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Final report

Demonstration of Flat Panel Display recycling technologies

Final report on the demonstration trials into Flat Panel Display recycling technologies

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Front cover photography: Collection of desktop monitor flat panel displays

Executive summary

In the past decade Flat Panel Displays (FPDs) have become the market leading design of visual monitor screens in both television and IT applications. Currently in the UK and Europe there is no automated commercial process available which can recycle end of life FPDs safely, economically and at high volume to European waste treatment standards. It is anticipated in the next few years that the number of FPDs arising in the waste stream will increase dramatically and therefore a suitable recycling process is required to deal with the units.

This demonstration project considered four types of FPDs:

- Liquid Crystal Display Televisions (LCD TVs).
- Desktop monitors.
- Laptop computer screens.
- Plasma Televisions.

The first three types of FPDs require separate, internal lighting sources to illuminate the liquid crystal flat screens from behind. The most common source of these 'backlights' are cold compact fluorescent lamps (CCFL) which contain mercury. As a result of the use of CCFLs and the amount of mercury they contain, end of life FPDs are classified as hazardous by the European Waste Catalogue (EWC), refer to Appendix 1 for further details on Environment Agency guidance. Therefore disposal to non-hazardous landfill is not an option and a treatment process to remove the hazardous mercury is required. Plasma televisions are also considered within this project as there are not easily distinguishable from the other three.

The overall aim of this project was to demonstrate a technically and commercially viable recycling process for FPDs based on existing available technology and treatment techniques.

Four demonstration trials were conducted as part of the project:

- manual disassembly of the FPDs at Bruce Metals (UK);
- shredding of the FPDs at Erdwich (Germany);
- optical sorting of the shredded FPDs with TITECH (Germany); and
- mercury decontamination with Mercury Recycling (UK).

The aim of the manual disassembly trial was to remove the hazardous mercury backlights from the LCD TVs, desktop monitors and laptop screens and was successful. Care was taken during the removal process to limit the number of breakages of backlights. A number of units from each FPD category were also fully stripped down to component level in order to collect data about the material composition. Observation of the manual process also enabled an evaluation of potential operator exposure hazards to be carried out. The categories of FPDs were kept separate during this trial and the subsequent trials.

Additional data about the units including weight, age, make, model and ease of disassembly was collected during the disassembly process. From the units which were fully disassembled, a mass balance for the different components was obtained. There were clear variations between the different FPD categories. The easiest category to disassemble was the laptops, whilst the hardest were the plasma TVs.

Removal of the backlights rendered the FPD units safe for shredding. The shredding trial size reduced the material to approximately 40mm. After shredding, each category of FPD was split into two batches; one fraction was sent to TITECH and the other to Mercury Recycling.

The shredding trial at Erdwich went according to plan and all of the units were successfully shredded. Full analysis of the shredded material was completed to assess the particle size distribution of the shred, degree of liberation between materials and composition of the shred.

The aim of the TITECH trial was to separate the shredded FPDs into the various material categories present. This was successful and the main materials identified were metal (ferrous, non-ferrous, circuit boards), plastics (polystyrene (PS), acrylonitrile butadiene styrene (ABS) and polycarbonate (PC)), glass/film composites and thin plastic films. The liquid crystal display (LCD) panels consisted of glass, films and the liquid crystals. The LCD panel is the main fraction for which there was no existing sorting technique. A solution was found with the TITECH x-tract machine, which uses x-ray signals to identify different materials and produce a separation. The results from the trial using this method were very promising.

The mercury decontamination trial took the removed backlights from the manual disassembly trial and re-associated them in the correct proportions with the shredded FPD. The trial was able to safely simulate the envisaged full-scale commercial process, where whole FPDs would be shredded in an enclosed environment designed for full containment of the mercury hazard prior to feeding into a bulk washing process.

Samples of the mercury contaminated and washed shred were taken and analysed. The results of this analysis were inconclusive and did not demonstrate that the shredded FPDs could be washed clean of mercury using this process. The lack of clarity about the location of the mercury before and after the washing trial led to a small scale laboratory trial, to closely monitor and trace the mercury through the washing process.

The results from the laboratory trial were also inconclusive. The results showed that using water to wash the mercury contaminated material was not a suitable approach, as the majority of the mercury was not removed by the washing process. The use of Aqua Regia, a very strong acid, removed more mercury compared to the water washing results. However, even with Aqua Regia only 56% of the mercury added to the shredded material was accounted for in the output fractions.

The main conclusion from the mercury decontamination trial is that further work is required to determine a suitable washing medium which recovers the mercury whilst also being safe, economic and suitable for use at a commercial scale.

Based on the combined results of the four individual demonstration trials, a process plant layout for the recycling of FPDs has been proposed. It is acknowledged that within this there would be a requirement for either manual removal of the backlights should an automated solution not be found or a mercury removal process. Additional research is being delivered to better understand this process. Assuming that mercury can be successfully washed from the shred, a plant layout is proposed and financially modelled. The plant is designed to take whole FPD units and shred them safely without manual removal of the backlights. In order for this to be possible, the shredder has to be adequately enclosed and fitted with appropriate extraction and containment systems. The output shredded material is then fed directly into a mercury washing process. Once complete removal of any mercury contamination has been established, the clean shredded particles are passed through an automated sorting and separation system to produce high purity product fractions.

An FPD recycling plant would consist of:

- 3-shaft shredder;
- 8mm flip-flop sieve to remove the fines;
- mercury washing stage to recovery the mercury;
- dryer to dry the shred prior to separation;
- air ballistic unit to remove the thin films;
- magnet to remove the ferrous metals;
- Eddy Current System (ECS) to remove the non-ferrous metals and circuit boards;
- TITECH x-tract machine to remove the glass/film composite; and
- TITECH PolySort to separate the polymers.

For the purpose of the proposed plant and financial modelling exercise it has been assumed that a suitable washing medium will be found which will not be significantly different from the economics of a plant which uses water as the washing medium.

The economics are based on a recycling plant which can process five tonnes per hour, which equates to approximately 20,000 tonnes per year. Table 1 shows the summary results from the economic assessment.

Table 1 Summary of FPD recycling plant economic assessment

Economics	Commercial scale plant 5te/hr
Project capital cost (£m)	3.8
Gate fee (£m)	2.02 (£100/te)
Product revenue (£m)	1.50
Total revenue (£m)	3.52
Operating cost (£m)	1.68
Disposal cost (£m)	0.28
Net margin (£m)	1.55
Payback (years)	2.4
10 year IRR	18%

The health and safety issues surrounding FPDs are important due to the mercury content of the backlights. The manual disassembly trial showed that backlight breakages did occur. In the scenario established for the trial, the operatives were not under significant time pressures and hence were able to work in a careful and diligent manner, reducing the number of backlight breakages. Manual disassembly at a commercial scale would result in an increase in the number of backlight breakages, and calculations indicate that the mercury levels which the operatives would be exposed to are higher than is acceptable. However, use of personal protective equipment and local extract ventilation reduces the mercury exposure risk to within acceptable levels.

Depending on the selected washing medium for the process, there may be additional risks if an acid based medium is required as opposed to water. The health and safety implications of the washing medium are difficult to assess as a suitable washing medium has not been selected at this stage and further work is required to determine one.

The overall conclusions from the project are:

- Mercury backlights can be removed manually; however at a commercial scale the process involves exposing the operatives to mercury levels which are higher than acceptable. Manual disassembly is also a slow process and therefore scale up to a commercial level would require significant man power.

- The FPDs can be shredded in a three shaft shredder which produces an output suitable for subsequent sorting.

- The sorting trial of the shredded FPDs had varying degrees of success:

    - metal removal with a TITECH finder was successful and could be used in a commercial plant. However the more likely option is the use of a magnet and an eddy current system;

    - the TITECH x-tract x-ray sorter was able to remove the glass/film composite fraction which originally formed the liquid crystal panel;

    - the NIR sorting of the plastics fraction did not produce successful results. The separation efficiencies measured during the trial were too low for use in a commercial plant. There were two main problems with the plastics fraction from the FPDs; the high quantity of black plastic which the NIR sorter cannot see and the wide range of different polymers used.

- The mercury washing trial produced unexpected results. The results from the large scale plant trial were inconclusive and the trial did not prove that the mercury contaminated shredded FPDs could be washed clean by the washing process at Mercury Recycling. The subsequent laboratory trial did not provide clear answers either. Hence, the project has been unable to conclude that the mercury from the backlights can be washed from the shredded FPDs.

The project makes the following recommendations and suggestions for further work:

- Further investigation to determine a wash medium capable of achieving acceptably high levels of mercury recovery in a commercial process and the optimum conditions for mercury removal using this medium.
- Investigation of alternative methods for mercury removal from the shred, for example heating.
- Investigation and trials to trace the location of the unaccounted for mercury.
- Investigation into the adherence relationship between mercury and plastic, to assess the ease at which mercury can be desorbed from the plastic.
- Based on selection of a suitable washing medium, reassessment of the economics and health and safety aspects of the process.

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Glossary

AATF	Approved and Authorised Treatment Facility
CFL	Compact Fluorescent Light
CRT	Cathode Ray Tubes
FPD	Flat Panel Display
LC	Liquid Crystal
LCD	Liquid Crystal Display
WEEE	Waste Electrical and Electronic Equipment
ABS	Acrylonitrile butadiene styrene
PCABS	Polycarbonate acrylonitrile butadiene styrene
PC	Polycarbonate
PMMA	Polymethyl methacrylate – 'Perspex'
PS	Polystyrene

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Active Recycling Ltd

Bruce R.I.D Recycling Ltd

Erdwich GmbH

Mercury Recycling Ltd

Scientific Analysis Laboratories (SAL Ltd)

TITECH GmbH

1.0 Introduction

1.1 Background to the project

In 2008 WRAP commissioned research into the recycling of Flat Panel Displays (FPDs) in the UK to identify the commercial technology and processes currently being used to recycling them. It was concluded that no commercial recycling routes for FPDs were in existence at the time presenting an opportunity to address this.

The project identified that there was an appropriate reuse market and that the volumes of FPDs arriving in the waste stream were relatively low. The combination of these two factors was delaying any urgency in developing a processing solution for recycling end of life FPDs. Currently recycling of FPDs is occurring on a small scale, with recyclers mainly conducting manual disassembly in order to remove the hazardous components.

FPDs sales are increasing, with 2007 seeing sales of liquid crystal display televisions (LCD TVs) outstrip conventional cathode ray tube (CRTs) displays for the first time[1]. Therefore, it is anticipated that in the next three to five years the number of FPDs in the waste stream will noticeably increase and hence a commercially viable recycling process will be necessary.

There are four types of FPDs discussed in this report:

- Liquid Crystal Display (LCD) TVs.
- Desktop monitors.
- Laptop computer screens.
- Plasma TVs.

The first three types of FPDs require external lighting sources to illuminate the screens. The most common lighting source is cold compact fluorescent lamps (CCFL) which contain mercury. As a result of the use of CCFLs in FPDs, end of life FPDs are classified as hazardous by the European Waste Catalogue[2] (EWC), refer to Appendix 1 for further information. Therefore disposal to landfill is not an option for this waste stream and a treatment process to remove the hazardous mercury is required.

1.2 Aims and objectives of the project

The original aim of the project was to demonstrate technically and commercially feasible technology for the recycling of FPD units in the UK. The specific objectives of the project were:

- to identify a suitable existing technology or technologies for the disassembly and recycling of FPD units;
- to deliver a demonstration trial or trials of the chosen technology; and
- to make an assessment of the financial and commercial viability of the technology and compare this to the manual disassembly process.

The technology selected had to have the potential to be commercialised at full-scale, whilst being able to adequately manage the risks associated with the hazardous components (mercury backlights) in the FPDs and meet the requirements of the current WEEE legislation. Demonstration that the reprocessed material products had a value which off-set the cost of the commercial process was necessary.

However, during the course of the work it became apparent that further work was required in order to understand and demonstrate with confidence the mercury removal from the shred.

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[1] *http://www.tgdaily.com/content/view/36119/118/*

[2] *EWC entry for FPDs with mercury containing backlights is 16 02 13* discarded equipment containing hazardous components other than those mentioned in 16 02 09 to 16 02 12. See appendix 1 for further details.*

1.3 Project partners

Axion worked with a number of project partners to deliver the demonstration trials. Project partners were chosen for their knowledge, experience and leading position they have in their specialised field. Each project partner hosted one of the demonstration trials.

Bruce R.I.D Recycling Ltd is a fully licensed Approved and Authorised Treatment Facility (AATF) and process all types of commercial and industrial WEEE. They are located in Sheffield, UK and hosted the manual disassembly trial. Please refer to http://www.weee-recycler.co.uk/index.html for more information.

Erdwich Zerkleinerungssysteme (Shredding systems) GmbH is located near Munich in southern Germany. They have experience in the shredding industry and their shredders have been used in various recycling applications including fridge reprocessing plants. Erdwich hosted the shredding trial. Please refer to http://www.erdwich.eu/index_en.php for more information.

TITECH GmbH has various locations around the world, with two test facilities in Germany. They are a provider of sensor based sorting systems. Applications of TITECH sorters include recycling of WEEE, end of life vehicles, plastic bottles and packaging. Axion worked with TITECH for the optical sorting trial. Please refer to http://www.TITECH.com/ for more information.

Mercury Recycling Ltd has expertise in the recycling of mercury containing light bulbs and fluorescent tubes, with a processing plant located at Trafford Park, Manchester, UK. One aspect of their involvement was to utilise their specialist knowledge in the processing of mercury containing items and the associated risks. In addition to this one of the demonstration trials was conducted at their processing plant. Please refer to http://www.mercuryrecycling.co.uk/ for more information.

In addition to these project partners, Axion also worked with Active Recycling Ltd at the beginning of this project. Active Recycling is involved in several research projects into the recycling of FPD units and conduct manual disassembly activities with HM Prison Service. Active Recycling provided input and advice at the start of the project and organised sourcing the FPD units used in the demonstration trials.

2.0 Review of Flat Panel Display waste stream

An initial review of the FPD waste stream was conducted to understand the issue and to assess what types and quantity of units would typically arrive in the waste stream. Appendix 2 contains the report from this initial review, which details the assessment of FPDs in the waste stream.

As LC FPDs have replaced conventional CRT based displays in most applications in recent years, the volume of devices has continued to grow and it is predicted that this growth will continue for the foreseeable future. Sales of FPDs began overtaking CRTs in late 2007[3] and the CRT sales market is nearly none existent now, with almost all new televisions and computer monitors being FPDs. The expected life span of FPDs varies depending on the type. It has been estimated that televisions have a lifespan of approximately eight to ten years; computer monitors six years and laptops four years. LC FPD televisions have been available on the consumer market for a number of years and it is anticipated that in the next ten years the quantity of FPDs in the waste stream will steadily increase. Due to the vast numbers of CRTs televisions already in use it is thought these will still form a significant part of the waste stream for a number of years.

Independently to this project, WRAP commissioned Optimat to conduct a study to predict future waste arisings of the FPD waste stream. Table 2 and Figure 1 show the results of the Optimat study.

Table 2 Optimat FPD waste arisings data

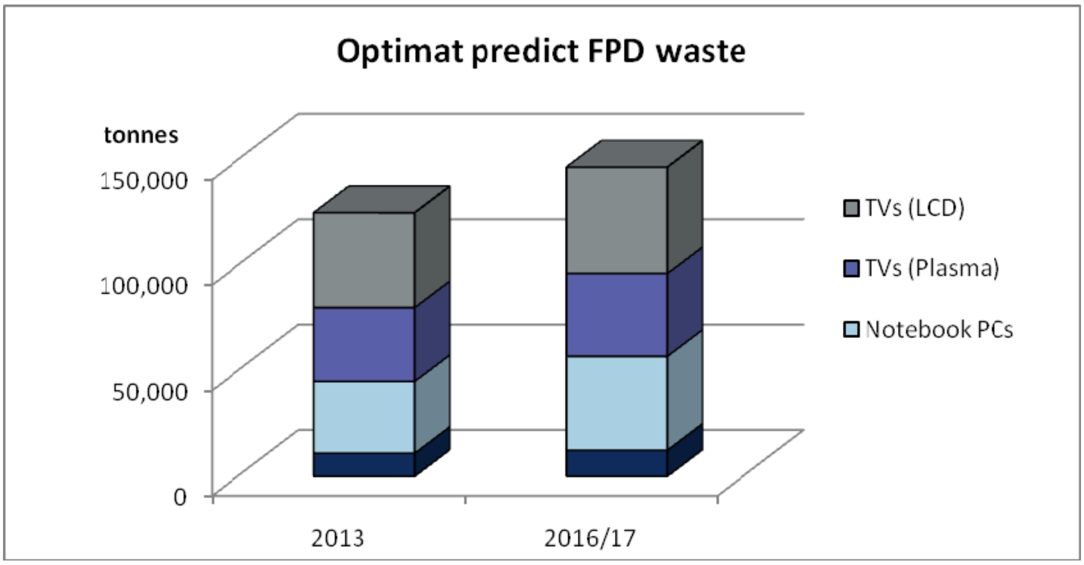
Product	**Estimated market volume (units)**		**Typical product weight (kg)**	**Product lifetime (yrs)**	**Estimated waste arisings (tonnes)**			
	2006	**2012**			**2009**	**2011**	**2013**	**2016/17**
Desktop monitors	1,095,060	1,369,083	9.00	5		**9,856**	10,866	12,322
Notebook PCs	5,820,865	10,124,525	4.00	3.4	**23,283**	28,173	34,089	44,548
TVs (Plasma)	1,000,000	1,212,121	35.00	7			**35,000**	39,242
TVs (LCD)	3,000,000	3,636,364	15.00	7			**45,000**	50,455
						Total	124,955	146,567

Notes to support Optimat calculations:

- Waste arisings data in bold are based on estimated market volumes shown in the table.
- Calculation of waste arisings in bold are based on 'market volume * item weight'.
- Notebook PC weights are for the whole item, where the display unit is only a small fraction of this amount.
- When the waste arisings occur is based on the lifetime of the product (for example monitors have an estimated five year lifetime, so 2006 sales are in the waste stream in 2011).
- Waste arisings for product in the year following those in bold are based on projected market growth data for that specific product.

[3] *http://www.tgdaily.com/business-and-law-features/36119-lcd-tvs-outship-crt-tvs-for-the-first-time*

Figure 1 Optimat predicted FPD waste



The Optimat study predicts there will be over 145,000 tonnes of FPDs in the waste stream by 2016/2017.

Waste predictions can vary significantly depending on the assumptions used in the models from different studies. The variables in the Optimat study include estimated market volumes, the typical weight per item and the average product lifetime for an item. Care should be taken to not assume the figures are firm and should be used with caution as they are only a prediction.

In addition to the above results the Environment Agency collects and collates data about the amount of EEE placed on the market and the waste arisings for all the WEEE categories.

The Category 11 of the WEEE Directive covers display equipment which includes televisions (including CRT) and computer screens. From January to June 2009 there were 65,000 tonnes of display equipment placed on the UK market, with just over 56,000 tonnes being household EEE. For the same time period nearly 60,000 tonnes of WEEE was collected in category 11.[4]

Extrapolating the data for a twelve month period gives a total amount of 120,000 tonnes. However as category 11 covers all display types, not all of the items will be FPDs. There are many CRT units still to be sent for disposal and these will be present in the display waste stream for a number of years. Taking this into account the Environment Agency data correlates reasonably well with the predictions from the Optimat study.

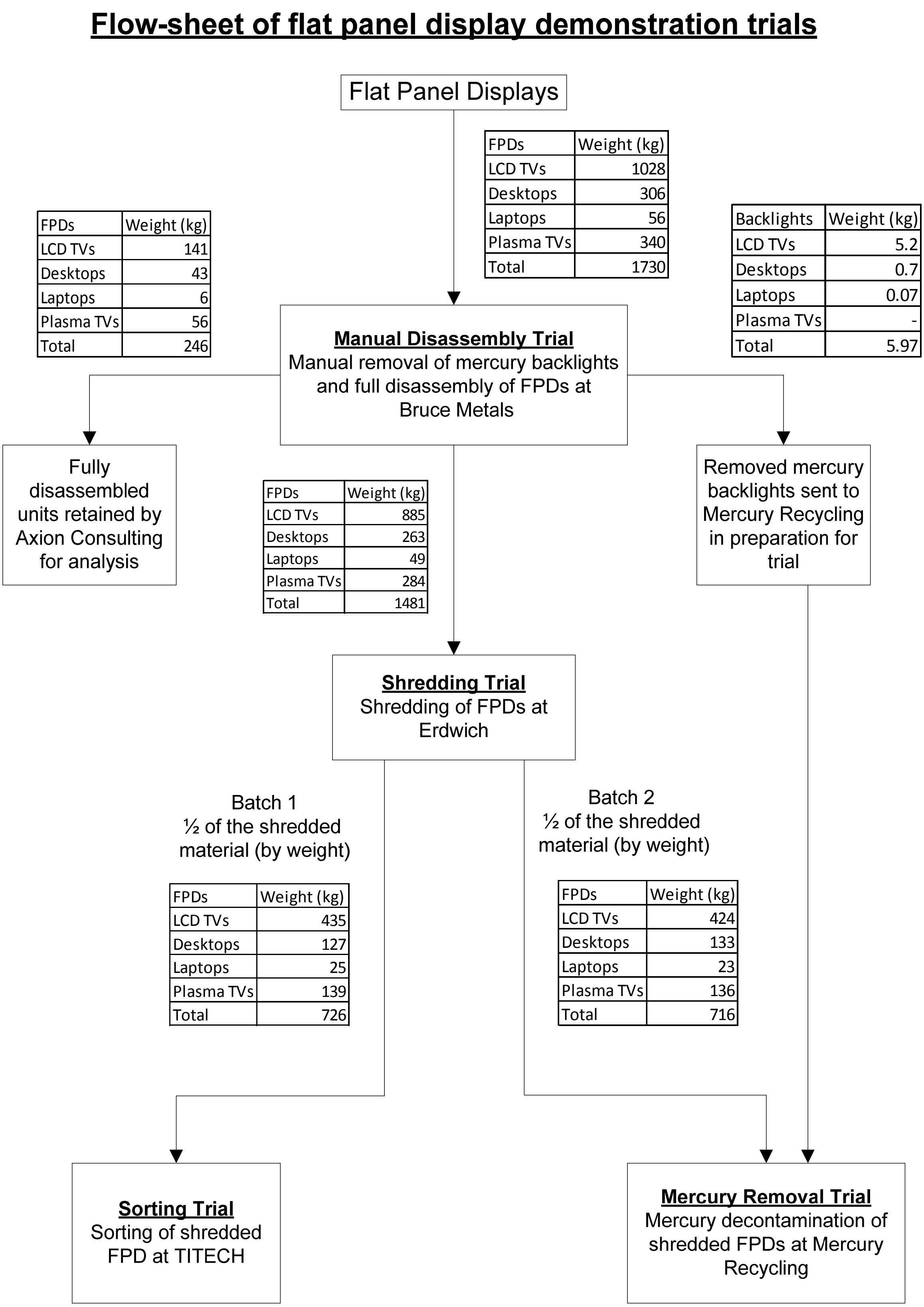
[4] *Data from the environment agency (http://www.environment-agency.gov.uk/business/topics/waste/111016.aspx)*

3.0 Demonstration trials

3.1 Overview of process stages

Axion's approach to the project was to deliver four demonstration trials which represented the complete recycling process for FPDs. Figure 2 is a process flow sheet showing the four demonstration trials.

Figure 2 Flow sheet of demonstration trials



Flat Panel Displays to Manual Disassembly Trial:

FPDs	Weight (kg)
LCD TVs	1028
Desktops	306
Laptops	56
Plasma TVs	340
Total	1730

Fully disassembled units retained by Axion Consulting for analysis:

FPDs	Weight (kg)
LCD TVs	141
Desktops	43
Laptops	6
Plasma TVs	56
Total	246

Removed mercury backlights sent to Mercury Recycling:

Backlights	Weight (kg)
LCD TVs	5.2
Desktops	0.7
Laptops	0.07
Plasma TVs	-
Total	5.97

Manual Disassembly Trial to Shredding Trial:

FPDs	Weight (kg)
LCD TVs	885
Desktops	263
Laptops	49
Plasma TVs	284
Total	1481

Batch 1:

FPDs	Weight (kg)
LCD TVs	435
Desktops	127
Laptops	25
Plasma TVs	139
Total	726

Batch 2:

FPDs	Weight (kg)
LCD TVs	424
Desktops	133
Laptops	23
Plasma TVs	136
Total	716

The first trial, held at Bruce R.I.D. Recycling, involved the manual disassembly of the FPDs. The aim of the trial was to remove all of the hazardous mercury backlights from the LCD TVs, desktop monitors and laptop screens. A number of the units from each FPD category underwent full disassembly to collect data about the materials used and composition of the units. These units were retained by Axion for further analysis.

The removed backlights were carefully packaged for shipment to Mercury Recycling for use in one of the later demonstration trials.

The FPDs, without the backlights, were shipped to Erdwich for the second trial - the shredding of the FPDs. Trial 1 allowed for the optimal shredder to be tested in an un-enclosed environment as the hazardous mercury backlights had been removed. After the shredding trial each category of FPD was split in to two batches.

One batch of each of the FPD categories was shipped to TITECH for the sorting trial. The aim of the trial was to use various TITECH machines to separate the shredded FPDs into the respective material categories.

The remaining batches of FPD material were shipped to Mercury Recycling for the mercury decontamination trial. The backlights removed during the manual disassembly trial were re-associated with the shredded FPDs. The material was processed through Mercury Recycling's contained mercury washing process, which uses the best available technology and containment for the control of mercury found in compact fluorescent lights (CFLs).

3.2 Sample material

The initial sample material for the trials was 1730kg of FPDs consisting of:

- 72 LCD TVs, 1028kg.
- 89 Desktop monitors, 306kg.
- 69 Laptop screens, 56kg.
- 12 Plasma TVs, 340kg.

The units were sourced from CCL (North) Ltd, a UK electronics recycling company.

3.3 Trial procedure

A set plan was developed and followed by Axion for each of the demonstration trials conducted. Details of the specific methodology for each individual trial are given in the relevant sections later in the report. Full trial reports can be found as appendices to this document.

The plan for each trial ensured the aims and method for the trial is clear to everyone involved. Details listed in the trial plan include:

- the time, date and duration of the trial;
- trial attendees and contact details;
- brief description of the trial equipment if possible;
- list of feed material samples;
- detailed trial methodology;
- list of samples for collection;
- planned post trial analysis; and
- forwarding address for trial products.

A risk assessment for each trial was also prepared by Axion and provided to each trial host, in advance of the trial, to ensure all parties involved were aware of the potential risks and hazards. This covered health, safety, and environmental risks.

Axion attended and managed the delivery of all of the demonstration trials to ensure that the trial plans were adhered to and observations and trial data were recorded. Any problems were noted and the presence of Axion personnel meant any arising issues could be dealt with immediately.

During the trials, samples were collected and labelled in preparation for post trial analysis. An individual report was written for each demonstration trial, which included full details of the demonstration trial, supporting photography, analytical data and conclusions about the trials overall performance and success.

3.4 Manual disassembly trial

3.4.1 Project partner

The trial host for the manual disassembly trial was Bruce R.I.D Recycling Ltd based in Sheffield, UK.

3.4.2 Trial objectives

The primary aim of the trial was to remove the hazardous mercury backlights from the FPDs in preparation of the 'safe' shredding of the whole units in the next stage of the demonstration project. Care was taken to record key data about each backlight, and then to label and store the backlights whilst incurring the minimum level of breakages.

The secondary aims of the trial were:

- to assess the risks and hazards associated with the manual disassembly method;
- to assess the time required to dismantle each type of unit in a safe manner; and
- to disassemble some of the units down to individual component level, in order to obtain a detailed mass balance for the different categories of FPD. The types of plastics used to make the component parts of the FPDs were also a particular area of interest.

3.4.3 Methodology

Initially the manual disassembly process was relatively slow, in order to develop a procedure which was both efficient and productive. Using the assumption that all units within a given category would be assembled in a similar way, the decision was made to disassembly all of the units from one FPD category at a time. This would ensure that operatives became familiar with the disassembly process for that specific category and therefore speed up the overall disassembly process.

Units were selected at random (within each FPD category) and a data sheet was completed during the dismantling process. The data sheets collected the following information:

- Name of Axion supervisor.
- Date of disassembly.
- Unique reference number for the item (T for LCD TVs, D for desktop monitors, L for laptops and P for plasma TVs, followed by a number).
- Flat panel type.
- Manufacturer name.
- Brand/model.
- Date of manufacture (or estimated age if no date stamp could be found).
- Dimensions of the unit.
- Overall unit mass.
- Start and finish time for the dismantling.
- Number of backlights, the number of broken backlights and the weight of the backlights in total.
- Separation index (a qualitative measure of how difficult/easy the unit was to dismantle).

After collecting and recording the initial data each FPD unit was labelled and passed to the operative for dismantling. Operatives used hand held tools including power drills, screwdrivers and pliers to disassemble the units and to access the backlights. After disassembly and removal of the backlights the units were re-constructed as best as possible and held in place with strong tape. It was often difficult to reassemble the units back to their original size due to the complex manner in which they were first constructed. The units were placed in labelled containers ready for shipment to Erdwich for the shredding trial. The removed backlights were counted, weighed and measured. All the backlights from an individual FPD unit were placed into a clear, labelled plastic bag and stored ready for transport to Mercury Recycling.

The start and finish time for the disassembly of each unit was recorded. Based on the time taken to dismantle a unit and from observing the difficulty the operatives had during the disassembly process, a judgement was made by the Axion supervisor into the overall difficulty of dismantling the unit. Each unit was given a value, known as the 'separation index', which has a scale of 1 to 5, where 1 meant the unit was very easy to separate and 5 meant it was very difficult to separate.

For the units which were fully stripped down, the backlights were removed in the same way as described above. The units were then separated into the individual material components and weighed. The main unit components were identified as:

- back panel casing;
- screen front surround;
- screen glass;
- screen plastic;
- screen films;
- circuit boards;
- cabling;
- ferrous metal;
- non-ferrous metal;
- backlight cover;
- backlights;
- speakers; and
- other pieces.

This additional information was added to the data sheet and the individual components were placed in clear labelled plastic bags, ready for shipment to Axion for further analysis.

3.4.4 Results and discussion

The manual disassembly trial was a success and all the FPDs went through the manual disassembly process.

Extensive data was collected from all of the FPDs including:

- evaluation of time and ease of manually disassembly;
- material/component composition of each type of FPDs; and
- backlight breakages.

Assessment of the FPDs indicated that there were three potential reasons for disposal of the units:

- unit had broken and was beyond economic repair;
- catastrophic damage to the unit; and
- unit functional but presumably no longer required by owner.

The following numbers of units, from each FPD category, were disassembled to component level:

- 11 (15%) of the LCD TVs;
- 12 (13%) of the desktop monitors;
- 8 (12%) of the laptop screens; and
- 6 (50%) of the plasma TVs.

Table 3 shows a summary of the results collected during the manual disassembly.

Table 3 Data from the manual disassembly of the FPDs

	LCD TVs	Desktop monitors	Laptop screens[5]	Plasma TVs
Weight range (kg)	8.4 - 24.0	2.1 - 6.4	0.4 - 1.4	25.5 - 35.7
Screen size range (inches)	20 - 40	13 - 19	7.75 - 15	32 - 42
Age range (years)	1 - 10	2 - 10	2 - 16	2 - 6
Number of backlights	6 - 20	1 - 5	1	-
% of backlights broken	15%	23%	35%	-
Average time for disassembly (mins)	12	9	9	35
Average separation difficulty	3.2/5	3.0/5	2.1/5	4.7/5

Unit comments

The LCD TVs and desktop monitors had a similar age range of up to ten years; over 50% of the laptop computers were over ten years old, although some were only a few years old. None of the plasma TVs were older than six years. Overall the FPDs covered a varied range of manufacturers and screen sizes.

Disassembly comments

The separation difficulty of the different units was a measure of both the time taken to disassemble an individual unit and the physical effort required. The laptop screens were the easiest FPD category to disassemble overall, followed by the desktop monitors. Both these units had similar average times of just over nine minutes for disassembly, but the desktop category scored slightly higher on the separation index. The LCD TVs took twelve minutes to disassemble on average and scored 3.2 on the separation index. By far the hardest category to separate was the plasma TVs, which took, on average, over 30 minutes to separate and scored 4.7 on the separation index.

The laptop screens and desktop monitors were fairly straightforward to re-assemble, albeit not back to the original depth. The LCD TVs and plasma TVs were harder to re-assemble. All units required taping together; they could not simply be screwed or clipped back in to place. Reassembly was required for later trials where the panel are to be shredded.

Backlights

The trial objective was achieved as all of the mercury backlights were removed from the FPD units, whether or not they were already broken upon opening the units.

[5] NB - The laptop screens were separated from the base section of the laptop computers. The base section was disposed of and only the laptop screen itself underwent manual disassembly and subsequent processing. The term 'laptop screen' refers to just the screen/FPD section whilst the term' laptop computer' refers to the whole laptop unit.

Overall across the three categories of FPDs 17% of the backlights were broken. Table 4 shows the backlight data for these categories. Due to the location of the backlights within the FPDs, the units were nearly completely disassembled before the backlights were reached. This meant it was very difficult to tell if the backlight was broken prior to disassembly commencing or during the disassembly process itself. Of the backlights which were intact upon reaching them, very few were then actually broken during the removal process.

Table 4 Backlight data for the FPD categories

FPD category	Total number of backlights	Number of backlights broken	% backlights broken
LCD TVs	1105	160	14.5%
Desktop monitors	292	66	22.6%
Laptop screens	68	24	35.3%
Total	**1465**	**250**	**17.1%**

The difference in the number of backlights in the different FPD categories was due to the different size screens. The number of backlights in the LCD TV's varied from six to 20, with the smaller screens (20 inches) having six lights and the larger screens (40 inches) requiring 20 lights. The desktops had between one and five backlights, whilst every laptop screen had just one backlight. The number of backlights directly correlates to the screen size.

The number of backlight breakages varied for the different FPD categories. The laptop screens suffered the highest number of backlight breakages, whilst the LCD TVs had the least number of breakages. Again there appears to be a correlation between the size of the unit and the number of breakages. The smaller, more delicate laptop screens suffered a higher breakage level, which was contributed to by the technique used to remove the screens from the base unit of the laptop. The more robust LCD TV units suffered fewer breakages, even taking into account the complex backlight arrays which were used in the LCD TVs.

The percentage of breakages recorded during the manual disassembly trial is thought to be much lower than would be expected in a commercial manual disassembly process. In a commercial scenario operatives are much more likely to be under time pressure and therefore less diligent and rougher with the disassembly process. This will inevitably result in a higher number of breakages of backlights.

Unit composition

A number of units were fully disassembled in order to obtain mass compositions for the different categories of FPDs. All of the fully disassembled LCD TVs, desktop monitors and laptop screens were retained by Axion for further analysis. Due to the low quantity of plasma TVs only two were retained for further analysis to ensure there was a sufficient quantity of units available for the subsequent demonstration trials.

Conducting full disassembly on a number of units allowed for a comparison of the mass composition all be it based on a small samples size, in order to identify any similarities and differences between the various categories of FPDs. The LCD TVs and desktop monitors had similar compositions and components and were assembled in a similar manner. The laptop screens had similar components but had a different mass composition to the LCD TVs and desktop monitors, along with a simpler design and construction. The plasma TVs had a very different mass composition to the other types of unit.

The main material fractions were ferrous and non-ferrous metal, circuit boards, plastic, glass including the liquid crystal section and thin film sheets.

The mercury backlights made up a tiny fraction of the overall weight of a unit. In the LCD TV category the backlights and the covers were approximately 6%. The backlights in the desktop monitors were less than 1% and in the case of the laptop screens the backlights accounted for less than 0.1% of a unit's weight.

The liquid crystal display panel itself, comprising of a glass/film composite fraction which contained the liquid crystals and a set of thin film sheets, may be of commercial interest as it contains precious materials such as indium. There is ongoing research by a consortium lead by the University of York, entitled REFLATED[6], into the recycling of liquid crystals. As of yet there are no published results available about their recycling potential.

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[6]Please see http://www.york.ac.uk/res/gcg/site/news/rushlight.html for details about the REFLATED project and http://www.york.ac.uk/chemistry/staff/academic/h-n/amatharu/ for details about the academic leading the project.

Please refer to the manual disassembly trial report in Appendix 3 for further results and findings about the FPDs.

3.4.5 Health and safety assessment

During the manual disassembly trial Axion observed and assessed the health and safety risks of the manual disassembly process.

The manual disassembly process was conducted under strict controls and the operatives were not under significant time pressures. This meant that the operatives were able to work in a careful and diligent manner and hence the number of backlights broken during the process was limited to as few as possible. The operatives carrying out the manual disassembly process wore the necessary personal protective equipment including Tyvek disposable overall, gloves and face masks. When a backlight broke the quantity of powder released was very minimal and care was taken to follow the set procedure to clean the area after the breakage.

If the manual disassembly process were to be scaled up to a commercial level, the operatives would be under significantly more pressure to disassemble the units at a faster rate than observed in the trial. This would result in many more breakages of the backlights which in turn would increase the risk of mercury exposure to the operatives. Carrying out large scale manual disassembly would put the operative at risk of long term mercury exposure and hence, from a health and safety point of view, should be avoided if possible.

3.4.6 Conclusions

The range of FPDs sourced for the disassembly trial covered various manufacturers, ages and screen sizes. However, within certain categories there did appear to be a lack of well known market leading brands. As discovered with the plasma TVs, it may be that some of the less well known brands were actually manufactured by the better known manufacturers.

The hazardous mercury backlights were removed from all of the FPDs rendering them 'safe' for further processing in subsequent stages of the demonstration trials.

A number of the FPDs were fully disassembled in order to collect mass composition data about the individual components within the different FPD units. Detailed information about the backlights was recorded including length, diameter, weight and number in each unit.

Observation of the manual disassembly process was helpful for assessing the risks and hazards associated with the process. In the scenario established for the trial, the operatives were not under significant time pressures and hence were able to work in a careful and diligent manner, reducing the number of backlight breakages. From the disassembly trial it was obvious that manual removal of the backlights is not only a time consuming process, but also a potentially hazardous one which could place operatives at risk of long term mercury exposure.

The manual disassembly trial held at Bruce Metals was a successful in preparing the material for the next stage of the project, whilst also providing detailed information about the FPDs.

3.5 Shredding trial

The aim of the shredding trial was to size reduce the FPDs down to even pieces of approximately 40-50mm, with minimum generation of fines. The particle size was chosen as it should be optimal for optical sorting.

3.5.1 Project partner

The trial host for the shredding trial was Erdwich GmbH. Axion has previously completed shredding trials with Erdwich and were confident in their technical knowledge and ability to conduct a professional trial. The three shaft shredder chosen for the trial was based on the experience and recommendation of Erdwich and its previous widespread application in commercial WEEE recycling plants.

3.5.2 Trial objectives

The objectives of the shredding trial were:

- to shred the four categories of FPDs using a three shaft shredder to square particles of approximately 40mm;
- to measure the throughput achieved by the shredder; and
- to evaluate the shredded materials in terms of the particle size distribution, the quantity of fines produced and the degree of liberation achieved between the different material components of the FPDs.

3.5.3 Methodology

The trial plan ensured that during the manual disassembly trial, care had been taken to give each FPD unit, and corresponding backlights, a unique identification number. This was to ensure the units and backlights could be traced through the series of demonstration trials, which was particularly important for the mercury washing trial so that any differences between flat panels and the ability for the mercury to be removed would be noted. In the mercury washing trial the removed backlights were to be re-associated with the shredded FPDs. Therefore it was important that only the backlights which had originally come from the specific FPDs units Mercury Recycling had were re-associated with those units. By indentifying the FPDs with individual numbers it was possible to track the FPDs through the demonstration trials.

The FPDs were shredded in the following order:

- plasma TVs;
- LCD TVs;
- desktop monitors; and
- laptop screens.

The plasma TV category was chosen to be processed first because of observations made during the manual disassembly trial in which the plasma TVs construction was found to be very solid, with a large quantity of sheet metal parts and very strong fixtures to support the heavy glass plasma screen section. The plasma TVs were considered to be the hardest and most challenging category to shred and was therefore used to test the capabilities of the shredder and to find the optimal shredder settings for the rest of the trial.

Minor set up problems at the beginning of the trial, such as power supply faults and issues with the product collection technique, were easily overcome to ensure a smooth trial was conducted.

The FPD units were removed from the shipping containers and loaded onto a forklift truck for manual feeding into the shredder. The FPDs were fed into the shredder in controlled batches to match the power demand of the shredder and ensure it was not overloaded. Representative samples of shred were taken from the collection bins for post-trial analysis by Axion. Two samples were taken from each batch of shred, giving four samples for each FPD category and 16 samples in total. Each representative sample was approximately 2kg.

Each category of FPD was shredded in two distinct batches which were not mixed at any point. This was to ensure that the unit numbers could be tracked through the demonstration trials. Table 5 shows which units were shredded in each batch. TITECH received the batch one units to carry out the separation trials, whilst Mercury Recycling received the batch two units to carry out the mercury removal trials.

Table 5 Units processed, batch weights and final destination

FPD category	Batch	Unit numbers	TITECH	Mercury Recycling	Weight (kg)
Plasma TVs	1	P2, P3, P5, P6, P7.	X		139
Plasma TVs	2	P8, P9, P10, P11, P12		X	136
LCD TVs	1	T1-T36, excluding; T22, T23, T25, T33, T36.	X		435
LCD TVs	2	T37-T71, excluding: T37, T39, T42, T44, T52, T57		X	424
Desktop monitors	1	D1-D38	X		127
Desktop monitors	2	D39-D88, excluding D67, D68, D69, D71, D72, D73, D74, D76, D77, D79, D81, D84.		X	133
Laptop screens	1	L1-L38, excluding L3, L4, L11, L14, L22, L34, L38.	X		25
Laptop screens	2	L39-L69, excluding, L69.		X	23

Post trial analysis of the samples was broken down into three elements. The first analysis was to hand sort the samples into the different materials present. This typically consisted of the following categories:

- Plastic.
- Screen plastic.
- Thin films.
- Glass and glass/film composite.
- Ferrous metal.
- Non-ferrous metal.
- Circuit boards.
- Cables and wires.
- Others.

The second analysis was a particle size distribution assessment. This involved sieving a sample into four fractions:

- +50mm oversized fraction.
- 25-50mm target particle size fraction.
- 8-25mm undersized but acceptable fraction.
- -8mm fines fraction.

The shredder screen size used in the trial was 40mm. Hence a target particle size of 25-50mm was chosen to ensure an even distribution around the specific 40mm target.

The third analysis was a measurement of the degree of liberation of the material. Non-liberated material was hand-picked from a sample. Non-liberated material is defined as a piece of shred which consists of two or more materials. Liberated material is a piece of shred which consists of only one material category. The degree of liberation is measured as a percentage, by the following equation, and should be over 90% for a successful shredding operation.

$$\text{degree of liberation } (\%) = \frac{\text{weight of liberated material}}{\text{total weight of sample}}$$

3.5.4 Results and discussion

The shredding trial was a success and went according to plan. All of the FPDs were shredded with no major problems. The shredded material was assessed as described in the above methodology section.

Table 6 shows the results of the compositional analysis.

Table 6 Shredded FPD compositions

FPD		Shred composition									
	Total	Plastic	Screen plastic	Thin films	Glass/film composite	Ferrous metal	Non-ferrous metal	Circuit boards	Cables and wires	Fines	Others
LCD TVs	100%	28%	0%	1%	1%	46%	12%	6%	2%	3%	1%
	859kg	241kg	0kg	8kg	8kg	395kg	103kg	52kg	17kg	26kg	8kg
Desktop monitors	100%	22%	20%	3%	2%	36%	7%	4%	3%	2%	1%
	260kg	57kg	52kg	8kg	5kg	94kg	18kg	10kg	8kg	5kg	3kg
Laptop screens	100%	43%	8%	3%	10%	9%	3%	12%	2%	3%	6%
	48kg	21kg	4kg	1kg	5kg	4kg	1kg	6kg	1kg	1kg	3kg
Plasma TVs	100%	4%	0%	0%	19%	26%	23%	9%	3%	10%	7%
	275kg	11kg	0kg	0kg	52kg	72kg	63kg	25kg	8kg	28kg	19kg

There are clear differences in the shred compositions of the different categories of FPDs. The laptop screens contain the highest percentage of plastic; however as the individual laptop screens do not weigh very much, compared to the LCD TVs, so the actual quantity of plastic per unit is low. The other main fraction of potential commercial interest is the metal (ferrous, non-ferrous and circuit boards) as this fraction is likely to generate the most revenue. With the exception of the laptop screens all the units contain over 25% ferrous metal. A number of the fractions including the thin films and glass/film composite, do not at present, have any end markets and hence their value and revenue will be very little or none.

The particle size distribution of the shred was assessed, Table 7 shows the results.

Table 7 Particle size distribution of shredded FPDs

FPD	Particle size distribution			
	Fines 0-8mm	8-25mm	25-50mm	Oversize +50mm
LCD TVs	4%	15%	69%	13%
Desktop monitors	3%	18%	65%	14%
Laptop screens	3%	15%	72%	10%
Plasma TVs	11%	16%	57%	16%

The particle size distributions of three of the four categories of FPDs are similar. The plasma TVs produced slightly different results, with a higher percentage of fines and less material within the target category of 25-50mm. The high fines content is due to the glass sheets in the plasma TVs which shatter during shredding to less than 8mm. The laptop screens produced the best particle size distribution, with the lowest percentage of fines and highest percentage of material within the target fractions.

Samples of shredded material were analysed to determine the degree of liberation achieved by the shredding process. The results are shown in Table 8.

Table 8 Degree of liberation of shredded FPDs

FPD category	Degree of liberation
LCD TVs	96.8%
Desktop monitors	94.0%
Laptop screens	95.6%
Plasma TVs	92.4%

All of the results are over 92% which means a high degree of liberation was achieved for all the FPD categories and there were very few pieces of shred which consisted of two or more materials. This is advantageous for the separation stages as it means the material should be easier to separate as it consisted of pieces made from one material only. A lower degree of liberation would results in comingled particles which are more difficult to separate.

The throughput time for shredding the FPDs was also estimated. The throughput varied from 1100kg/hr for the plasma TVs to 740kg/hr for the laptop screens. The throughput range is acceptable for a small scale commercial plant. With a larger shredder a more attractive commercial throughput rate of up to five tonnes per hour should be achievable.

Table 9 Throughput data for FPD categories

FPD category	Maximum estimated throughput	Minimum estimated throughput	Average estimated throughput
	kg/hr	kg/hr	kg/hr
LCD TVs	1050	750	885
Desktop monitors	990	870	930
Laptop screens	-	-	740
Plasma TVs	-	-	1100

3.5.5 Conclusions

The three shaft shredder processed the different types of FPDs efficiently and was observed to be operating well within its designed capability. The plasma TVs, which had the most solid construction and highest amount of metal components, were successfully shredded with little interruption to the material flow. The shredder did slow down and cutting shafts went into reverse rotation but this is a normal safety aspect to prevent damage to the motor by overloading it.

The speed at which the shredder processed units was generally proportional to the dimensions and weight of the units. A higher shredding rate per unit was observed with the smaller laptop units but the measured mass throughput rate was broadly similar for all the units.

The particle size distribution produced by the shredder varied for the different types of FPDs. Only 57% of the plasma TV shred was in the target range of 25-50mm, where as 71% of the laptop screen shred was within the desired range. The amount of fines and oversize shred generated was low over all four categories, with the plasma TVs generating the most at 11%. This is due to the high glass content of the plasma TVs compared to the other categories and the glass shattering into particles less than 10mm in size.

The degree of liberation achieved was between 92% and 97% for the different FPD categories, which is good and acceptable for a commercial process.

While a reduction in the level of fines and sub-25mm particles observed might be possible by selecting a larger shedding screen size, it was felt that the high level of liberation achieved justified the selected screen size used in the trial.

Overall, the Erdwich three shaft shredder selected for the size reduction of FPDs was judged to be well suited to the application and fit for purpose.

Please refer to Erdwich shredding trial report in Appendix 4 for further details about the shredding trial.

3.6 Optical sorting trial

The aim of the optical sorting stage was to separate the shredded FPDs into the various material categories present. The shredded FPD were treated like other WEEE in terms of the separations required.

3.6.1 Project partner

The trial host for the separation of the FPDs was TITECH GmbH. Axion has conducted a number of previous trials with TITECH using their optical sorting techniques.

3.6.2 Trial objectives

From the disassembly stage of the project the main material categories had been identified as plastic, ferrous metal, non-ferrous metal, circuit boards, glass and glass/film composites, thin films and other residual material. Two fractions of particular interest were the thin films and glass/film composites which contained the liquid crystals. The thin films and composites could potentially pose a major issue to the further processing of the other fractions, especially the plastic, as they are incompatible with the size reduction and separation techniques used by most WEEE plastic recyclers.

There were two objectives for the TITECH sorting trial:

- to separate the shredded FPDs into the different material categories and assess the degree of separation and the purity of each fraction produced; and

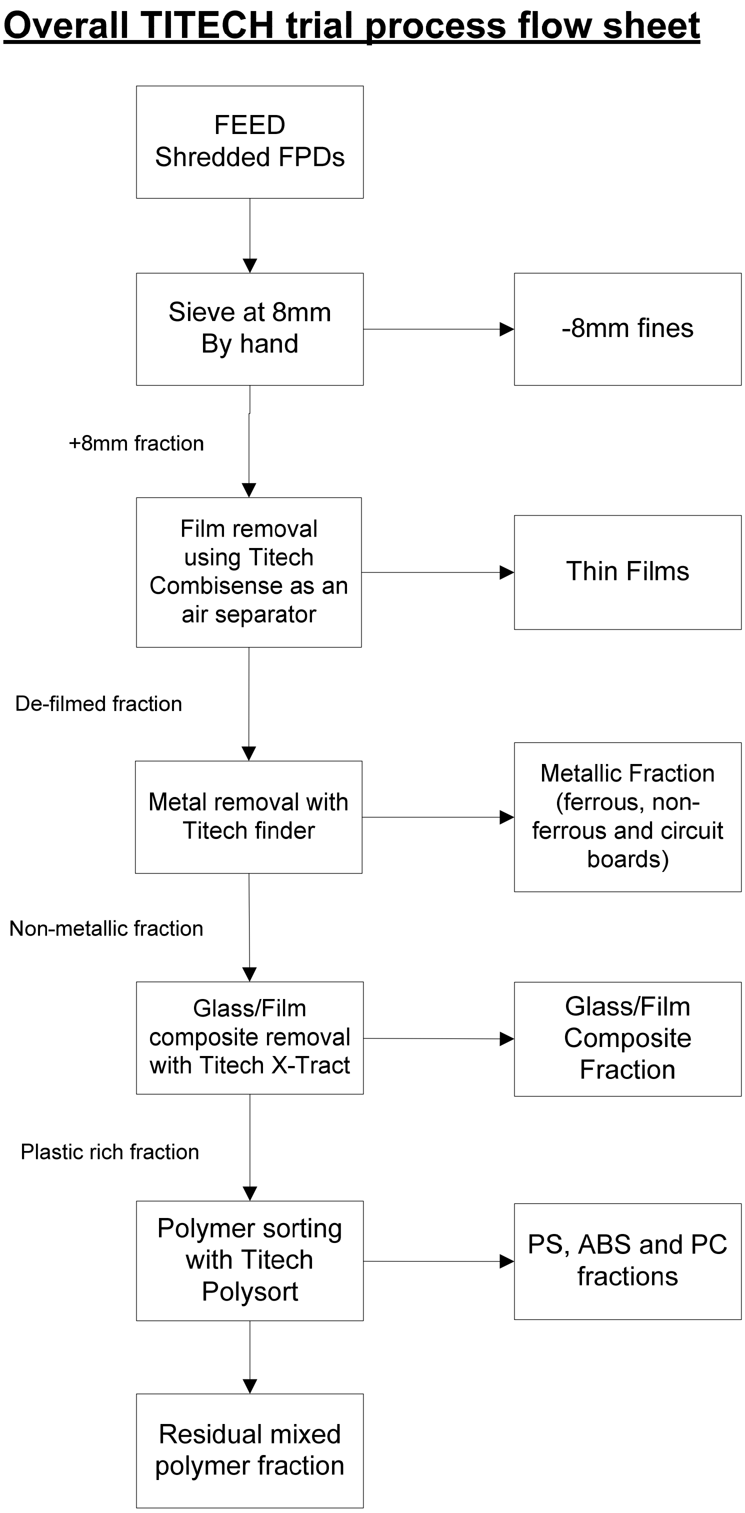
- to assess the various TITECH sensor-based sorting techniques in terms of separation efficiency and suitability for the separation required and in turn recommend the best combination of sorting technologies required to maximise the materials recovered for recycling.

3.6.3 Methodology

The trial methodology included a degree of flexibility so that it could be adapted during the delivery of the trial based on the results observed. A suggested separation order for the material categories was proposed prior to the trial. Figure 3 shows an overall flow diagram for the separation of the shredded FPDs. This is followed by a detailed description of the separations conducted.

As with the other trials the four categories of FPDs were kept separate during the trial.

Figure 3 TITECH separation trial flow sheet



For details of each TITECH machine used during the trial please refer to the individual trial report in Appendix 5.

Initially the shredded FPDs were sieved at 8mm to remove the fines. The fines were considered to be below the acceptable particle size for optical sorting and had little economic value and therefore removal was advisable.

The next separation was the removal of the thin films. This was done using the TITECH 'Combisense' machine but with no sensors or detectors active. The material was fed through the machine and passed over the air jets located at the end of the belt. The air jets were set to constantly blow which removed the majority of the thin films from the main material stream.

The de-filmed heavy fraction was processed through the TITECH Finder to remove all of the metals (ferrous, non-ferrous and circuit boards).

The non-metallic fraction from the Finder separation was then sent through the TITECH X-tract machine to remove the glass/film composite fraction which originally formed the liquid crystal part of the display. The x-ray signal produced by the composite material was noticeably different to the polymer signals which enabled a separation to be achieved.

The plastic-rich fraction was processed though the TITECH PolySort machine to eject PS initially. The reject stream from the PS sort was re-processed to remove ABS. The ABS separation reject was then processed to remove the PC fraction. This gave three plastic-rich fractions and a residual mixed polymer fraction.

During the trial it was decided that nothing further would be learned by doing the NIR polymer separations on the laptop screens and desktop monitor categories, as the results would be similar to those produced by the LCD polymer separations. Both these categories were subjected to the initial separation processes which involved sieving at 8mm, metal removal and glass/film composite removal.

None of the plasma TV material was processed, due to time restrictions during delivery of the trial. However the work carried out with the other FPD categories generated sufficient information to indicate that the separation of plasma TV material would be achievable.

The same method was followed for each individual separation trial stage:

- a quantity of feed material was weighed;
- the sample was processed through the separation machine;
- two product fractions were generated; an eject fraction which contained the material the machine had been set to identify and a reject fraction which is the residual material the machine does not identify;
- the product fractions were collected in containers and weighed; and
- samples of the product fractions were taken for post trial analysis along with labelled photographs.

Fractions which did not require any further processing were bagged, labelled and stored ready for shipment back to Axion. Typically, it was the eject fractions which were not processed any further and the reject fractions went on to the next separation stage.

Post trial analysis involved hand sorting of the samples into the material categories present in order to determine the efficiency of the separation techniques. The following material categories were used:

- Plastic.
- Screen plastic.
- Thin films.
- Glass and glass/film composite.
- Ferrous metals.
- Non-ferrous metals.
- Circuit boards.
- Cables and wires.
- Others.

The plastic fractions were also tested by Fourier Transform Infrared Spectroscopy (FTIR) which identifies the polymer type of each individual plastic chip and X-Ray Fluorescence (XRF) to identify the presence of brominated flame retardants.

Separation efficiency was calculated for the product and reject fractions using the Q and R convention. The product separation efficiency, Q, is the probability that the target material is correctly separated into the desired product stream. The reject separation efficiency, R, is the probability that all other materials are correctly separated into the secondary stream. Ideally the Q and R values should be above 80% for the process to be commercially attractive and viable.

3.6.4 Results and discussion

As detailed previously a number of separation trials were conducted on the shredded materials using a range of TITECH equipment with the main focus of the trial being the separation of the LCD TVs.

Table 10 summarises the results for all of the separation trials conducted during the TITECH trial and Figure 4 is a diagram showing the weight split of material for each separation conducted on the LCD TVs as a percentage of the input mass (100%).

The trials to sort and separate the shredded FPDs showed different levels of success for each primary material fraction:

- the pre-separation sieving step was clearly required as it removed between 9-17% of the material, depending on the FPD category. In a commercial plant it is anticipated that the fines fraction would be sent to landfill as further recovery is not economically realistic. As the quantity of fines is quite high it may be necessary to adjust the shredder settings to further minimise the quantity of fines generated;

- using the TITECH Combisense to remove the films provided an acceptable solution during the trial, as 63% of the films were removed from the LCD TV category and 72% of the films removed from the laptop screens;

- the metal removal trial using the TITECH Finder successfully removed over 98% of the metal from each FPD category;

- the use of x-ray technology removed between 75-94% of the glass/film composite from the different FPD categories; and

- the polymer separations with the TITECH PolySort were successful to some extent, although the high proportion of black particles present in the mixture meant that the sorter was not able to identify all of the material and hence the efficiency of the separations was not high enough for commercial acceptability.

The current WEEE regulations state that at least 65% of TV screens or computer monitors should be reused or recycled and with an additional 10% recovery allowed giving an overall target of 75%. Analysis of the results showed the following.

Table 10 Estimated recycling and recovery levels for each FPD category

FPD category	LCD TVs	Desktop monitors	Laptop screens	Plasma TVs	Target
Recycled	72.6%	62.8%	49.3%	69.0%	65%
Recovery	0%	0%	0%	0%	10%
Overall	72.6%	62.8%	49.3%	69.0%	75%

The LCD TVs and plasma TVs exceed the recycled target but with no energy recovery, the overall WEEE target is not achieved. The desktop monitors and laptop screens do not achieve the required recycling and recovery targets.

However in the case of the laptops the above figures only cover the FPD screen and not the base section of the laptop. Separation of the laptop screen from the base before recycling is unlikely to happen in a commercial process and therefore, once the metal and circuit boards contained in the base have been taken into account, it is expected that the recycling target would be met.
Additionally, if the plastic sorting technology could be improved to achieve higher separation efficiencies then the amount of recycled material should increase. With an improved plastic yield the recycling target for the LCD TVs and plasma TVs should achieved.

For example, with the LCD TVs, if the plastics separation efficiency can be increased so that 90% of the plastic are sorted and recycled, the overall recycled rate increase from 73% to 81% and hence the WEEE recycling and recovery target would be met.

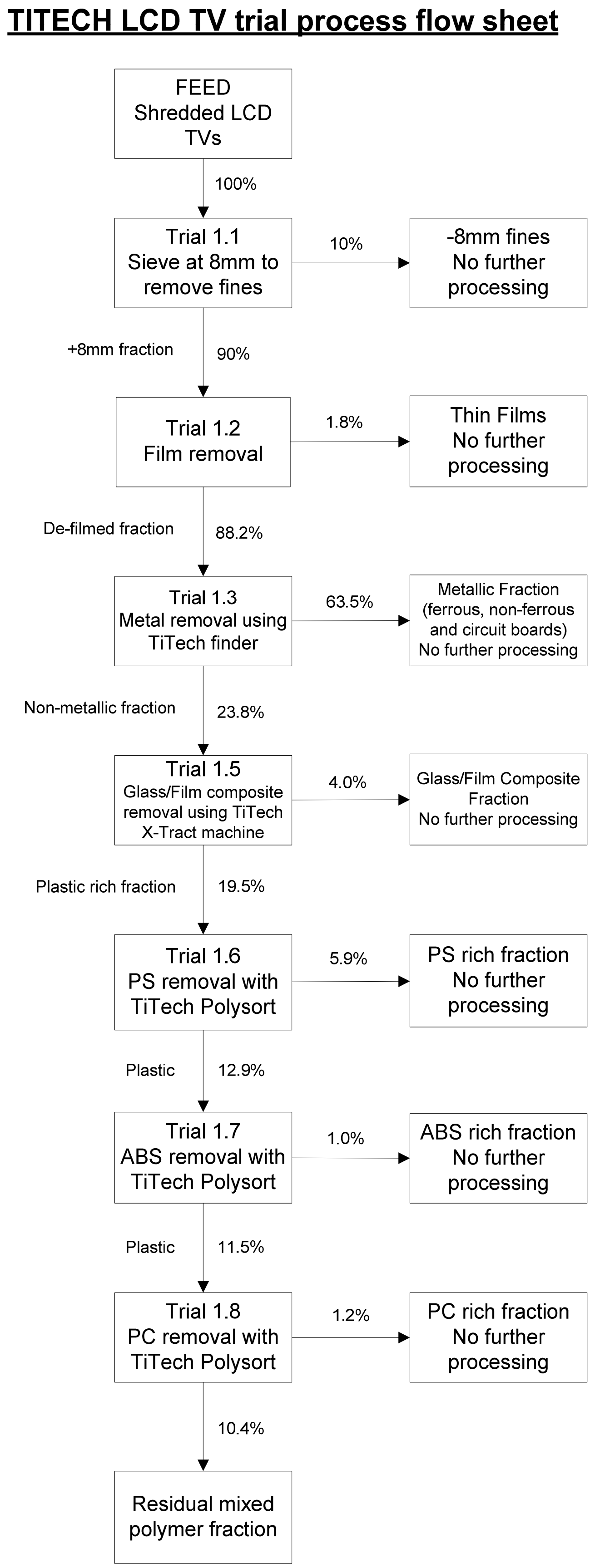
Finding an end market for fractions such as the thin polymer films and the glass/film composite fraction would also improve the recycling results.

It may be that the fines fraction and residual waste could be suitable for energy recovery. There is plastic present in both of these fractions. The fines fraction contains plastic in similar quantities to the shredded composition of the FPDs. For example 10% of the LCD TV material was classed as fines and approximately 30-40% of this is plastic. The waste fraction has a high proportion of plastic due to the low sorting efficiency for the plastic separations. The residual waste fraction from the LCD TV was 10% and the plastic content is at least 80%. Therefore approximately 12% of the feed could be plastic which could go for energy recovery. However, it should be noted that this material was not tested for suitability for energy recovery as part of the project and it is thought that the material is unlikely to be attractive to standard energy from waste plants.

Table 11 Summary of TITECH trial results

Trial	**LCD TVs**		**Laptop screens**		**Desktop monitors**	
Sieving at 8mm	10% fines removed		17% fines removed		9% fines removed	
Film removal	Q = 63%	Eject is 94% films Reject contains 1% films	Q = 72%	Eject is 83% films Reject contains 2% films	-	-
Metal removal	Q = 99%	84% metal in eject 3% metal in non-metallic fraction Throughput measured at 1.5te/hr/m	Q = 99%	58% metal in eject Virtually no metal in reject Throughput measured at 0.76te/hr/m	Q = 98%	69% metal in eject 4% metal in non-metallic fraction Throughput measured at 1.4te/hr/m
Glass/film composite separation	Q = 94%	62% glass/film composite in eject 1% glass/film composite remains in plastic fractions Throughput measured at 0.8te/hr/m	Q = 75%	55% glass/film composite in eject 4% glass/film composite remains in plastic fractions	Q = 82%	28% glass/film composite in eject 2% glass/film composite remains in plastic fractions
PS separation	Q = 65%	Eject is 88% PS Throughput measured at 1te/hr/m	-	-	-	-
ABS separation	Q = 18%	Eject is 76% ABS Throughput measured at 0.95te/hr/m	-	-	-	-
PC separation	Q = 55%	Eject is 75% PC Throughput measured at 0.76te/hr/m	-	-	-	-

Figure 4 Summary of LCD TV trial results showing the mass splits of material for each separation



3.6.5 Conclusions

Overall the several different separation technologies investigated during the FPD TITECH sorting trial showed varying degrees of success, for the following reasons:

- the most successful separations were the metal removal and the glass/film composite separation. Both achieved separation efficiencies of above 75%. The results achieved by the TITECH finder for the metal removal were very good. In a commercial scale plant it is probable that a magnet and an eddy current separator would be used to remove the metal fractions. A magnet and eddy current has two key advantages over a TITECH finder. Firstly the metal is removed in two fractions, ferrous and non-ferrous, where as the TITECH Finder removes all metal so a second separation is required to separate the ferrous and non-ferrous. This would obviously increase the costs for a commercial scale plant, which relates to the second advantage of a magnet and eddy current separator. A magnet and eddy current separator are a cheaper option compared to using a TITECH finder however they have not been tested as part of this project, therefore;

- testing of a magnet and eddy current on a FPD waste stream is recommended to assess the separation efficiencies and product purities compared to the TITECH finder. Axion estimate that an over band magnet would remove 75% of the ferrous metal and a high pole high speed eddy current system, designed for small metal fragments, should remove 85-90% of the non-ferrous material;

- the results from the X-tract trial to remove the glass/film composite fraction which initially formed the liquid crystal part of FPDs were promising. The most successful separation was with the LCD TVs. The material has not been separated before by TITECH. Bearing this in mind the initial results show potential and would be considered as the first option in a commercial plant for the removal of the glass/film composite;

- the results of the film removal trial with the TITECH combisense were acceptable and the technique was shown to be satisfactory for the trial, it is not likely to be the technique used in a commercial scale plant but was the most relevant for the purposes of this work. A simple air separator would be a better option for film removal as it will have been designed specifically to remove a light fraction and therefore should achieve a higher separation efficiency than the combisense, as well costing less; and

- the results of the polymer separations were not as good as expected. The separation efficiencies were relatively low, varying from 18-65% and the purity of the polymer fractions were below the desired level of 95%. In a previous WRAP project[7] Axion trialled the TITECH NIR sorter with WEEE derived plastics and achieved similar separation efficiencies of between 41% and 66% for the separation of ABS from PS and product purities of 80-85% for the ABS and PS fractions. Calculations indicated that by re-processing the material the desired target purity of 95% could be achieved. As the trial in this project was conducted in a short time period it is possible that further work with TITECH and testing of the machine would yield better results. The high percentage of black plastic and wide range of different polymer types in FPDs made this separation difficult. A further separation to remove bromine-containing polymers and more purification would be required before the plastic fraction could be sold commercially for high grade applications.

The trials demonstrated that the shredded FPD can be separated. This can be achieved with a combination of TITECH equipment tested during this trial and other techniques that already exist in the recycling and reprocessing sector.

Please refer to the trial report in appendix 6 for more information about the TITECH sorting trial.

3.7 Mercury decontamination stage

3.7.1 Plant scale trial

The fourth trial of the FPD project was the mercury decontamination trial. The aim of the trial was to test the ability of the Mercury Recycling washing process to clean the FPDs contaminated with mercury from the backlights.

[7] Please refer to *http://www.wrap.org.uk/recycling_industry/publications/separation_of_mixed.html* for a report into the separation of mixed WEEE plastics which reports on a number of separation techniques suitable for WEEE processes including plastic separations with a TITECH NIR sorter.

3.7.2 Project partner

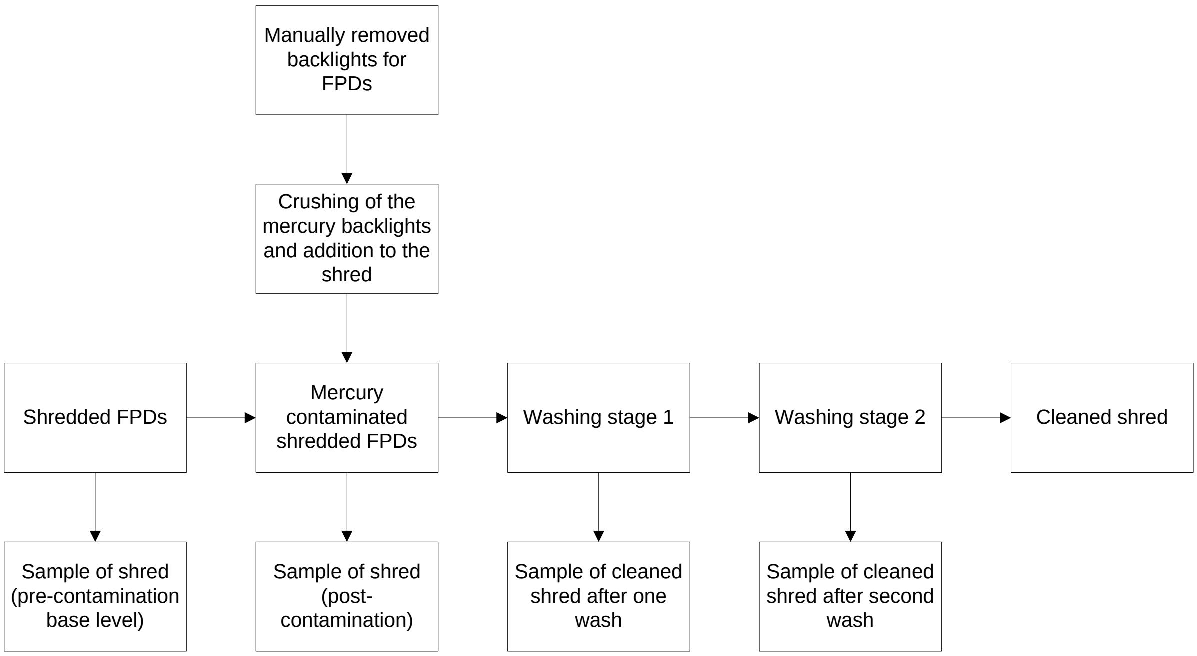
The project partner for the mercury decontamination stage was Mercury Recycling Ltd. They are a mercury lamp recycler and use state-of-the-art technology to recycle fluorescent tubes and lamps. They brought to the project valuable experience in handling mercury, as well as the use of their lamp recycling plant for the demonstration trial.

3.7.3 Methodology for plant scale trial

The following section details the methodology and procedures used during the trial. The trial involved the following stages, as displayed in Figure 5:

- crushing and re-association of the mercury backlights with the shredded FPDs;
- processing of the mercury contaminated material through the washing system; and
- testing of the samples collected during the trial at an external laboratory.

Figure 5 Diagram showing mercury decontamination trial process



The aim of the backlight re-association stage was to contaminate the shredded FPDs with mercury and, in effect, simulate the process of shredding the whole FPDs with the backlights present.

3.7.4 Crushing and re-association of the mercury backlights

A strict procedure was followed to ensure that each batch of shredded FPDs was correctly re-associated with exactly the right type and number of labelled backlights. The backlights were carefully crushed while still enclosed in the plastic sample bags and then quickly mixed with the shredded FPDs immediately before being fed into the washing process.

The shredded LCD TVs were split into three batches, with the backlights also being split into three batches. In total there was 3.9kg of backlights from the LCD TVs so each batch received approximately 1.3kg. Splitting of the backlights from the desktop monitors and laptop screens was not necessary as the shredded FPDs had not been split into batches, so all backlights corresponding to these categories were re-associated with the relevant materials.

Before the crushed backlights were re-associated with the shredded material, samples were taken from each category of FPD units. The 'pre-contamination' samples would provide the base sample level of mercury within the shredded FPDs. The samples collected were approximately 1kg and two samples were taken from each category/batch. One sample was for analysis whilst the other was retained by Axion. Care was taken to ensure that the samples were representative of the whole batch of material by taking material from all areas of the container.

3.7.5 Processing of the mercury contaminated material

The next stage of the trial was to re-associate the crushed backlights with the shredded FPDs. The time from commencing the mixing of the backlights into the shredded FPDs to the feeding of the contaminated material into the mercury wash process was kept to ten minutes[8]. The actual mixing time for the mercury backlights was therefore a proportion of the ten minutes. This meant that the mercury residence time for the different FPD categories was the same, allowing for a fair comparison. In a commercial process it is assumed that after shredding the material would be sent straight to the mercury wash plant and therefore the residence time would be fairly low, only minutes.

The re-association of the backlights with the shredded FPDs was done manually. The shredded FPDs were transferred from one container to another, whilst the mercury backlights were dosed into the shred to encourage an even distribution of the mercury through the shred. After the re-association stage the material was mixed in the container again to ensure an even distribution of mercury.

To ensure an even distribution, a range of samles were taken half way through the mixing, with an additional quantity being collected at the end of mixing stage. Again two samples were taken from each category/batch. It should be noted that this complex mixture is inherently difficult to sample in a truly representative manner but care was taken to obtain samples that were as representative as possible.

As the plasma TVs do not contain any mercury backlights they did not have to go through the re-association stage. Samples of the shredded plasma TVs were taken to give a base level concentration of mercury.

The mercury wash process is fed manually and therefore the operatives were advised to keep the shovel portions similar to ensure regular flows of material through the system. The batches of contaminated FPDs were processed through the wash system. The time for the material to pass from the input chute to the output chute was recorded, along with the time to process the entire batch of material. Note that due to the confidential nature of the Mercury Recycling's mercury washing process a detailed description cannot be given.

The output consisted of a small collection container which was replaced once full. The small containers were emptied into one large container which could hold the whole batch. Once the whole batch was processed the output weight was recorded and two samples were collected. Any material which missed the collection boxes was collected at the end of each run, weighed and added to the mass balance.

The output batch was then processed through the wash system a second time using the same procedure as described above.

Once the FPD batch had been processed the system was stopped and cleaned. The cleaning process involved collecting the fines from the system and taking samples, clearing the system of residual material, taking samples of the wash waters and finally changing the filters on the wash system. In the case of the LCD TVs, all three batches were processed one after another before the system was cleaned.

At the end of the full trial a sample of the sediment from the wash water tank was also taken.

3.7.6 Analytical testing of the samples

The following samples were sent for mercury analysis at Scientific Analysis Laboratories (SAL Ltd), an independent analytical laboratory.

The samples taken for analysis were:

- pre-backlight contamination, post backlight contamination, after washing stage one, and after washing stage two from:
    - LCD TVs batches one, two and three;

[8] *Studies on release of mercury from energy-saving lamps show peak Hg concentrations in atmosphere before 15 minutes.*

- desktop monitors; and
- laptop screens.

- a pre-washing, after washing stage one and after washing stage two from the plasma TVs;
- a fines samples from each FPD category;
- seven wash water samples;
- sample of sediment from the water tank;
- sample of powder from the filters; and
- five samples from the crushed backlights.

All the samples were analysed using the following methodology:

- the samples were received as a bulk sample and upon visual inspection, the samples contained a wide range of materials, from dust and glass shards to large (40mm) pieces of display units, metals and plastics;
- a representative sample of 200g was taken by hand, selecting as many varied parts of each sample and placed into a clean 1 litre HDPE bottle, approximately 300mls of 5% nitric acid was added to each sample (enough acid to cover the sample being extracted);
- each sample was then rolled on an automatic end over end roller for 24 hours;
- with each batch of samples a blank sample was prepared which contained 300mls of 5% nitric acid;
- after rolling the sample extracts were filtered;
- the filtered leachate samples, but not the filtered solids, were analysed for mercury by Cold Vapour Atomic Fluorescence Spectroscopy (CVAFS); and
- results are reported in µg/kg or mg/kg, exact volumes and weights have been used in the final calculation.

Some of the samples underwent further testing using Inductively Coupled Plasma Optical Emission Spectrometry (ICP/OES) to verify the results obtained from the CVAFS analysis. The original results from the plant trial samples were tested using CVAFS, which has a limit of detection of 0.2µg/kg. However the samples required significant dilution, to such an extent that the dilution factor brought larger errors than the analytical technique. The positive results from the plant trial were re-tested with ICP/OES, which has a detection limit of 0.01mg/kg. These limits apply to the results in Table 12 and Table 13.

3.7.7 Results and discussion of plant scale trial

Table 12 shows the mercury levels in the shred, before and after the mercury backlights had been re-associated with the shredded FPDs. The results show a small amount of variation across the different types of FPDs. The results do not show a significant increase in the mercury levels from before to after the re-association stage. In some cases there is actually a decrease in the mercury level after contamination which is puzzling.

Table 12 Comparison of mercury levels of pre and post contaminated shred

FPD category		Pre-contamination mercury levels using CVAFS	Pre-contamination mercury levels using ICP/OES	Post contamination mercury levels using CVAFS	Post contamination mercury levels using ICP/OES
		µg/kg	µg/kg	µg/kg	µg/kg
LCD TVs	Batch 1	0.25	-	0.23	-
	Batch 2	0.23	-	0.10	-
	Batch 3	1.20	<20	7.80	<20
Desktop monitors		1.5	<20	1.9	<30
Laptop screens		0.60	-	0.33	-

Table 13 shows the mercury levels after one and two washes, with the results from the two different analytical techniques which were used.

Table 13 Comparison of mercury levels after one and two washes

FPD category		One wash mercury levels using CVAFS	One wash mercury levels using ICP/OES	Two washes mercury levels using CVAFS	Two washes mercury levels using ICP/OES
		µg/kg	µg/kg	µg/kg	µg/kg
LCD TVs	Batch 1	0.05	-	0.24	-
	Batch 2	0.24	-	0.20	-
	Batch 3	9.50	<20	2.80	<20
Desktop monitors		1.8	<30	4.8	<20
Laptop screens		0.30	-	0.21	-
Plasma TVs		4.70	<20	1.83	<20

In some cases after washing the mercury levels of the shred was higher than the "pre-wash" samples, indicating either variability in analysis or uptake of mercury by the shred, in other cases the washing process appeared to have had no effect and the mercury levels did not change.

The results of the washing trials at plant demonstration scale were inconclusive and were unable to show that the mercury had been successfully washed off the shredded FPDs.

The physical processing of the FPD units themselves was not problematic and the plant processed the units at throughput rates significantly below the rated maximum throughput for the washing system. The throughput rate was controlled by the manual addition of the material into the system; however this is also the case in normal processing at Mercury Recycling.

3.7.8 Conclusions from plant scale trial

The findings from the plant trial were inconclusive and the trial objective of proving that technically the mercury could be removed from the shredded FPDs was not achieved.

The plant trial indicated that the quantity of mercury within the backlights is exceptionally low and once dispersed into the shredded FPDs it becomes very difficult to measure on the material and trace through the process. The contradictory and difficult-to-interpret results meant it was not possible to produce a mercury mass balance for the demonstration trial.

It was anticipated that there would be a spike in mercury after the backlights had been re-associated with the shredded FPDs however this was not observed. This is possibly due to the quantity of mercury in the backlights being very low and not significant enough to create a measureable increase.

The results showed that in some cases higher levels of mercury were detected after the washing process. In the majority of cases washing the material once, and then for a second time, did not result in a noticeable decrease in the mercury levels.

The reasons for the inconclusive results were attributed to a combination of poor mixing of the broken tubes back into the shred, the difficulty of getting a truly representative sample of the shred for analysis, the possibility that absorption and/or adsorption of mercury by the shred components affected removal, and potential errors at the analytical stage as dilutions of up to 50,000 had to be used to bring the results within the range of the analytical method. It is recognised that methodology is a limiting factor to this work.

The physical processing of the material was successful and the Mercury Recycling plant was able to handle the material without any problems. The input rate of material into the system by the operatives was kept as consistent as practicable throughout the trial. The throughput rates varied for the different FPD categories from 380kg/hr for the laptop screens, through to 812kg/hr for the LCD TVs. The average throughput rate was 687kg/hr. However this figure is slightly skewed by the low throughput rates of the laptop shred. On average, it took 70 seconds for material to pass from input shaft to output chute.

3.7.9 Laboratory scale trial

The analytical results from the washing trial at Mercury Recycling Ltd were inconclusive. The results did not show the expected pattern of a higher result initially, followed by reducing figures as the material went through the washing process. Also, it was not possible to achieve a satisfactory mass balance for mercury over any part of the demonstration trial; therefore the fate of the mercury in the tubes added back into the shredded material could not be confirmed.

To overcome these potential sources of error mentioned above, and to try to carry out the washing process in a highly controllable manner, it was decided to perform the washing process on a small laboratory scale.

3.7.10 Trial host

In addition to Mercury Recycling, the further laboratory scale trial was conducted with Scientific Analysis Laboratory (SAL Ltd). The trial took place at SAL under the supervision of Axion.

3.7.11 Laboratory trial methodology

The trial was conducted on a 203g sample of shred and the whole of the shred was analysed to avoid sampling errors. To assess whether absorption was significant, the samples were extracted with water and then by using Aqua Regia (AR), a very strong mix of concentrated nitric acid and concentrated hydrochloric acid, to maximise total mercury recovery for analysis.

The trial was conducted in the following manner:

- one unbroken tube (Tube A) was broken and ground with a pestle and mortar, in a fume cupboard, to as fine a particle size as possible. The tube was weighed before breaking and after grinding.
- two further tubes (Tubes B and C) were also ground in this manner to try to assess whether mercury loss as vapour was significant.
- tube A was split into half, with one half of the ground tube being analysed using first water extraction then followed by AR extraction.
- the other half of the ground Tube A was added to 203.47g of shred and mixed.
- washing was done using 1000ml of water. After adding the water, the sample was mixed using a laboratory roller for ten minutes to simulate the residence time used in the Mercury Recycling washing process.
- the wash water was decanted from the mixture and filtered to remove fines. The filtrate was analysed for mercury directly. The fines were extracted with AR and analysed.
- the washing process was completed with a further 1000ml of water. The wash water was decanted, filtered and analysed as for the first wash.
- the final washed shred was weighed and analysed after water and AR extractions.

Strict controls were applied during the process with blanks used and analysed throughout to eliminate extraneous errors.

3.7.12 Results and discussion of laboratory scale trial

The results of the trial are shown Table 14.

Appendix 7 contains the laboratory report produced by SAL.

Table 14 Results of laboratory scale trial

Sample	Weight	Water Extraction		AR Extraction		Total
		Hg	Wt Hg	Hg	Wt Hg	Wt Hg
	G	mg/kg	mg	mg/kg	mg	mg
Hg Input						
Tube	4.356	0.238	0.0010367	119	0.518364	
Total Hg In			**0.0010367**		**0.518364**	**0.5194007**
Hg Output						
Wash 1	978.44	0.0053	0.0051857			
Filtered fines ex wash1	0.09764			20	0.001953	
Wash2	996.38	0.0028	0.0027899			
Filtered fines ex wash2	0.14787			15	0.002218	
Washed Shred	206.04	0.0052	0.0010714	1.34	0.276094	
Total Hg Out			**0.0090470**		**0.280264**	**0.2893115**
Hg difference (mg)			**-0.0080103**		**0.238100**	**0.2300893**

The water extracts were initially analysed using ICP/OES, with a limit of detection of 0.01mg/kg, but many of the results were below the LOD. The samples were reanalysed using ICPMS, which has a detection limit of 1μg/kg, and these are the results shown in Table 14.

Where water and AR extractions are shown on the same line, the extractions were done on the same sample and are added together to give the total mercury content analysed.

Figure 6 is a diagrammatic representation of the laboratory scale trial mercury mass balance.

Figure 6 Laboratory scale trial mercury mass balance

Laboratory scale trial mass balance

Input		
Shred weight	203.47g	
Tube weight	4.36g	
	Wt Hg	Hg conc.
Water ext.	0.0010367mg	0.238mg/kg
AR ext.	0.5183640mg	119mg/kg
Total Hg	0.5194007mg	
	100%	

Wash 1

Wash 2

Washed Shred		
Shred Weight	206.04g	
	Wt Hg	Hg conc.
Water ext.	0.0010714mg	0.0052mg
AR ext.	0.276094mg	1.34mg
Total Hg out	0.2771654mg	
	53.36%	

Filtered fines from wash 1		
Weight	0.0976g	
	Wt Hg	Hg conc.
AR ext.	0.001953mg	20mg/kg
	0.376%	

Filtered fines from wash 2		
Weight	0.1479g	
	Wt Hg	Hg conc.
AR ext.	0.002218mg	15mg/kg
	0.427%	

Wash waters 1		
Weight	978.44g	
	Wt Hg	Hg conc.
AR ext.	0.0051857mg	0.0053mg/kg
	0.998%	

Wash waters 2		
Weight	996.38g	
	Wt Hg	Hg conc.
AR ext.	0.0027899mg	0.0028mg/kg
	0.537%	

Merucry balance	In		Out		Difference	
Water extraction	0.0010367	0.200%	0.009047	1.742%	-0.0080103	-1.542%
AR extraction	0.518364	99.800%	0.280265	53.959%	0.238099	45.841%
Total	0.5194007	100%	0.289312	55.701%	0.2300887	44.299%

The weights of the tubes broken are given in Table 15.

Table 15 Weights of backlight tubes before and after crushing

	Weight before	Weight after	Weight loss	Weight loss
	g	g	mg	%
Tube A	8.9612	8.8958	65.4	0.73
Tube B	9.0929	9.0545	38.4	0.42
Tube C	9.1834	9.10562	77.78	0.85

The weight loss from weighing of the tubes is higher than expected. Great care was taken when breaking the tubes to avoid loss of glass and no source of weight loss was evident in observing the activity. Mercury is known to vaporise on exposure to air so there will be some loss to atmosphere when tubes are broken. The weight loss is higher than could be accounted for by mercury loss, as the drop in weight is greater than the anticipated level of mercury in the tubes initially. A research report from the New Jersey Department of Environmental Protection[9] suggests that between 17-40% of mercury is vaporised when fluorescent tubes are broken. The release can take place over many hours, with around one third being released in the first eight hours.

The quantity of mercury within an individual tube varies but is typically in the range of 2-10mg. Therefore the weight loss during the crushing process is more than the quantity of mercury found in the tubes. While noting the weight loss, the reasons for the loss are not explained.

The results for water washing can be looked at in two steps. The water wash process alone appears to show that more mercury has been removed than was indicated as being added from the tube analysis. This observation was made on the results for the plant scale washing demonstration trial and contributed to the lack of conclusion that could be drawn from this trial.

When the samples are AR extracted to try to ensure complete removal of mercury a different picture emerges. Now, the quantity of mercury detected in the shred increases significantly. The water washing alone, as shown by the water extraction results, achieves less than 2% removal of the true mercury added figure which has been taken from the tube analysis in Table 14, although this may not have detected all of mercury present. The final washed shred analysis shows an acceptable level of mercury present and shows that the material would be accepted for landfill, based on the current landfill mercury threshold level of 0.01mg/kg or 10 parts per billion.

The AR extraction shows that mercury removal by water alone is poor and the final shred contains some 53% of the mercury added according to the mass balance results. While the sample would appear to meet the leachate test for landfill, the mercury content is actually significantly higher.

The overall mass balance does not account for all of the mercury added to the shred. Although there is some uncertainty in the exact quantity of mercury added, the mass balance indicates that only 56% of the added mercury was accounted for in the output fractions. Therefore 44% of the mercury is unaccounted for. There was some analytical difficulty in the procedure for AR extraction of the final shred because of the amount of metal present in the sample. This caused significant frothing and great care had to be taken to avoid boil over and loss of the extraction medium. Additional dilutions had to be made which potentially introduces further error.

The reasons for the differences observed in the water and AR extraction analysis have been considered and could be due to:

- the solubility of mercury can be affected by pH with the lowest levels found at neutral pH;
- there is some evidence[10] that iron and copper inhibit mercury solubility and as the FPD units contain both elements, this could be a factor; and

[9] NJDPE - Environmental Protection and Risk Analysis Element, research project summary, *Release of mercury from broken fluorescent bulbs ,* Michael Aucotta, Michael McLindenb , and Michael Winkac, February 2004.

[10] *US patent 5736813 - PH control of leachable mercury in fluorescent lamps, Issued 7th April 1998.*

- there is also evidence from a university project report[11] that mercury is absorbed by plastic thus making it inaccessible to removal by water washing.

Further investigation is required to confirm with certainty why water washing appears to be ineffective. Washing with an acid medium does appear to remove more of the mercury present in FPD units and this could be incorporated into a full scale commercial process and plant. Accuracy of measuring and confidence of removal of mercury to a level below regulatory minimum would be required to ensure safe working. The greater mercury removal achieved would increase mercury recovery value. However, there remains mercury unaccounted for so there is potential for higher recovery levels.

The current commercial process for removal of mercury from fluorescent tubes does use water washing. The presence of large quantities of plastic in the FPD unit shred may alone account for the differences in washing performance observed in this trial. Further testing is required to test this.

A brief post trial assessment of the plastic by Axion indicated that the mercury may have been absorbed into the plastic making its removal very difficult. A small number of plastic pieces were tested with a XRF analyser to determine the mercury content. The plastic pieces were then washed and re-tested with the XRF machine. The results of the second test indicated the presence of mercury which shows that there may be some adherence or absorption of the mercury onto or into the plastic. This result may explain the why all the mercury could not be accounted for in the mass balance.

The plastic analysis also raises doubts about whether the mercury backlights should have been stored and broken in plastic bags. The mercury may have absorbed into the plastic bags and hence may provide an explanation the lower than expected mercury levels measured in the backlights. Further testing on this could be carried out.

3.7.13 Laboratory scale trial conclusions

Water washing alone is believed to be ineffective in removing mercury from shredded FPD units, removing less than 2% of the total mercury present. Sampling issues may have affected this measurement but without further testing this is not confirmed.

Mercury can be removed from FPD units following shredding using an appropriate washing medium but further research into the preferred medium is required. Acidification of the washing medium would appear to be required to ensure that a higher level of mercury is captured. Mercury removal using Aqua Regia did not demonstrate a full mass balance, confirming the fate of 55.7% of the mercury added to the shredded FPD material. Further investigation and optimisation of the medium and the process may achieve higher removal rates.

The reasons for water washing alone being ineffective in recovering mercury from FPDs are not clear, even though it is an established commercial method in use today for fluorescent lighting. Preliminary suggestions include:

- pH effect on water solubility;
- solubility inhibition by iron and/or copper;
- absorption and/or adsorption of mercury by the plastic present in FPD units; and
- the complexity of obtaining truly representative samples.

As the current commercial processing of fluorescent lighting does not involve the presence of significant amounts of plastic, this may account for the poor water washing performance on FPDs.

While some mercury is expected to vaporise when backlight tubes are broken, this trial has not been able to determine what quantity is actually lost in this way.

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[11] Orebro University, Department of Natural Sciences, *The matrix dependent solubility and speciation of mercury, Erik* Hagelberg.

The landfill acceptance criterion for mercury assesses the water leachable content of material. The water leachate value of a sample may not accurately reflect the total mass fraction of mercury within the waste sample being assessed. Other materials within the sample may influence the leachability of the mercury into the water during the test. Therefore the actual mass of mercury in the waste sample may be higher than the mercury level of the leachate sample. Although not the intended destination for the material, if it was sent to landfill the fact that the mercury does not show in the water leachate test gives some reassurance that it will not leach out from a landfill site.

3.7.14 Overall mercury decontamination trial conclusions

The overall conclusion from the mercury washing trial of the FPDs is that the process used was unsuccessful and would not be suitable at a commercial scale, without further investigations of more effective washing media. This is mainly due to the inability of the water to remove the mercury, in conjunction with the mercury levels being very low and the analytical uncertainties, makes tracing the mercury around the system very difficult.

The laboratory scale trial concluded that water was not a suitable medium for washing the mercury contaminated shredded FPDs. The use of Aqua Regia, a very strong acid, produced significantly better results however Aqua Regia is highly toxic and corrosive and would not necessarily be suitable for use in a commercial plant.

Based on the observations made during the plant and laboratory trial it can be concluded that further work is required to develop a process with technical and commercial potential. The recommendations from the project into the mercury removal process are that:

- further investigation to determine a wash medium capable of achieving acceptably high levels of mercury recovery in a commercial process;
- further literature search and experimental work to investigate the optimum conditions for mercury removal using this medium;
- investigation of alternative methods for mercury removal from the shred, for example heating;
- investigation and trials to trace the location of the unaccounted for mercury; and
- investigation into the adherence relationship between mercury and plastic to assess the ease at which mercury can be desorbed from the plastic, if it found that the mercury absorbs to the plastic.

If a suitable washing medium can be found then the commercial scale plant could be designed taking into account any process risk associated with the chosen washing medium. Inevitably the use of any liquid washing medium other than water is likely to increase the cost and complexity of the wash equipment and its engineering design.

Please refer to the mercury washing trial report in appendix 6 for more information.

4.0 Development of commercial recycling process

4.1 Overview of process

Based on the results obtained from the four demonstration trials a commercial scale recycling process has been proposed. This section of the report gives details of the proposed process including a flow sheet, mass balance and economic assessment as well discussing the environmental and safety hazards.

Figure 7 shows the proposed process flow sheet for the FPD recycling plant.

The main items of equipment required are:

- a three shaft shredder;
- an 8mm screen;
- a mercury wash and recovery system;
- an air separator;
- a magnet;
- a eddy current system;
- a TITECH X-Tract machine; and
- a TITECH PolySort machine.

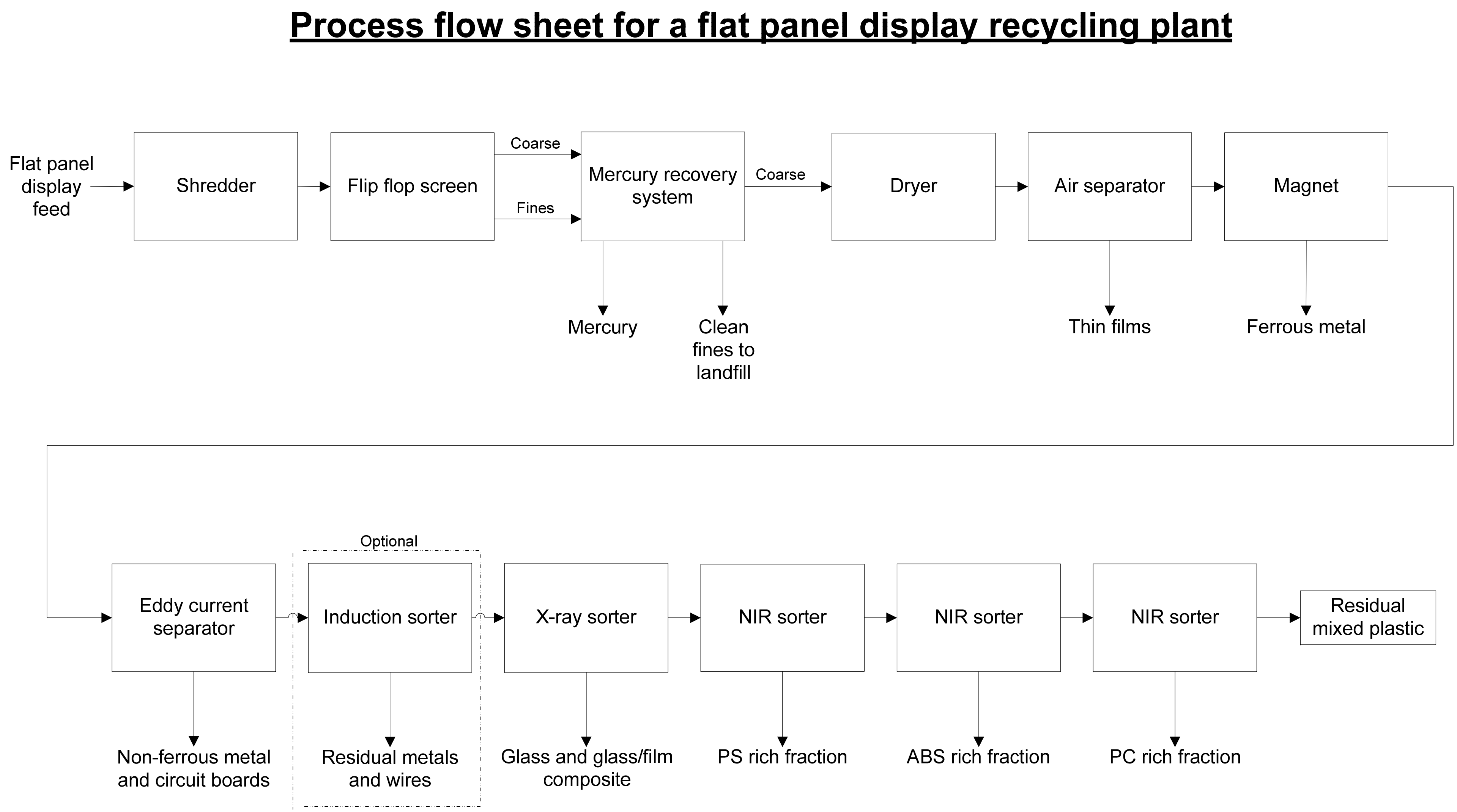
4.1.1 Process description

The complete FPDs, with mercury backlights present, are fed into the three shaft shredder. The material then passes over a flip flop screen which removes the less than 8mm material as fines. The fines and coarse materials are then separately processed in the mercury washing system. The shredder, flip-flop and washing system are all enclosed to ensure capture of mercury. After the washing system the clean fines are sent to landfill or for energy recovery, whilst the coarse material goes into the separation process part of the plant. It is noted that due to the currently inconclusive ability to remove all the mercury the exact removal process would require clarification.

The shred is initially dried to avoid sticking and then passed over an air separator to remove the thin plastic films. The de-filmed fraction then passes over a magnet and through an eddy current system, which removes the ferrous metals, non-ferrous metals and circuit boards in turn. The non-metallic material could also potentially pass through an induction sorter to remove any wires and residual metals to further segregate; however this is an optional stage in the process. The next stage of the process is to remove the glass/film composite fraction which originally formed the liquid crystal panel by the use of an x-ray sorter.

The residual material from the x-ray sorter consists mainly of plastic and the final stage is to conduct polymer separations on the material using NIR sorting machines. Depending on the FPD type, the target plastics for sorting are slightly different. In the case of the LCD TVs the three main fractions are PS, ABS and PC. The desktop monitors and laptop computers contain a PMMA fraction, which would also be targeted for removal.

Figure 7 Proposed process flow diagram for a FPD recycling plant



4.2 Mass balance model

A mass balance model for the process was developed based on a commercial processing scale of 5 tonnes per hours. A key part of the mass balance is the input composition of the FPD material. There are two aspects to the input composition; the composition of the waste stream itself in terms of the numbers of FPDs arising and the composition of the FPDs themselves. Because the current quantities of FPDs in the waste stream are fairly low it is difficult to accurately predict the numbers of FPDs which will arise in the future and the ratios between the different categories of FPDs. Therefore the input to the recycling plant requires estimation based on currently available data.

The mass balance model has the following assumptions:

- The input is based on the number of units arising in the waste stream as opposed to the mass of units.
- The LCD TVs and plasma TVs are grouped together into a 'TVs' category.
- The desktop monitors and laptop screens are grouped together into a 'computers' category.
- The split between the number of units of 'TVs and 'computers' is estimated at 50:50.
- Within the 'TV' category the split between the number of LCD TVs and plasma TVs is estimated at 90:10.
- Within the 'computer' category the split between the number of laptop screens and desktop monitors is estimated at 70:30.
- Data collected during the manual disassembly trial has been used to calculate the input weight for each FPD category, based on the average weight for each type of FPD.
- The mass split between the different categories of FPD is calculated.
- Using the compositional data for each category of FPD, collected from the demonstration trials, and the mass split, an average input composition for the 'TVs' and 'computers' is calculated.
- Finally, using the average composition of the 'TVs' and 'computers' one single overall average input composition has been determined.

The overall average input composition forms the in feed composition for the mass balance. Calculating one average input composition eliminates the need for a different mass balance for each FPD category.

Table 16 shows the in feed calculation outlined above. The total number of units has been set to give an in feed throughput rate of 5 tonnes per hour which equates to 20,000 tonnes per year. The market research data presented earlier in this report indicates that this quantity of material should be arising in the waste stream.

Table 17 shows the composition of each FPD category, the average composition for the 'TVs' and 'computers' and the overall average composition weighted against the number of units. The data in the table is from the hand sorting and analysis of the shredded material from the Erdwich trial.

Table 18 shows the output product stream and waste created by the FPD recycling plant.

Table 16 In feed to FPD plant based on the number of units

In feed based on the number of units					
	TVs		**Computers**		**Total**
% split between TVs and computers	**50%**		**50%**		**100%**
Number of units	**1259213**		**1259213**		**2518426**
	LCD TVs	**Plasma TVs**	**Desktop monitors**	**Laptops**	
% split by number of units	**90%**	**10%**	**30%**	**70%**	
Number of units	1133292	125921	377764	881449	
Average weight of unit (kg)	12.7	29.4	3.6	0.8	
Weight of category (tonnes)	14393	3702	1360	705	
Total weight (tonnes)	18095		2065		**20160**
% split by mass	80%	20%	66%	34%	

Table 17 In feed composition

In feed composition	LCD TVs		Plasma TVs		TV Average		Desktops		Laptops		Computer Average		Overall Average	
	%	tonnes	%	tonnes	tonnes	%	%	tonnes	%	tonnes	tonnes	%	tonnes	%
ABS	6%	864	1%	37	901	5%	7%	100	2%	16	116	6%	1017	5%
PCABS	6%	864	3%	96	960	5%	10%	137	18%	127	264	13%	1224	6%
PC	4%	576	0%	0	576	3%	3%	37	6%	45	82	4%	657	3%
PS	11%	1583	0%	3	1586	9%	1%	11	0%	0	11	1%	1598	8%
PMMA	2%	288	0%	0	288	2%	0%	0	0%	0	0	0%	288	1%
Others	2%	288	0%	12	300	2%	0%	0	7%	47	47	2%	347	2%
Screen plastic	0%	0	0%	0	0	0%	15%	204	11%	79	283	14%	283	1%
Thin films	2%	288	0%	0	288	2%	2%	27	3%	23	51	2%	339	2%
Glass and glass/films	4%	576	19%	703	1279	7%	5%	68	10%	72	140	7%	1419	7%
Ferrous	46%	6621	26%	963	7583	42%	37%	503	16%	116	619	30%	8202	41%
Non-ferrous	5%	720	23%	833	1553	9%	4%	54	3%	24	78	4%	1631	8%
Circuit boards	4%	576	9%	333	909	5%	6%	82	4%	27	109	5%	1018	5%
Cables and wires	2%	288	2%	93	380	2%	1%	14	1%	4	17	1%	398	2%
Fines	5%	720	10%	370	1090	6%	9%	122	17%	120	242	12%	1332	7%
Others	1%	144	7%	259	403	2%	0%	0	1%	7	7	0%	410	2%
Totals	100%	14393	100%	3702	18095	100%	100%	1360	100%	706	2066	100%	20161	100%

Table 18 Output products and waste

Products	Te/year
Mercury	Unknown , required further investigation
Thin films	354
Ferrous	8127
Non-ferrous and circuit boards	2603
Glass/film composite	1242
PS	1104
ABS	359
PC	442
Total	14231
Waste	**Te/year**
Fines	1332
Residual waste	4597
Total	5929
Overall total output	20160

4.3 Financial assessment

The following section details the financial assessment of the FPD processing plant. The main parts of the financial assessment are:

- Capital costs.
- Operating costs.
- Cash flow forecast.

For the purpose of this financial modelling exercise it has been assumed that a suitable washing medium can be found which will not significantly impact upon the overall process economics, compared to the use of water as the washing medium. If the removal of mercury by any washing medium is found to be impossible a reassessment of the economics will be necessary.

4.3.1 Market values of output materials

The main fractions of economic significance are the ferrous metals, non-ferrous metals and plastics (PS, ABS, and PC). In the current process model the non-ferrous metals and circuit boards are removed together. It may be necessary to separate this fraction into non-ferrous and circuit boards, as the two separate fractions may sell for more than the combined fraction.

The other two fractions recovered in the recycling of FPDs are thin films and glass/film composite. No other WEEE material currently being recycled contains these materials. At the moment there are no well developed markets for these fractions and therefore it is difficult to estimate how much revenue they may achieve in the future. The initial estimate is that there will be no market for the glass/film composite and it will have to be sent to landfill for disposal.

The anticipated market values, from September 2009, which have been used in the base case economic model are shown in Table 19.

Table 19 Market values for output materials

Material	Market value (£/te)
Ferrous metal	80
Non-ferrous metals (including circuit boards)	250
PS	140
ABS	125
PC	125
Thin films	10
Mercury	10,000
Glass/film composites with may contain liquid crystals and indium tin oxide	-48 (i.e. landfilled)

The model is based on the assumption the there is no market value for the mercury as it has not been proven that a saleable mercury fraction can be created by the process.

4.3.2 Economic analysis

A full economic analysis of the FPD recycling plant was completed in order to assess the commercial potential of the proposal. Assumptions in the economic model include:

- a gate fee can be charged, if necessary, to make the economics work; and
- the model takes into account the increases in landfill taxes in the future.

Table 20 shows the capital cost estimate for the 5te/hr plant.

Table 20 Capital cost estimate for 5te/hr plant

Item	Cost estimate
	5 te/hr plant
Civils and buildings	£756,250
Conveyors and structures	£288,495
Process equipment	£1,817,897
Pneumatic equipment	£100,000
Electrical	£212,271
Installation	£181,890
HSE	£27,600
Mobile plant	£39,000
Power supply	£29,900
Sub total	£3,453,302
Project management (10%)	£345,330
Contingency 10%)	£345,330
Total	**£3,798,633**

It has been assumed in the capital cost that the land for the FPD plant has already been purchased and cleared/levelled.

A detailed breakdown of the process equipment cost, for a 5te/hr plant, is shown in Table 21.

Table 21 Process equipment costs

Process equipment		
€/£ conversion rate taken as	0.9	
	£	**Basis**
Shredder	£425,097	Erdwich quotes - 09240/09ns and 09187/09ns
Mercury wash plant	£880,000	Estimates ex Mercury Recycling
Fines separator	£20,000	Based on £35,000 for 7.5 te/hr Spalek quote
Air ballistic	£30,000	Estimate based on £30,000 quoted for 2 te/hr from another Axion project
Magnet	£20,000	Based on £30 for 8 te/hr Steinert quote
ECS	£46,800	Used Goudsmit 400/600mm size quotes from another Axion project
TITECH X-tract	£280,000	Quote from TITECH
TITEHC Polysort	£110,000	Quote from TITECH
Big bag/skip filling units x 6	£6,000	Estimated at £1,000 each
Total	£1,817,897	

The operating costs for a 5te/hr plant are £1.67million per annum. The main contributors to the operating costs are:

- Electricity (£196,940).
- Man power (£443,000).
- Waste disposal (£402,900).
- Maintenance (£401,945).

Taking the base case 5te/hr model the following results are produced.

Table 22 Mass balance and economic assessment output

Mass balance and investment summary					
Input	Quantity	Value per tonne	Total		
Complete FPDs	20160	£100	£2,016,000		
Outputs	Tonnes	Value per tonne	Total	% weight	% revenue
Mercury		£5,000		0%	0%
Films	324	£10	£3,535	1.75%	0.2%
Ferrous	8,127	£80	£650,191	40.31%	43%
Non-ferrous	2,603	£250	£650,846	12.91%	43%
Glass/film composite	1,242	-£48	-£59,600	6.16%	-4%
Plastic PS	1,104	£140	£154,628	5.48%	10%
Plastic ABS	359	£125	£44,834	1.78%	3%
Plastic PC	442	£125	£55,272	2.19%	4%
Totals	14,201	**Total materials**	**£1,499,706**	**71%**	**100%**
Wastes					
Waste to landfill	5,929	£48	£284,578	**29%**	
		Total disposal	**£284,578**		
Total project cost	**£3.8million**		Gate fees *(£m)*		2.02
Payback/years	**2.4 years**		Materials *(£m)*		1.50
10 year IRR	**18%**		**Total revenue *(£m)***		**3.52**
			Operating costs *(£m)*		1.68
			Disposal costs *(£m)*		0.28
			Net margin *(£m)*		**1.55**

The financial assessment indicates that a 5te/hr plant has commercial potential assuming that the gate fee of £100/te (80p per FPD) can be charged.

4.3.3 Sensitivity analysis

A sensitivity analysis into the economic model has been conducted to assess which variables have the most impact on the results.

Table 23 Sensitivity analysis of economic model

Scenario	Sensitivity value	Gate fee	Payback	IRR
Base case model	-	£100	2.4 years	18%
Increased gate fee	Gate fee = £120	£120	1.9 years	27%
	Gate fee = £150	£150	1.5 years	38%
	Gate fee = £200	£200	1.1 years	54%
Reduced gate fee	Gate fee = £80	£80	3.3 years	9%
	Gate fee = £50	£50	6.9 years	-11%
Increased product prices Base case prices Films £10, Ferrous, £80, Non-ferrous £250, PS £140, ABS £125, PC £125	Films £20, Ferrous £100, Non-ferrous £300, PS £170, ABS £150, PC £150	£100	2.0 years	25%
	Films £20, Ferrous £100, Non-ferrous £300, PS £170, ABS £150, PC £150	£80	2.5 years	17%
	Films £20, Ferrous £100, Non-ferrous £300, PS £170, ABS £150, PC £150	£120	1.6 years	32%
Reduced product prices Base case prices Films £10, Ferrous, £80, Non-ferrous £250, PS £140, ABS £125, PC £125	Films £5, Ferrous £50, Non-ferrous £200, PS £120, ABS £100, PC £100	£100	3.3 years	9%
	Films £5, Ferrous £50, Non-ferrous £200, PS £120, ABS £100, PC £100	£80	5.2 years	-3%
	Films £5, Ferrous £50, Non-ferrous £200, PS £120, ABS £100, PC £100	£120	2.5 years	19%
Staff wages reduced	Average wage decreased from £17,720 to £16,640	£100	2.4 years	19%
Staff wages increased	Average wage increased from £17,720 to £18,880	£100	2.5 years	18%
Increase separation efficiency of NIR sorters	Separations efficiency increased to 80% for PS, 50% for ABS and 70% for PC	£100	2.2 years	21%
Higher power costs	Power costs increased from 9p/kW hr to 12 p/kW hr	£100	2.6 years	16%
Higher capital costs	Capital cost increased from £3.8m to 4.5m	£100	3.0 years	14%
Lower capital costs	Capital cost reduced from £3.8m to £3.2m	£100	2.0 years	23%
Changes to the in-feed composition from 50:50 spilt between TVs and computers	Process 75% TVs, 25% computers	£100	2.4 years	20%
	Process 25% TVs, 75% computers	£100	2.7 years	16%
Increased throughput	Increased throughput to 6te/hr	£100	1.8 years	29%
Reduced throughput	Reduced throughput to 3te/hr	£100	9.9 years	-
Reduced throughput, reduced capital costs, increased gate fee	Throughput reduced to 3te/hr, capital cost reduced to £3.2m, and gate fee increased to £150	£150	3.2 years	9%

The sensitivity analysis shows that certain scenarios are unfavourable in terms of the economics.

The plant can handle a reduction in the product prices if the gate fee remains at £100/te, but if the gate fee is reduced to £80/te in conjunction with the lower product prices the IRR becomes negative. If no other parameters are changed and the gate fee is reduced to £50/te the IRR becomes negative. Therefore a gate fee approaching £100/te is required in order for the plant to be economically viable.

None of the other scenarios which were modelled have a dramatically negative impact on the economics.

4.4 Environmental risk and hazard assessment

As stated previously, end of life FPDs are classified as hazardous by the European Waste Catalogue[12] (EWC). Therefore disposal to landfill is not an option and a treatment process to remove the hazardous mercury is required.

During all stages of the demonstration trials project the health, safety and environmental risks were a priority. Individual risk assessments were completed for each of the demonstration trials. Potentially hazardous materials and chemicals which were identified included:

- mercury (exposure due to broken/damaged backlights);
- lead (from solders in circuit boards); and
- liquid crystals contain varying quantities of other potentially harmful chemicals including chromium, beryllium, nickel, cadmium, arsenic, poly-brominated organics, organo-halogen compounds and plasticisers. However, Axion's research, reported in Appendix 2, indicated that liquid crystals are generally not considered to be toxic in the quantities used in FPDs.

Potential exposure routes for hazardous chemicals included:

- inhalation of vapours;
- direct skin contact; and
- incidental ingestion.

It is difficult to find precise data in relation to the amounts of mercury used in the backlights and hence calculation of the associated health, safety and environmental risks are complicated. Research conducted on behalf of the European Commission found that a typical 32 inch LCD TV contains 45mg of mercury on average.[13]

The following section looks into the occupational health issues associated with the potential exposure to mercury from the backlights.

4.4.1 FPD disassembly

Manual disassembly of FPD screens to remove the backlights resulted in breakages of between 15% and 35%, putting the operative at risk of exposure to the mercury contained within. Control measures such as local extract venting and personal protective equipment are necessary

The actual extent to which the mercury present in the backlights would be released into the breathing zone of the operative is difficult to determine. This indicates that FPD disassembly should be done in a controlled manner, utilising local exhaust ventilation (for example laminar flow booths, extraction hoods, etc.) to reduce the risk of operative exposure to mercury to as low as reasonably practicable. Such systems should be routed to a scrubber or other means of removal of mercury from the exhaust air.

In addition to local exhaust ventilation, operatives should be provided with personal protective equipment (for example 'Tyvek' disposable overalls, latex barrier gloves) in order to minimise the risk of skin exposure to

[12] EWC entry for FPDs with mercury containing backlights is 16 02 13 discarded equipment containing hazardous components other than those mentioned in 16 02 09 to 16 02 12.*

[13] White, P. et al (2006). Environmental, Technical and Market Analysis Concerning the Eco-design of Television Devices (http://www.jrc.es/publications/pub.cfm?id=1388)

mercury contaminated dust. All operatives should be subjected to routine urine testing to check on the efficacy of these protective systems.

4.4.2 Handling of dismantled FPDs

This section assesses the risk of handling the FPDs after manual disassembly. Given that some of the backlights will be broken during dismantling of the FPD screens, the residue for recycling may also become contaminated with mercury. The quantity of backlights broken and hence the potential mercury vaporisation, will be variable. At the level of breakage experienced in this trial the level of mercury vapour is unlikely to present an operative exposure issue. The maximum risk of exposure occurs immediately after the backlight breakage occurs. While some residual mercury contamination of the FPDs is possible the expected concentration and potential for it to become air borne is many times lower. Hence the level of protection required to guard against the risk of mercury transmission by manual handling is lower. An operative handling a FPD unit after the backlights have been removed should be provided with personal protective equipment (for example 'Tyvek' disposable overalls, latex barrier gloves, dust masks) to minimise the risk of skin exposure to mercury contaminated dust, and subjected to routine urine testing.

4.4.3 Shredding of FPDs

Shredding of FPD screens will lead to mercury contamination of the shredder product, whether or not the backlights are removed prior to shredding. These levels are still very much lower than the backlights alone (and conventional fluorescent lighting tubes), but local exhaust ventilation should be provided where there is a risk of dust generation, since the mercury will be present as a finely dispersed dust throughout the shred. Operatives working with the shredded material should be provided with personal protective equipment (for example 'Tyvek' disposable overalls, latex barrier gloves) to minimise the risk of skin exposure to mercury contaminated dust, and subjected to routine urine testing. Respiratory protective equipment will be required where there is a risk of dust release into the working environment.

Shredding operations generally produce a lot of dust, and it is in this dust that the mercury will tend to accumulate. Any dust extraction system should be considered to be a high risk source of mercury exposure, with respiratory protective equipment as well as other personal protective equipment, worn when handling the dust or maintaining the equipment. It may be necessary to replace conventional dust extraction systems with wet scrubbing systems to minimise mercury releases into the environment from such equipment.

Care should also be taken when processing the shred to separate it into useful recyclate fractions. Mercury will tend to accumulate in dusts and sludges from dust extraction equipment and wet processing, and should be monitored to ensure that hazards from mercury exposure are controlled.

4.4.4 Washing medium

Depending on the selected washing medium for the process, there will be additional health and safety risks where an acid based medium is required as opposed to just water. The health and safety implications of the washing medium would need to be assessed dependant on the washing medium. Therefore, at this stage, it is not possible to comment in detail on the associated risk but in selection of the washing medium the health and safety risk from using the chosen medium in a large scale commercial process should be considered. A balance between a washing medium which successfully removes as much of the mercury from the shredded FPDs as possible, whilst not introducing unacceptable health and safety risks, needs to be found.

In addition to the health and safety risk, the selected washing medium may require a re-assessment of the material of construction. If the washing medium is acidic, the material of construction must be compatible and able to handle strong acids. This is likely to add extra capital costs to the project and will result in a reassessment of the overall project economics being required.

5.0 Conclusions and recommendations

The manual disassembly trial held at Bruce Metals, to remove the hazardous mercury backlights from the FPDs, was a success and prepared the material for the next stage of the demonstration project whilst also providing detailed information about the FPDs.

The manual disassembly demonstrated that the backlights can be removed but feasibly the process cannot be scaled up to handle the number of expected units arriving in the waste stream. The risks posed during manual disassembly to the operatives are such that an automated process eliminating the mercury risk would be beneficial.

The Erdwich shredding trial successfully showed that the three shaft shredder chosen was suitable for processing FPDs. Process design to ensure that the shredder could be enclosed to contain the mercury during shredding is required.

Overall the different separation technologies investigated during the FPD TITECH sorting trial showed varying degrees of success, for the following reasons:

- The most successful separations were the metal removal and the glass/film composite separation, with both achieving separation efficiencies of above 75%. The results achieved by the TITECH finder for the metal removal were also very good. In a commercial scale plant it is probable that a magnet and an eddy current separator would be used to remove the metal fractions. A system with a separate magnet and eddy current separator has two key advantages over a TITECH finder. Firstly the metal is removed in two fractions, ferrous and non-ferrous, where as the TITECH Finder removes all metal so a second separation is required to separate the ferrous and non-ferrous. This would obviously increase the costs for the commercial plant, which links to the second advantage. A magnet and eddy current is a cheaper option compared to using a TITECH finder. Testing of a magnet and eddy current is required to assess the separation efficiencies and product purities compared to the TITECH finder.

- The results from the X-tract trial to remove the glass/film composite fraction which initially formed the liquid crystal part of FPDs were promising. The most successful separation was with the LCD TVs. This type of material has not been separated before by TITECH. Bearing this in mind, the initial results show potential and would be considered as the first option in a commercial plant for the removal of the glass/film composite.

- The results of the film removal trial with the TITECH combisense were acceptable and the technique was satisfactory for the trial, but as mentioned previously this would not be the technique used in a commercial scale plant. A simple air separator would be a better option for film removal.

- The results of the polymer separations were not as good as expected. The separation efficiencies were relatively low and the purity of the polymer fractions were below the desired level of 95%. As the trial was conducted in a short time period it is possible that further work with TITECH and further testing of the machine would yield better results. The high percentage of black plastic in FPDs made this separation difficult. A further separation to remove bromine-containing polymers and more purification would be required before the plastic fraction could be sold commercially for high grade applications.

The overall conclusion from the mercury washing trial of the FPDs is that the process used was unsuccessful and would not be suitable at a commercial scale. This is due to the inability of the water to remove the mercury, in conjunction with the mercury levels being very low and the analytical uncertainties, which makes it difficult to trace the mercury around the system.

The laboratory scale trial concluded that water was not a suitable medium for washing the mercury contaminated shredded FPDs. The use of Aqua Regia, a very strong acid, produced significantly better results however Aqua Regia is highly toxic and corrosive and would not necessarily be suitable for use in a commercial plant. The identification of a suitable medium is therefore still required,

Based on the observations made during the plant and laboratory trials it can be concluded that further work is required to develop a process with commercial potential and technical success. The following recommendations are suggested:

- further investigation to determine a wash medium capable of achieving acceptably high levels of mercury recovery in a commercial process and the optimum conditions for use;

- further literature search and experimental work to investigate the optimum conditions for mercury removal using this medium;

- investigation into the adherence relationship between mercury and plastic to assess the ease at which mercury can be desorbed from the plastic;

- further work with to develop the NIR sorting technique and investigation of alternative polymer separations; and

- research to better understand what happens to the mercury when mixed with the shred.

Once the above recommendations have been considered and addressed there would be a requirement to remodel the plant based on the findings.

Appendices

Appendix 1 - Environment Agency classification of FPD waste

Appendix 2 - Review of FPD waste stream report

Appendix 3 - Bruce Metals manual disassembly trial report and trial plan

Appendix 4 - Erdwich shredding trial report and trial plan

Appendix 5 - TITECH FPD sorting trial report and trial plan

Appendix 6 - Mercury Recycling mercury recovery trial report and trial plan

Appendix 7 - SAL Laboratory trial results

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