR	▓	▓	█	█						
PMMA	▒	▒	▒	▒	█					
PC/ABS	█	█	▓	▓	▒	█				
SAN	█	█	▒	▒	█	█	█			
PC/ABS+PFR	█	░	▒	░	█	█	█	█		
HIPS/PPE	▒	▒	█	█	▒	▓ up to 15 %	▒	▓ up to 15 %	█	
HIPS/PPE +PFR	▒	▒	█	█	▒	▓ up to 15 %	▒	▓ up to 15 %	█	█

Fig. 6 Miscibility chart of polymers of this study

6. Conclusion

Currently the total volume of plastic recycling from WEEE is still very low. Recyclers are faced with issues such as scale of economy, the lack of identification and sorting techniques and the lack of information of the used plastics and FRs. Mixing virgin plastics with recycled fractions has a risk; contaminants with inferior mixing properties are introduced. A mixing chart is introduced that provides an indication of the level of risk.

Selective collection of FPDs is required because of the mercury content of the LCDs. This inherent disadvantage, however, is beneficial to the separation of the plastics after shredding. The produced mix is less complex than would have been the case with mixed WEEE as input. A similar case is found with the processing of fridges.

Due to the WEEE recast currently higher recycle rates are required with the consequence that plastics need to be recycled at a higher rate with better grades as is done today.

The study of characterizing and defining the main properties of plastics and the presence of FRs within the 500 LCD back covers is a first step in the setting up of an on paper scheme for further mechanical recycling. The list of 500 back covers shows that separation between HIPS and PC-ABS is possible with a combination of type/additive and density sorting, how-ever, the shredding of a complete LCD set results in a mixture of plastics with more different types that needs more processing steps.

The main plastics: HIPS, ABS (w/o Br-FR), PC/ABS and HIPS/PPE (with P-FR) found in the back covers can be recycled if disassembled and processed separately [14]. However, this is a costly process. The study presented here has searched for a full mechanical solution.

Depending on the quality of the identification and separation techniques it is believed to be possible to obtain acceptable grades that prove the recyclability of the different individual plastic types. Additional work to define the real quality after recycling and the limitations due to lower physical properties is required and planned.

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References

[1] Imai, T., Hamm, S., Rothenbacher, K.P. (2003). Comparison of the recyclability of flame retarded plastics, *Environmental Science & Technology*, Vol. 37, No. 3, 652-657.

[2] Eldik, R. (1999). Report by University of Erlangen, Institute for Inorganic Chemistry, University of Erlangen.

[3] The European parliament and the council of the EU, Directive 2011/65/EU, from *http://eurlex.europa.eu*, accessed June 10, 2012.

[4] European Flame Retardants Association, from *http://www.flameretardants.eu*, accessed June 1, 2012.

[5] REWARD. Recovery of electronic waste through advanced recycling and demonstration, A three year project in the Eco-Innovation Program of EACI, Brussels, from *http://www.reward-weee.eu*, accessed June 1, 2012.

[6] European commission, from *http://ec.europa.eu/atoz_en.htm*, accessed June 10, 2012.

[7] Salhofer, S., Spitzbart, M., Maurer, K. (2011). Recycling of LCD screens in Europe – State of the art and challenges, In: *Proceedings of 18th CIRP International Conference on Life Cycle Engineering – Globalized Solutions for Sustainability in Manufacturing*, Technische Universität Braunschweig, Braunschweig, 454-458.

[8] Zachmann, G. (1997). Rapid characterization of black plastics by MID infrared reflectance spectroscopy, In: Barrage, A., Edelmann, X. (eds.), *R'97 Recovery Recycling Reintegration, Vol III, Mechanical Processes Separation Technologies, Logistic Networks*.

[9] Menad, N., Guignot, S., Van Houwelingen, J.A. (2012). New Characterization method of electrical and electronic equipment wastes (WEEE), *Waste Management*, Vol. 33, No. 3, 706-713.

[10] Peeters, J.R., Vanegas, P., Devoldere, T., Dewulf, W., Duflou, J.R. (2013). Product clustering for closed loop recycling of flame retardant plastics: A case study for flat screen TVs, In: *Proceeding of 20th CIRP International Conference on Life Cycle Engineering*, Singapore.

[11] EACI (2007-2013). Bringing dark plastics to light, Boosting green business, from *http://ec.europa.eu/environment/eco-innovation/files/docs/publi/eaci_brochure_eco_innovation_a4_lr_en.pdf*, 16, accessed July 1, 2013.

[12] Morrish, L., Morton, R., Myles, N. (2009). Flat panel display recycling technologies, TITECH FPD Sorting Trial, WRAP MDD014 – Trial Report, July 2009, Axion Consulting, from *http://www.wrap.org.uk*, accessed June 10, 2012.

[13] Kobler, R., Foss, H. (2004). Successful recovery of end of life electronics plastics using RPIs skin flotation technology, GPEC 2004 Paper Abstract #32.

[14] Vanegas, P., Peeters, J.R., Devoldere, T., Cattrysse, D., Duflou, J.R. (2012). Closed loop recycling of Philips TV housing plastics, In: *Proceedings of i-SUP 2012 International Conference – Innovation for Sustainable Production*, Bruges, Belgium.