
Project report

Recycling of laminated packaging



Trials to optimise pilot plant for recycling of laminated packaging wastes

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Front cover photography: Examples of laminated retail packaging

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Executive summary

Laminated films used in the manufacture of the packaging targeted for this project are an increasingly popular option for lightweight product packaging. They comprise a thin foil of aluminium, which is sandwiched, or laminated in a matrix of paper and/or plastic layers, and are used in a range of packaging formats, including pouches, bags and tubes, for the packaging of consumer goods such as food, drinks, pet foods, toothpastes, and cosmetic products. For convenience, this report refers to the range of products as 'laminated packaging'. Because of the relative lightness of laminated packaging, and due to the absence of a commercially viable recycling process, it has not historically been a targeted material for collection by local authorities, as are other, more common forms of packaging.

Enval Limited has developed a technology for recycling these materials. The process is based on a technology known as Microwave Induced Pyrolysis, which is a pyrolytic process in which the energy required for heating the material is provided by microwaves. The outputs are aluminium flakes, and hydrocarbons, in the form of an oil and a gas, suitable for the production of energy.

This report details a series of trials, using a pilot plant built by Enval, to process laminated packaging as a post-consumer waste and reviews the technical, commercial and environmental performance of the process. The project involved research into the market for laminated packaging, including the mix, form and quality of typical materials, how they might be recovered from the household waste stream, practical trials of the process using the pilot plant, and detailed analysis of the findings.

A total of six process trials were performed using a total of 600kg of a 'recipe' of laminated packaging which was formulated to closely simulate the predicted post-consumer mix, including product residues and non-target contamination materials. Output materials were tested for quality and chemical composition. The aluminium was valued by potential reprocessors and the hydrocarbons were priced based on their useable energy equivalents.

The results indicate that the process is technologically and environmentally sound. The carbon emissions associated with the process would be approximately half of that associated with the production of primary aluminium alone. This environmental benefit will be considerably greater in practice due to the surplus energy available from the recovered hydrocarbon outputs which would substitute for non-sustainable energy sources.

The most conservative estimate of the size of the UK market for laminated packaging is some 139,000 tonnes annually, containing approximately 13,500 tonnes of aluminium. Some laminated packaging formats are estimated to be growing by between 10% and 15% per year.

In assessing the commercial viability of the process, it was assumed that post-consumer laminated packaging would become a targeted kerbside recyclable material by waste collection authorities within regions, each supplying one materials recovery facility (MRF). It was further assumed that it would be possible to access one-third of the total laminated packaging disposed by households following a suitable promotional campaign within any region. In this way, the amount of material recovered in any region would be sufficient to feed a commercial scale processing system of 2,000 tonnes per annum gross capacity. This could be placed within, or adjacent to, the MRF. Prior to this happening, the plant will require further development to be sufficiently robust and reliable for operation by semi-skilled operatives. Some modifications would be required within the MRF to automatically recover the materials separately from other aluminium based materials, in particular, used

beverage cans. Based on these assumptions, and including the costs of the modifications to the MRF and those of the transportation of materials, it is estimated that a minimum payback of some four years would be achieved from investment in each commercial scale processing plant. The lifetime of the plant is at least ten years. The payback period, based on the value of the aluminium and the hydrocarbons and the avoided landfill costs, would be improved if the percentage of aluminium in the waste mix was increased, either by the addition of cleaner, post-industrial, waste laminated packaging to the feedstock or by the collection of additional aluminium packaging within the MRF sorting processes.

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Glossary

MBT	Mechanical-Biological Treatment
MRF	Material Recovery Facility
NE	Nichteisen [<i>non-ferrous</i>]
2D	Two-dimensional
3D	Three-dimensional

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1.0 Introduction

1.1 Aluminium/plastic laminated packaging

As a result of a twin approach to making packaging more reliable whilst minimising its environmental impact, there have been many developments in the packaging sector and one product of these developments has been the aluminium/plastic laminate which is commonly used as packaging for consumer goods such as food, drinks, pet foods, toothpastes and cosmetic products. For convenience, this report refers to the packaging under consideration as 'laminated packaging'.

Laminated packaging has become a concern within the recycling sector because, by its very design, it is of low weight, relatively low value, and has, to date, been considered to be completely unrecyclable. In an environment where collection and recovery of recyclates is driven by weight-based targets, they will not be highlighted as an issue until heavier packaging options have been replaced. However, because it makes a significant positive impact on the environmental performance of the packaging product, its use is increasing rapidly.

The low weight of the laminate improves the ratio of product to pack weight and reduces the fraction of transport costs and environmental impacts attributable to the packaging. Also, it ultimately reduces the weight of material that has to be disposed of after the product has been consumed, thus mitigating the effects of landfill taxes. However, the problems associated with recycling the materials used to fabricate these pouches, bags and tubes negate some of their benefits, especially in the view of the consumer who cannot find any environmentally satisfactory method of disposal.

For clarity, reference is made at this point to two other high volume packaging formats that use aluminium as a barrier material but which are not target materials in this project for the reasons given. They need consideration, however, since their aluminium content may bring them into the same recyclable waste streams as the laminated packaging that is targeted for these trials. They are:

- Aseptic beverage cartons – These are predominately fibre-based cartons with aluminium inner linings which serve as a barrier to oxygen, aroma and light. The fibre material is the major element of the pack, with the aluminium content being less than 5% by weight. Used beverage cartons are being collected from the UK household waste stream in increasing numbers for recycling driven by the value of the relatively high quality fibre materials. The recycling process for these items is, therefore, configured around de-pulping and recovery of the fibres, requiring different equipment from that being trialled.
- Crisp packets – These are predominately plastic packs with a very thin aluminium inner coating which is deposited onto the base material. In this instance the aluminium is too thin to recover economically and these packs are not, currently, collected for recycling in the UK.

1.2 Objectives of the project

In an attempt to resolve the problem of recycling laminated packaging, Enval Limited has developed a technology that can recycle these materials and the company had carried out various preliminary studies to assess the technical feasibility of the process. In parallel with this initiative, WRAP supports and promotes the packaging recycling industry with collaborative projects that address the issues of collection, market knowledge, process integration and development with a holistic life cycle assessment view.

Given the potential capability of the Enval process, WRAP commissioned a project to undertake a trial of the Enval process to assess its technical, commercial and environmental

viability and whether it may offer a recycling solution for laminated aluminium packaging not currently recycled or reprocessed in the UK. Oakdene Hollins has worked closely with Enval to deliver the project.

This report details the findings of the project over three phases. These were:

- Research into the mix, form and quality of typical laminated packaging materials that would be found in the household waste stream and sourcing of significant quantities of laminated packaging, including contaminants, such as residual waste product and sundry waste items that would typically be present in these materials should they be recovered from the household waste stream.
- Carrying out practical trials including:
 - a minimum of six recycling process trial runs, each of approximately 100kg gross mass per trial, to establish the technical robustness of the process
 - analysis of process trial data
 - trialling the application of waste sorting technologies at a municipal Materials Recovery Facility (MRF) to determine the technologies required for the recovery of feedstock to the process.
- Detailed consideration of the findings, including the economics of collection and recovery of feedstocks, and marketing of output materials to assess the wider technical, environmental and economic viability of the process in the recovery and recycling of post-consumer laminated packaging.

Whilst the application of the process to post-industrial laminated packaging waste may present a further opportunity to exploit the intellectual property of the process, this is not considered within this project.

1.3 Methodology

The work was carried out between September 2010 and March 2011 by Enval and Oakdene Hollins working in collaboration. The research elements of the project were managed jointly. Enval technical staff carried out the physical sourcing, preparation and processing of the feedstock materials with critical monitoring at all stages by Oakdene Hollins technical consultants.

The following tasks were completed:

- Office-based research using web searches, email, telephone interviews, and peer meetings to establish:
 - the market size for laminated packaging in the UK;
 - the theoretical mix and quality of feedstock that would be expected to be available from householders, were local authorities to include laminated packaging on their lists of targeted recyclable materials;
 - issues associated with the practicalities and costs of recovering waste laminated packaging from the household waste stream; and
 - the potential values of output materials to reprocessors and other end users.
- Visit to a Mechanical Biological Treatment (MBT) plant and a MRF to support the findings of the desk-based research on the mix and quality of feedstock, and to assess and discuss typical optimum sorting processes and the contaminants that might be expected to be present when recovering laminated packaging from co-mingled waste streams using appropriate waste sorting technologies.
- Sourcing, preparation and delivery of feedstock to the trial site.

- Management of six process trials including recording and analysis of all process parameters, mass balance calculations, and characterisation of all output materials, as follows:
 - determination of a set of optimised process parameters that enable Enval to extract clean aluminium foil from the waste;
 - qualitative and quantitative assessments of the reproducibility of the performance of the Enval process when operating with near-industrial scale quantities and on a near-continuous basis;
 - demonstration that the technology is capable of processing mixed post-consumer laminated packaging waste including product residues;
 - demonstration of the recovery of high quality aluminium and a mixed hydrocarbon that may be used as a fuel; and
 - generation of sufficient data to produce detailed assessments of the environmental and financial impact and viability of the Enval process at this scale.
- Analysis of product output qualities, quantities, values and potential end use markets.
- Critical review of the technical, environmental and economic viability of the process.
- Preparation of the final report.

1.4 Report layout

This report presents an introduction to laminates and the Enval process followed by the detailed feedback for each project task and the results obtained.

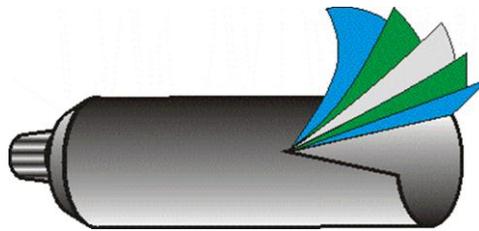
2.0 Laminated packaging

2.1 Materials and applications

Laminated packaging is an increasingly popular option for lightweight product packaging, comprising multiple thin layers of material, each with a particular function. These laminates are currently used in numerous packaging applications such as stand-up pouches, e.g. drinks containers or coffee pouches, or laminate tubes, e.g. toothpaste or cosmetic tubes. They have extremely low densities and the market for laminates is growing particularly strongly at the present due to a trend for 'light-weighting' product packaging.

The laminated packaging targeted for this project is available in a wide range of formats. They all contain a thin foil of aluminium, which is typically between 6-30µm (microns) thick and is sandwiched, or laminated, in a matrix of paper and/or plastic layers. The most commonly used plastic is normally polyethylene terephthalate (PET), often in conjunction with low density polyethylene (LDPE). A typical example of laminate packaging is the tubes used for toothpaste and cosmetic products, a schematic diagram of which is shown in **Error! Reference source not found.**

Figure 1: Different layers present in a typical toothpaste tube



Key:

Blue:	Polyethylene
Green:	Polyethylene copolymer
Light Grey:	Aluminium foil

Other examples include pouches for pet food, ready meals (for example soups and pulses), baby food, fruit juice and smoothies, bags for ground coffee and sachets for powders such as hot chocolate or sauce mixes etc.

The aluminium foil barrier performs two major functions. Firstly it prevents the loss of any aromas or perfumes in the product, as otherwise it would permeate through the polymer layers and would become slowly lost. Secondly, it also provides long-life protection from ultraviolet (UV) light and gas diffusion into the packaged products. UV light causes photo-oxidation reactions in many foods and other products, especially those containing fats (like milk and cream), thus reducing some of their nutritional value and giving an unpleasant rancid taste caused by the reaction products. Besides these protective attributes, the aluminium foil also helps provide mechanical rigidity to the packaging.

As well as these fundamental attributes provided by the laminated packaging the use of these materials has additional secondary advantages, such as:

- It has an aseptic nature. Products can be packaged for many months without suffering deterioration. This results in a reduced need for refrigeration or freezing, resulting in reduced energy consumption during product storage.
- The preserved food can be transported economically because the volume/weight ratio of the packaging is high.

- In many situations the manufacturers of products packed using these laminates save money because they receive the packaging in the form of printed reels ready to be shaped and filled. This significantly reduces both the transport and storage requirements of empty containers and hence the cost of their products.

In contrast to these advantages, however, laminated packaging systems have one serious drawback: there is currently no adequate and proven technology capable of fully recycling these materials in an efficient and cost-effective manner. Indeed, the combination of plastic and aluminium in the waste presents a technical recycling challenge that until now has remained unsolved, resulting in the need for these materials to be disposed of by conventional means. Despite their lightweight nature, the huge quantities of packages that are involved dictate that many thousands of tonnes per annum of laminate waste are being disposed to landfill or incinerated. Environmentally this is undesirable since the resources (aluminium and plastic) employed to produce it are wasted and more must be extracted from nature to replenish them. Beyond this, on an economic level, not only is the current disposal method costly, there is considerable value in both the aluminium and plastics that could be exploited if a viable recycling route could be identified.

Based on discussions with the Aluminium Packaging Recycling Organisation (Alupro), it was established that aluminium used for laminated packaging is an '8000 series' alloy. This differentiates it from that used in aluminium cans which are produced using a '3000 series' alloy. According to Alupro, this does not detract significantly from the potential value of the material in the reprocessing market since the tonnages of aluminium that might be recovered from laminated packaging using the Enval process would be low relative to that from aluminium can recycling. It follows that the two recycled materials do not necessarily need to be kept separate during waste recovery sorting processes.

2.2 Summary of market size, market trends and product mass

The adoption of laminated packaging has increased significantly in recent years driven by the advantages it offers over more established packaging systems. An estimate of the UK market size is calculated in Section 3.2 at 139,000 tonnes of packaging per year, containing, on average, some 9.7% aluminium foil by weight. The market has a growth rate of approximately 10% annually.

Weights of the laminated materials for the most common products range from 3 grammes each, for some pet food pouches, up to 11 grammes each for some coffee packs. Also, when recovered from the household waste stream the presence of residual product, such as pet food, drinks and toothpaste, add substantially to the waste mass and this has to be considered when assessing waste handling volumes and the organic material outputs from the recycling process.

2.3 The Enval process

The Enval process has been developed to focus on the recycling of aluminium-containing laminate structures and is based on a technology known as Microwave Induced Pyrolysis, which is a pyrolytic process in which the energy required for heating the material is provided by microwave energy.

In general, pyrolysis is a process in which an organic material, such as paper or plastic, is heated in the absence of oxygen, thereby causing the degradation of the material by effectively shortening the material's molecular length, but without any oxidation, combustion or incineration taking place.

Everyday experience demonstrates that plastics do not readily heat up using microwaves; for instance, plastic dishes stay relatively cool even if their contents do become hotter.

However, in the Enval process, carbon is heated by microwaves and the hot carbon is used as the heat source for the pyrolysis of the plastics.

Carbon is a highly efficient microwave absorber that can absorb the microwave energy and then transfer it by conduction to the plastic. This provides a very efficient, but mechanically gentle, heat exchange. In the case of laminates, the Enval process causes the degradation of the plastics present in the laminate and the formation of other useful products, known as pyrolysis oils, which can be used either as fuel to generate electricity or as feedstock for speciality chemicals. The fragile aluminium foil remains undamaged after processing and is extracted as clean material that is suitable for reintroduction into the aluminium recycling supply chain.

It is understood that the Enval process has the potential to treat most flexible aluminium/plastic laminated packaging systems, whether they are in the form of post-consumer waste or commercial and industrial waste from the packaging, production and filling processes.

Commercially, therefore, it offers a route to enable the almost complete recycling of laminated packaging waste by separating and extracting the high value materials contained within. In addition to the value derived from the production of aluminium and energy/chemicals, there is the potential to realise an additional revenue stream by avoiding transport of wastes, gate fees and landfill charges.

Environmentally, the recovery and recycling of aluminium, as well as reducing the demand for virgin materials, is expected to save considerable energy, as the energy consumption used in the production of recovered aluminium is just 4% of that used in the production of primary aluminium from bauxite.

Furthermore, when recycling aluminium, the industry estimates that about 1-2% of the aluminium being reprocessed is lost as oxide; this is in addition to a further 1-2% lost by the presence of aluminium oxide on the feedstock material. When laminated packaging is pyrolysed, the aluminium is not exposed to oxygen during the process, so there is no further oxidation and loss of metal.

The scientific foundations behind the Enval process have been presented in a number of forums and publications.

3.0 Phase I - Initial research

3.1 Introduction

Clearly the mix of packaging formats and contamination is of paramount importance to the validity of the process trials. The waste materials to be used must consist of, or must closely simulate, mixed post-consumer laminated tubes and pouches.

Prior to the start of the project it had been intended to undertake at least one process trial using post-consumer waste taken from actual household collection rounds and recovered in a sorting process at an MBT plant or a MRF. In this way, a typical mix of the different packaging formats, together with appropriate contaminants in the form of product residues, non-targeted items and other wastes, would be achieved.

The balance of the tests were planned to be carried out using a simulated mix of materials sourced from post-industrial sources, i.e. the material that is scrapped during the manufacturing and filling of the packaging. These materials are easily accessible and available in substantial amounts.

In the event, field tests carried out at the MBT plant demonstrated that the option to source an adequate quantity of post-consumer waste taken from household collection rounds was not found to be practical, as described in Section 3.3.1. All of the process trials were, therefore, carried out on the simulated mix of materials sourced from post-industrial sources.

Laminated tubes are predominantly used for toothpaste, but they also contain cosmetics, food, pharmaceutical, and other household and industrial products. Laminated pouches are used for pet food, human food, and drinks and non-food items. To simplify feedstock sourcing for the bulk of the trials, the range of packaging products considered in the research was reduced to:

- toothpaste tubes;
- pet food pouches;
- drinks pouches; and
- coffee bags.

3.2 Market size

Given the diverse range of laminated packaging formats currently being used by the food, drinks and pharmaceutical industries, accurate confirmation of the market size, of packaging items relevant to this project, is not possible. The rapid growth in the use of these products is also a factor. Estimates have been made based on:

- data provided by packaging manufacturers;
- data for aluminium consumption; and
- field analysis of packaging weights.

Data provided by the packaging manufacturers suggest that, on average, laminated packaging contains some 9.7% foil, as a percentage of its total weight. This figure is supported by research carried out by Judge Business School, Cambridge, in 2008, which was based on interviews with the key laminate packaging manufacturers in Europe and on practical studies of aluminium content of sample packs.

Additional data for aluminium in the waste stream is provided by Alupro based on data from Defra in 2008¹. This suggested that some 14,400 tonnes of aluminium was in the UK waste stream in composite packaging, a figure which includes aseptic fibre based beverage

¹ <http://www.alupro.org.uk/facts-and-figures.html>

cartons. To arrive at a gross weight of laminated packaging relevant to this project, the weight of aluminium used in beverage cartons in the UK must be deducted. According to Tetrapak the recovery and recycling of used beverage cartons totals some 900 tonnes per year².

The above puts our estimate of laminated packaging entering the UK market and, thereby, ultimately entering the household waste stream, at 139,000 tonnes, as set out in **Error! Reference source not found.**

Table 1: UK Laminate packaging market and potential for the Enval process (2008)

Aluminium foil in composite packaging in the UK	14,400 tonnes / annum
Less aluminium foil in beverage cartons	(900 tonnes / annum)
Net aluminium content of laminated packaging	13,500 tonnes / annum
Average percentage of foil used in laminated packaging	9.7%
Total amount of laminated packaging in the UK (= 13,500 ÷ 9.7%)	139,000 tonnes / annum

Also, according to a report on complex packaging trends, commissioned by WRAP in 2010, and a further study by PCI Films Consulting³, the growth rates for the total production of pouches and tubes have been of the order of 10% to 15% per annum over the past five years. Assuming that this trend is continuing, and that it applies to other plastic laminated packaging formats, the figures shown in Table 1 are likely to be considerably understated.

The Judge Business School report also estimates that, approximately 190,000 tonnes of aluminium are used in laminated packaging in Europe, excluding those used in fibre-bonded beverage cartons. Information obtained directly from the commercial laminators and converters of these materials indicates that the production yield loss for laminate pouches is approximately 5% and that wastage for toothpaste or cosmetics tubes can be as high as 20%. This high reject rate, arising both from the manufacture of the laminated packaging and packs and from product filling, strongly indicates that there is also a potentially significant market for a recycling process based on production waste alone. The application of the process to post-industrial waste, however, is outside the scope of this project.

It should be noted that the figures in Table 1 represent 100% of the total available market and it would be unrealistic to expect that all of the above material would be recoverable from the post-consumer waste stream. The commercial analysis of the recycling process that follows, therefore, is based on a realistic estimate of the proportion of this material that is likely to be collectable from households following a promotional drive by the collection authorities.

3.3 Determination of post-consumer material mix

3.3.1 Practical tests with sorted materials from the household waste stream

The data gathered from the above research were analysed to determine the packaging weights and the 'predicted' mix of the targeted packaging types that is currently present in the household residual waste stream.

² www.tetrapakrecycling.co.uk/tp_faqs_renew.asp

³ PCI Films Consulting 'The European Market for Stand-Up Pouches 2010'

Secondly, a practical material recovery trial was carried out at an MBT plant which receives 'black bag' household waste and recovers a range of recyclates and a compostable fraction. By manually sampling the recovered aluminium fractions from the plant it was possible to sense-check the market data derived from the desk research and, importantly, to provide best estimates of the degree and type of residual product remaining in the packaging materials at the point of disposal.

The material recovery trial was performed using samples taken from Donarbon's MBT facility near Waterbeach, Cambridgeshire. The plant takes black bag waste and uses a number of separation techniques, including eddy current separators, ballistic separators and near infra-red detection to separate the waste into different fractions. After an initial visit to the MBT plant, it appeared that the laminates could end up in two of the output fractions: the 2D plastics and the NE (Nichteisen or non-ferrous) materials. The 2D bin contained essentially flat, mainly-plastic material and the NE bin contains flat or semi-flat non-ferrous metal-containing materials. It was therefore decided that samples from both fractions would be taken and analysed so that the composition and the kind of laminate could be determined.

A 330kg sample of material was taken from the NE collection bin, after passing through the MBT plant, and manually sorted to determine the presence and quantity of laminates.

Discussions took place with the operator of a municipal MRF to establish if the non-ferrous output stream from a MRF could provide an alternative source of post-consumer waste. However, since laminated packaging is not a targeted recyclable material for collection authorities, it is only present in the MRF feedstock by accident and, therefore, arrives in even smaller quantities in the MRF output stream. It was concluded, therefore, that the process trials could only be carried out by using a simulated mix of post-industrial materials.

Following sorting of material at the MBT plant, samples of the laminates recovered were taken and their individual masses measured. They were then cleaned, dried and reweighed. This allowed the quantification of the residual content to packaging ratio in a representative sample of packaging. A minimum of five samples of each type of laminate was investigated.

3.3.2 Establishing a feedstock recipe for the process trials

Calculations were then performed to estimate the quantity of specific laminate materials (inclusive of residual product) which would be expected to be found in the samples taken from the MBT plant based on the foregoing estimated market data. It was assumed that the flow through to the waste stream, of post-consumer packaging to that particular MBT plant, is in proportion to the estimated consumption

A final calculation was required to establish quantities of non-target materials that might be present in any recovered waste stream. If laminated packaging becomes a targeted material for waste collection authorities, it is anticipated that much of the feedstock for future processing will be collected through MBT plants and/or MRFs. In general, material stream outputs from either sorting process contain a small amount of non-target materials. Therefore to correctly simulate post-consumer waste, non-target materials (non-laminates) should be added to the mix. Previous work by Oakdene Hollins, concentrating on line speeds at MRFs, has generated a significant amount of data on the amount and type of non-target materials found in recyclates. From this, an estimate was made of the amount of non-target materials to add.

Based on the above trials, and considering the materials which are easily accessible in substantial amounts, it was decided that the material 'recipe' to be used for all of the process trials would be as Table 2 (by mass).

Table 2: Material mix, by percentage of clean material and residues

Item	Proportion of clean material	Add	Product residue material	Proportion of product residue
Pet food pouches	30.4%	+	Pet food	11.5%
Drinks pouches	12.0%	+	Juice	2.5%
Coffee pouches	16.3%	+	Coffee	2.7%
Toothpaste tubes	6.1%	+	Toothpaste	14.5%
Aluminium cans	2.0%			
Plastic bottles	1.0%			
Paper	1.0%			
Totals	68.80%	+		31.2%

4.0 Phase 2 - Process trials at Enval

4.1 Introduction

After determining the composition of feedstock laminate mixes in Phase 1, the next stage of the project was to source and prepare suitable feedstock materials and use them to undertake process trials with the Enval Microwave Induced Pyrolysis process.

The aims of this second phase of the project were to:

- establish optimised process conditions for the extraction of clean aluminium including optimisation of waste preparation (shredding, cleaning, etc.)
- explore the sensitivity of the process performance to different process variables to establish a standard process envelope for treating the waste
- assess the reproducibility of the process performance both within a given run and between runs performed at different times
- collect and characterise considerable amounts of hydrocarbon products so that these can be assessed to establish and maximise their value
- collect considerable amounts of aluminium so that the metal obtained can be analysed.

These tests were carried out using the recipe of laminated materials contaminated with product and as described in Section 3 above. Preparation tests were carried out on shredding the waste stream and were performed by Enval using several suppliers of shredding equipment. The pyrolysis tests were also carried out by Enval using its' continuous process pilot-plant in Luton. The aluminium and hydrocarbon process outputs were analysed by the University of Cambridge.

4.2 Waste preparation

The feedstock to the process trials had firstly to be shredded down to two dimensional flakes of approximately 30mm x 30mm, or smaller. Further preliminary trials, therefore, involved the shredding of small amounts of clean laminate with a variety of commercial shredders to find the best type of equipment for this operation. Samples were sent to various suppliers and the shredded samples were returned to Enval for assessment.

Results that conformed to Enval's process feedstock specification were achieved with a standard four-shaft shredder, with 30mm mesh, as shown in Figure 2 and specified in Table 3

Figure 2: An UNTHRA RS-30 Shredder



Table 3: Shredder specification

Model	Untha RS-30
Cutter clearance	450 x 560 mm
Driving power	11 kW
Through-put	Up to 1,000kg / h

Once the correct shredding parameters had been established, a variety of different laminates were separately shredded, down to flakes with a surface area of between 400 and 1,100mm².

Since drinks pouches and coffee bags for the trials were sourced from industrial filling operations, they already contained some product residues. They could, therefore, already be categorised as 'post-consumer' wastes and there was no need to add representative residual product to the batches.

However, it was not possible to obtain sufficient quantities of post-consumer pet food pouches or toothpaste tubes. As a result, the mix to be used in the process trials was prepared by using the following materials and the composition shown in Table 2. This comprised a mixture of:

- shredded used juice pouches;
- shredded used coffee bags;
- shredded clean toothpaste tubes;
- shredded clean pet food pouches;
- shredded post-consumer paper, plastic bottles and cans;
- toothpaste; and
- pet food.

It is important to appreciate that by using this formulation, the final mixture presented levels of product residue contamination that would be in excess of actual post-consumer waste, since most of the residual material present in pet food pouches is gravy and not the actual pieces of meat, which was added to the mix. In adding this type of contamination, the boundaries to which the process would normally be expected to operate were extended beyond the expected normal operating conditions. This may be countered in a small way by arguing that some residues, other than those expected to be found in the laminated packs, would be present in a mix of materials recovered from household waste. The form and quantity of such 'external' contamination would depend on the method of recovery. For instance, if recovered from residual waste, as within an MBT plant, such contamination would be greater than if the materials were recovered within a MRF from a co-mingled, recyclable feedstock which would be cleaner. Subsequent sorting trials, carried out at a MRF, are reported later in this report. Based on these trials, and from discussions with some local authorities, it is assumed that, if the recycling process were to be commercially exploited, the favoured source of post-consumer material would be the latter, i.e. the materials would be targeted by the authorities and would remain relatively clean within a co-mingled collection. External contamination of the laminated packaging from household waste collections is, therefore, not considered to be significant.

Trial batches of feedstock were produced by manual mixing of the weighed recipe components to form a homogeneous blend, as shown in Figure 3.

Figure 3: Photograph of the waste mix after preparation



4.3 Process trials

4.3.1 *Equipment and method*

Figure 4 shows a diagram of the experimental Microwave Induced Pyrolysis apparatus used to perform the tests.

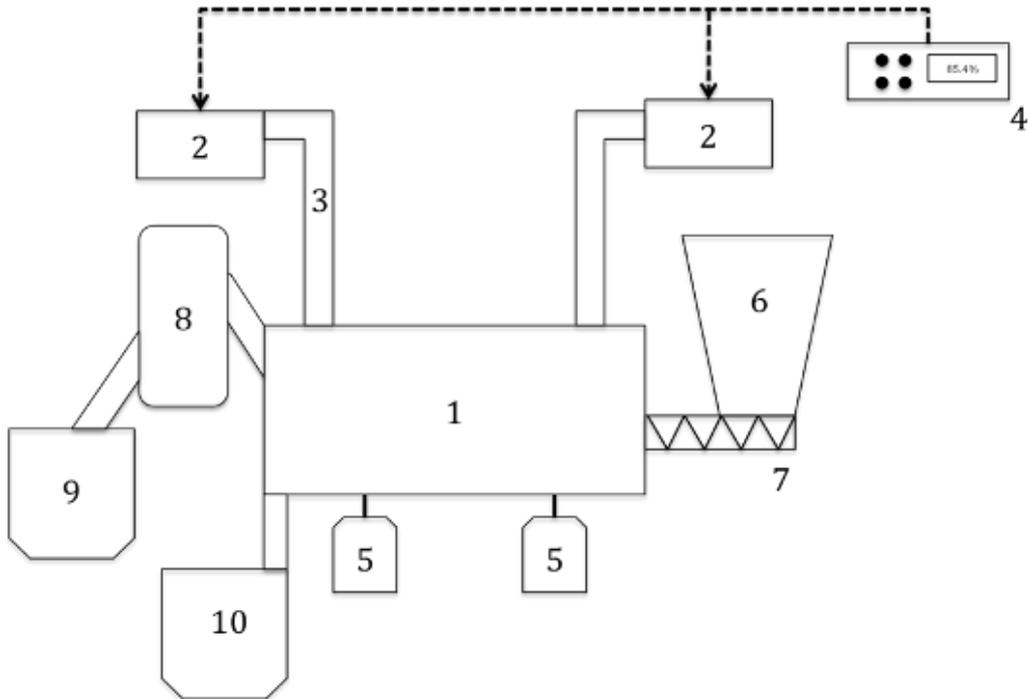
The equipment consists of a kiln (1) connected to two microwave sources (magnetron and iso-circulator) (2) using a standard microwave guide (3). The magnetron output power can be varied from 0 to 100% using the control panel on its power supply (4).

The kiln has an agitation system (5) that ensures an even temperature and promotes heat and mass transfer during the test. The temperature of the kiln is monitored using eight thermocouples that enter the chamber through the side walls. The thermocouples are in direct contact with the load inside the kiln, and are connected via a data acquisition card to a computer that continuously records the temperature.

The kiln is fed using a nitrogen-purged hopper (6) and a screw conveyor (7). The entire apparatus operates at atmospheric pressure and is completely sealed to avoid the presence of oxygen during pyrolysis and the escape of pyrolysis gases.

The pyrolysis products exit the reactor and pass through two water jacket condensers (8). The condensable products are collected in three separate collection drums (9). The recovered aluminium discharges into a solids recovery pot (10).

Figure 4: Schematic diagram of Enval's pilot plant



Key:

- | | | | |
|---|------------------------------|----|------------------------|
| 1 | Kiln | 2 | Microwave source |
| 3 | Microwave guide | 4 | Power supply |
| 5 | Agitation system | 6 | Hopper |
| 7 | Screw conveyor | 8 | Tube condenser |
| 9 | Condensables collection drum | 10 | Aluminium recovery pot |

An image of the plant is shown in Figure 5.

Figure 5: Photograph of Enval's Pilot Plant



4.3.2 Trial method

Each test commenced with heating the kiln and purging it with nitrogen. The kiln contains carbon, which acts as a microwave absorber. The kiln was heated to the required reaction temperature while a small flow of purging gas (N₂) flowed through it. The cooling system of the condensers was set to the appropriate temperature and the auxiliary systems (essentially the magnetrons and the cooling systems for the seals) were started.

Once the kiln had reached a stable operating temperature, material was fed into it from the feeding hopper at the desired feed rate, typically of between 25 and 35kg/hr. Each trial processed a feedstock of 87 to 107kg.

The operating temperature was maintained to within +/- 5% of the set point by manually changing the output power of the magnetron.

The waste laminated plastic feedstock was continuously fed into the kiln through a series of two hoppers that provided an air lock. The waste was put into the first hopper, which was then evacuated to a low pressure and backfilled with nitrogen to remove any oxygen. The feedstock in its nitrogen atmosphere was then transferred to the second hopper located beneath the first one, from where it was fed into the kiln. The feeding and purging of the first hopper is done in batches but the second hopper maintains a level of waste at all times, hence maintaining a continuous feed into the kiln.

The kiln also operates under a nitrogen atmosphere to prevent oxidation and combustion of the feedstock material. It comprises a bed of microwave heated carbon, onto which the laminated packaging is fed and from which heat is conductively transferred to the laminated packaging. Inert atmosphere pyrolysis of the laminate can then take place, during which the plastic is broken down into lower molecular weight species and the aluminium is released from the laminated structure.

The condensed products from the kiln were collected in the collection drums and the aluminium in the solids recovery pot. Gas sampling was possible at the exit of the condensation system by collection into a gas sampling bag which could be later analysed off-site.

After each test, samples of condensable and non-condensable products were analysed by gas-chromatography coupled with mass spectrometry (GC-MS) and the results from the analysis were inputted into a process simulator, to obtain the physical properties of the mixtures. The aluminium was analysed by a pressing and melting test to obtain its metal yield and hence the purity of the product.

A series of six pilot plant trials were conducted during which greater understanding of the process and the effects of feedstock on the process was sought. Trials 1-3 focussed on process parameter identification, whilst Trials 4-6 focussed on process reproducibility and finer tuning of the process parameters.

As is common with demonstration/pilot plant trials, there were a number of unexpected breakdowns of the plant. However, information and experience gained from the breakdowns provided opportunities to improve the robustness of operation of the plant. The results obtained from each successful trial also facilitated the process criteria to be incrementally modified as further experience and knowledge was gained.

5.0 Phase 2 (continued) – Results of process trials

5.1 Magnetron power

Pyrolysis of laminated packaging is an endothermic reaction, that is, it absorbs heat. To maintain the processing temperature, therefore, energy needs to be inputted into the reaction kiln.

Heat was input into the kiln by two separate magnetrons, with both operating at approximately 75% of maximum power, being controlled from one controller.

5.2 Mass balance analysis and process optimisation

During pyrolysis, thermal decomposition of the plastic and waste products takes place. It is important to understand that no oxidation takes place, so all the products are derived from the thermal decomposition of the feedstock materials.

There are four product streams derived from this pyrolysis process:

- Aluminium;
- Water;
- Condensables; and
- non-condensables.

Aluminium is the output material recovered from the laminated plastic and any other waste aluminium product that was present in the feedstock waste stream.

Water is a result of the drying and decomposition of the product contamination.

Condensables are oils and high molecular weight hydrocarbons that can be condensed from the gaseous outputs of the pyrolysis process; they are suitable for use as fuel.

Non-condensables are gases that cannot be easily condensed from the gaseous outputs. They are typically lower molecular weight hydrocarbons and are suitable for burning as a gaseous fuel.

Figure 6 shows a sample of the aluminium recovered from Trial 5, and **Error! Reference source not found.** shows the condensables output from Trial 3.

Figure 6: Photograph of the aluminium flakes produced (Test 5)



Figure 7: Photograph of the condensable products collected (Test 3)



The yields of aluminium and condensable products were obtained by direct measurement of the mass of waste fed into the equipment and the weight of the recovered solid and liquid products. The yield of non-condensable products was taken as the difference between these two weights.

It is possible to calculate the theoretical mass outputs from the laminated plastic waste stream used in the trials and these are compared against the actual mass outputs. The mass balance calculations are summarised in the following tables.

The assumptions used in the mass balance calculations are shown in Table 4.

Table 4: Data and assumptions used for theoretical mass balance

Item	Assumed percentage	Data source
Content of aluminium in packaging actually used in trials	Approx. 10%	Based on data sheets provided by suppliers
Content of polymer in packaging	Obtained by difference from point above	
Organic pyrolysable matter in pet food	25%	Based on data found at US FDA: http://www.fda.gov/animalveterinary/resourcesforyou/ucm047113.htm
Organic pyrolysable matter in coffee grains	90%	Based on data found at CoffeeResearch.org: http://www.coffeeresearch.org/coffee/scaaclass.htm
Organic pyrolysable matter in toothpaste	40%	Based on product data
Water content of products above	Obtained by difference from points above	
Water content of juice	100%	
Water collected with condensable products	100%	
Organic pyrolysable matter that turns into condensable products	10 – 70% depending on process conditions	

From these assumptions it is possible to estimate the theoretical yields of the aluminium, condensables and non-condensables.

Table 5: Theoretical yields of fractions from the pyrolysis of the waste mix

Aluminium yield (%)	Condensables yield (%)	Non-condensables yield (%)
11.7	32.0 - 65.7	22.6 – 56.3

The experimental data obtained are shown, by trial, in Table 6.

Table 6: Yields obtained during tests with the Enval process (% of total waste)

Trial	Aluminium yield (solid) (%)	Water yield (%)	Condensables yield (%)	Non-condensables yield (%)
1	15.7	22.9	39.9%	21.5%
2	13.0	13.2	62.2%	11.6%
3	11.9	24.7	42.6%	20.8%
4	9.1	21.9	16.7%	52.3%
5	9.6	24.3	18.2%	47.9%
6	9.3	28.4	19.2%	43.1%

Note should be made that the water yield is shown in Table 6 and not in Table 5. The water is a necessary by-product when pyrolysing contaminated laminated plastics. It is collected mainly as a condensable product and should be separated from the condensable oil yields. However, there is evidence to suggest that the presence of water in these oils can assist their combustion efficiency. Not all water will be collected as a condensable by-product as a very small amount will be carried over into the non-condensable stream.

Initial trials (Trials 1-3) focussed on process parameter identification, whilst later ones (Trials 4-6) focussed on process reproducibility and finer tuning of the process parameters. Apart from providing an initial check, it was noted that much more information could be obtained by analysing the differences in the aluminium yield between the earlier and later trials, and observing the quality of the metal recovered after each trial. For instance, Trials 1 and 2 gave aluminium yields that were considerably above the theoretical yield, which suggested that some char was present, and this was borne out by a visual check of the output material. This analysis allowed the possibility of assessing the quality of the pyrolysis process for a given set of process conditions and thereby optimising the overall process. Following this analysis and adjustments to the process conditions, the later trials produced more predictable yields and a cleaner output product.

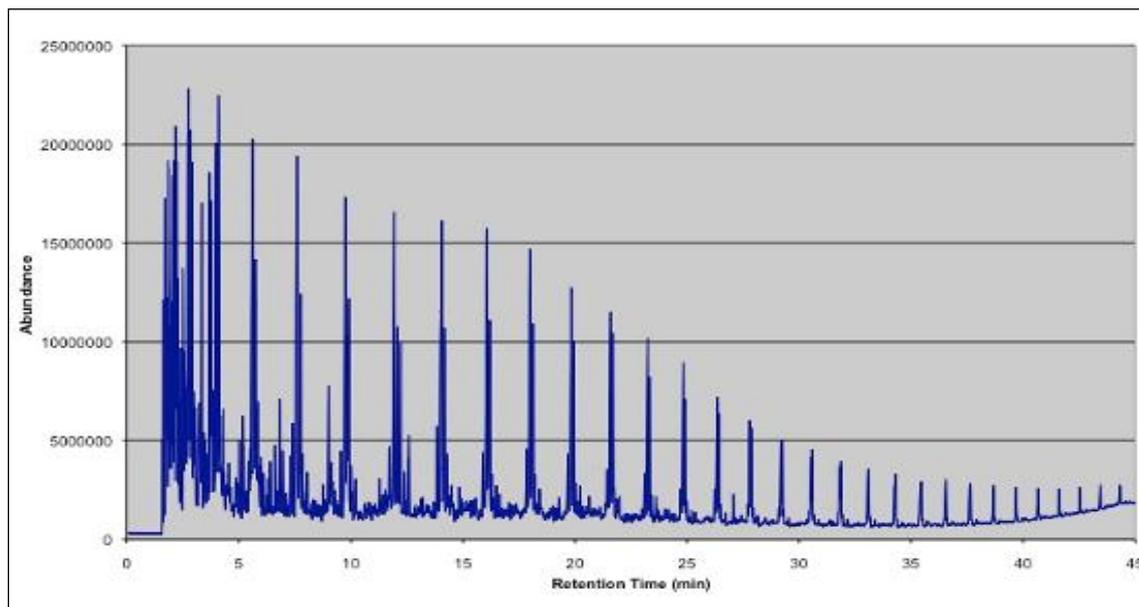
Using the above data, the theoretical yields are compared against the experimental data obtained in Trials 4-6. From this it can be concluded that the amount of aluminium recovered by the pyrolysis process is about 80% of the theoretical yield and that the amount of condensable material, including water, is about mid-range of the predicted range. The non-condensable recovery rate is again about midpoint of the predicted range, but a caveat should be given, as the non-condensable products are calculated by the difference between the quantifiable aluminium and condensable product recovered and the original total mass; it is therefore assumed that any unaccounted mass is due to it being non condensable products. Whilst being a valid assumption, it can also mask other unaccounted losses.

5.3 Chemical analysis of the condensable and non-condensable products

The hydrocarbon products were analysed using GC-MS. Figure 8 shows the typical Total Ion Chromatogram (TIC) obtained for the condensable fraction of the first two trials which, as can be seen, produced substantially more condensables than non-condensables. This was due to a combination of process conditions and carbon used.

The TIC obtained shows all the characteristics that would be expected from the pyrolysis products derived from compounds such as those found in the waste mix. For instance, the TIC shows a large number of aliphatic (linear and branched) and aromatic compounds at lower retention times (on the left hand side of the graph). These compounds would have been produced from the pyrolysis of PET, organic matter in the residues and the paper contamination. On the right hand side, which is the higher retention time area, it is possible to see the typical groups of peaks that are formed from the pyrolysis of LDPE.

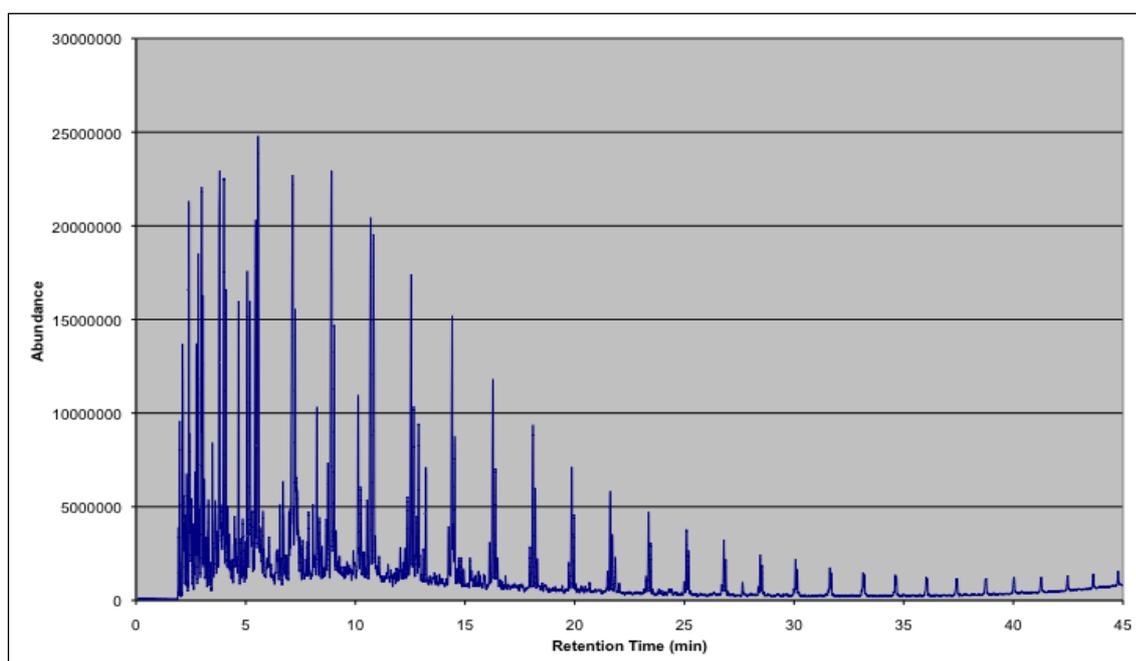
Figure 8: Typical TIC of the condensable products obtained (Tests 1 & 2)



It is important to note that the condensable products were analysed on a 'water-free' basis. This was because the organic compounds and the water form two distinctive liquid phases in the collection drum and it was possible therefore to take samples only of the organic phase for subsequent injection into the GC-MS.

Figure 9 shows a typical TIC obtained for the condensable products of Trials 3-6. Qualitatively, these products were more fluid than the ones obtained during the first two trials and this can easily be seen in the TIC: The number of long chain aliphatic hydrocarbons (right hand side) was substantially reduced and most compounds in the mix presented shorter retention times (left hand side). The compounds presented a higher degree of branching and aromaticity.

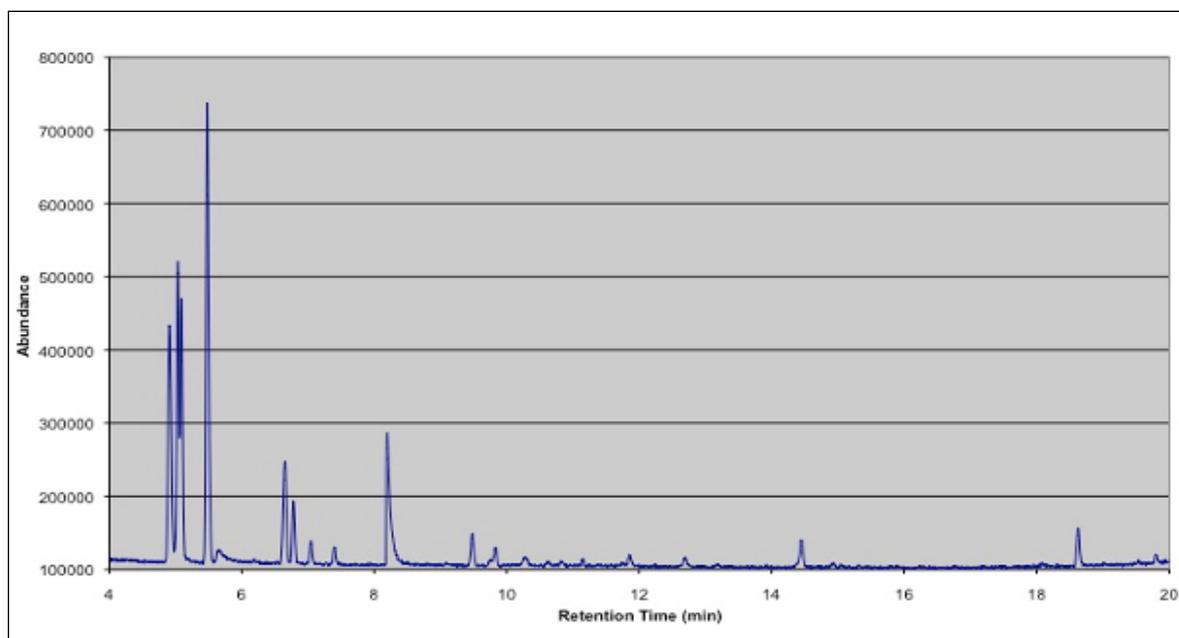
Figure 9: Typical TIC of the condensable products obtained (Trials 3-6)



It is possible to allocate certain compounds to each TIC peak, and this is most readily done by some analysis software included with the GC-MS equipment, from which a breakdown of the most abundant compounds was obtained.

The non-condensable products were also analysed using GC-MS and the number of compounds found in the mixtures was considerably less. Figure 10 shows a typical TIC obtained with the non-condensable products. As with the condensable products, the compounds found were those that would be expected when pyrolysing the kind of materials present in the waste mix. However it is important to note that water is listed in the compounds found. This is due to the fact that considerable amounts of steam were generated in the kiln, either by the pyrolytic reactions or simply from the water already present in the mix and clearly not all of it was being condensed in the condensers. Despite this fact, given that the amount of water found in the non-condensables was not considered substantial, the assumption presented in the analysis of the mass balance (that all the water condenses with the oils) is still considered valid.

Figure 10: TIC of the non-condensable products obtained



Given the nature of the mixtures produced during the process, the results of the GC-MS were entered into a chemical process simulator, so that the main physicochemical characteristics could be calculated; this was carried out using the average composition of the products obtained from Trials 3-5. The results of these simulations are presented in Table 7 and Table 8 for condensables and non-condensables respectively.

Table 7: Main physicochemical characteristics of the condensable products

Characteristic	Value
Molecular Weight (kg / kmol)	134.6
Molar density (kmol / m ³)	6.02
Mass density (kg / m ³)	810.3
Molar heat capacity (kJ / kmol °C)	256.7
Mass heat capacity (kJ /kg °C)	1.91
Mass high calorific value (MJ /kg)	37.2
Mass low calorific value (MJ /kg)	32.6
Molar Heat of vaporisation (kJ / kmol)	73650
Mass Heat of vaporisation (kJ /kg)	547.2
Surface Tension (dyne/cm)	22.7
Viscosity (Pa-s, calculated @ 60 °C)	0.000615

Table 8: Main physicochemical characteristics of the non-condensable products

Characteristic	Value
Molecular Weight (kg / kmol)	39.43
Molar calorific value (MJ / kmol)	1600.8
Mass calorific value (MJ /kg)	40.6
Heat capacity (kJ / kmol °C)	49.7
Compressibility factor (Z)	0.992
Density	1.32
Volume base calorific value (MJ / m ³)	41.7

The results shown in Tables 7 and 8 show that all the hydrocarbon produced by the pyrolysis reactions are suitable for energy generation. The mass calorific value for condensable by-products is between 32.6 and 37.2 MJ/Kg, whilst the value for non-condensable products was found to be 40.6 MJ/kg. These values are comparable with those normally quoted for conventional fuels such as diesel (46 MJ/kg) or natural gas (39 MJ/m³).

5.4 Analysis of aluminium

From pressing and melting tests with the aluminium obtained from the process, it was found that the aluminium recovered showed a metal yield between 70% and 75%, which correlates well with the visual examination of the product. These values for aluminium content are slightly below what Enval has obtained with other types of waste which did not include the substantial amounts of residual product in the waste mix.

As noted earlier, the type of aluminium used in beverage cans is 3000 series, compared with aluminium as used in laminated packaging, which is 8000 series, and this may affect the value of the recovered material.

The 3000 series aluminium is an aluminium-manganese alloy that can also contain silicon, copper and magnesium. It is widely used in sheet products and is non-heat treatable. It has good corrosion resistance and moderate strength when it is cold worked and is also used in the transportation industry for trucks and marine applications. It has good formability and weldability.

The 8000 series aluminium contains other elements, such as lithium and is a more specialist alloy that is designed to behave electrically more like copper, will retain its strength and does not easily work harden.

5.5 Proof of principle

In summary, the trials conducted on the Enval pilot plant have therefore shown that Microwave Induced Pyrolysis is capable of processing waste laminated packaging. The average weight of aluminium recovered by the process is about 9.3% of the total feedstock weight. About 18% of the waste feedstock weight can be recovered as condensable yields (oils), whilst a further 48% can be recovered as non-condensable combustible gases. The outstanding mass balance is water. Data collected from the pilot plant have been used for the calculation of costings for a commercial unit.

6.0 Phase 2 (continued) - Materials sorting trials at a MRF

The practicalities and cost of separation of laminated packaging from the household waste stream is a key factor in the consideration of the commercial application of recovery and recycling of these materials. Following the MBT plant trials, and subsequent discussions with waste management companies and waste collection authorities, it is considered that the most appropriate recovery method for these materials would be through their selection as a targeted recyclable in co-mingled collections by the authorities. Laminated packaging waste would then be increasingly present in MRF feedstock alongside other packaging items, particularly plastic, steel and aluminium containers. The option of recovering the materials from the residual ('black bag') household waste stream is inappropriate due to the likely increased contamination and the limited availability of appropriate MBT facilities in the UK that could be configured to sort these materials.

To establish the ability of a municipal MRF to sort laminated packaging from co-mingled recyclates, trials were undertaken at a MRF, owned and operated by Bywaters in Bow, London. This MRF processes both commercial and industrial waste and kerbside co-mingled collections. It does not process residual waste. The main waste streams collected at the MRF are plastic containers, other plastic materials, cardboard, mixed paper, ferrous materials, and non-ferrous materials.

For these trials a supply of whole drinks pouches were obtained from the drinks manufacturer. Some were clean and flat (2D) pouches taken from the line before filling, and the remainder were contaminated, crumpled (3D) pouches that had been rejected after filling, emptied, and baled. It is argued that the former form would more closely simulate the form of these materials as they would be presented to a MRF in a post-consumer co-mingled collection.

The trials comprised depositing the pouches into the processing line at the MRF to determine the effectiveness of the automatic sorting equipment to select and divert the materials and to establish which output stream they would be diverted to. It was expected that the eddy current separators, used in MRFs to divert non-ferrous materials from the waste stream, would be the key sorting device.

The items were inserted after the bag slitting and unwanted waste segregation stations. 22kg of the 2D, and 30kg of the 3D, pouches were used, representing in total some 7,000 pouches, which were placed on the belt at irregular intervals. With the existing configuration of the MRF, it was found that some of the 2D pouches passed through with other, mainly paper, 2D materials. Most of the 2D and practically all the 3D pouches were mechanically separated to the 'fines' output stream which comprised, mainly, glass and shredded paper. An estimated 95% of pouches, both 2D and 3D, fed into the MRF were collected with the fines – only 5% reached the eddy current separators at the end of the 3D line.

By feeding pouches manually into the 3D line separately, it was demonstrated that some of the crumpled and 100% of the flat pouches were identified and separated by the eddy current system at the MRF. To capture more of the 3D pouches would require the equipment, to be set specifically to capture these items, by appropriately setting the magnets and the physical barriers. Currently they are set to capture aluminium cans only and to reject foil material, which would otherwise contaminate the aluminium can output stream.

It is clear from these trials that eddy current separation can be used to recover pouches from the fines, along with any other aluminium waste streams that have evaded the MRF process. Clearly, an additional machine would be required for this line. If set up correctly,

the equipment should be capable of collecting both pre- and post-consumer waste stream pouches.

A budget price for a suitable eddy current system is £85,000. To allow for delivery, installation and training and modifications to conveyoring, we have assumed that the total investment would be in the order of £100,000. Since it is a necessary element in the feedstock supply chain to the Enval process, this amount is considered as an additional capital cost in the financial summary, Section 7 of this report. However, it may be that MRF operators are already considering installation of such an additional system in their fines stream to capture aluminium cans that have been missed in the upstream MRF sorting processes.

Initial considerations suggested that hand segregation of pouches may be an economic option. The employment costs of a hand picker are about £12/hr. However, the relatively low feed rate of laminated packaging that would arise in a typical MRF would not warrant the expense of a full time picker. If all the manual pickers were trained to hand pick these materials, along with other non-paper items from the waste paper stream, it is possible to assess the marginal labour cost that would be incurred from the additional picks that would be required. Assuming an average pick rate of, say, 30 items per minute, and an average weight of 7.5g per item, then the picking cost per tonne would be approximately £900. Unless the picking labour is seen as a fixed cost in the MRF, and would not need to be increased to handle the additional tonnage caused by the inclusion of laminated packaging, this would not be economically viable and, therefore, the automatic sorting option is likely to be the only recovery route.

7.0 Financial analysis

7.1 Overview of business model

This section presents the results of calculations to gain an understanding of the first order economic appraisal of the Enval process for recycling of post-consumer laminated packaging. The data obtained during the tests, including the amount of energy used during the process to treat each kilogram of waste mix and the potential value of the products recovered, in addition to a number of assumptions presented below, allow a calculation of the costs that the recycling operation would have and the value that could be extracted from the products.

7.2 Assumptions

The business model used to perform the financial analysis presented in this report contains the following assumptions:

- Process operating costs – Based on costs obtained from the pilot plant operation and scaled accordingly.
- Process operator - Third party, such as a waste management company or waste reprocessor.
- Process location - Operator's premises – the 'recycling centre'. Given that it is assumed that the operator is a waste handler, it is possible to assume that the operation will take place in a MRF belonging to the operator, where they could establish and operate an Enval plant without additional cost for space.
- Availability of feedstock to an individual recycling centre – Following discussions with local waste collection authorities, it is assumed that it would be possible to access one-third of the total laminated packaging disposed by households, in co-mingled kerbside collections, following a publicity campaign by a waste collection authority. It is further assumed that the recycling centre would service an urban or local authority population of around 2 million consumers, equivalent to approximately 3.2% of the UK population. Taking the national consumption of 139,000 tonnes, net weight of packaging, therefore, the feedstock to the recycling centre would be in the order of 1,500 tonnes per annum, net weight of packaging.
- The water content of the feedstock is reduced during storage and transportation. It is assumed that the percentage of laminated plastic is increased to 75% by weight, from the level of 69% of contaminated packaging materials found during the MBT trials. This puts the required throughput of the commercial processing plant at some 2,000 tonnes per annum, gross weight of feedstock.
- Collection of material and transportation to the recycling centre - As discussed in Section 6, it may be assumed that the laminated packaging could be included within the targeted co-mingled materials for each local collection authority. Whilst there may be a marginal increase in transport costs, this would be small, since the collection, bulking and delivery infrastructure will already be in place. However, to make the model more conservative, a cost of £25 per tonne is assumed.
- Operation Licence - It has been assumed that the operator uses the Enval process under licence paying a percentage of its gross margin.
- Quantity of laminated packaging recycled – Based on the availability of feedstock as estimated above, the envisaged capacity of the Enval commercial plant is 2,000 tonnes per annum. This involves a machine capable of treating a gross 500 kg/hr of packaging plus residual product (net 375 kg/hr packaging) over two 40 hour/week shifts.
- Waste composition - As described in previous sections of this report.

7.3 Detailed explanation of products' properties, yields and prices

- **Product yields** - The average yields obtained from Trials 4-6 show that the aluminium content was 9% of feedstock to the process, water was 25%, condensables were 18% and non condensables were 48%. As shown in Table 2, the feedstock material comprised about 69% packaging materials and 31% residual content. For the purposes of reviewing the financial viability of the process it is assumed that all the water is derived only from the residual product and not from any laminates, making it irrelevant to the mass balance of the laminates.
- The mass balance calculations are summarised in Table 9.

Table 9: Yields of fractions from the pyrolysis of the waste mix

Aluminium yield (%)	Condensables yield (%)	Non-condensables yield (%)
9.3	20.0	70.7

- **Value of hydrocarbon products** - The value for the hydrocarbon products both condensable and non-condensable was obtained by using the results of the chemical analysis. As can be seen in the results presented in Section 5, the average calorific value for the two fractions is 38.9 MJ/kg. Using a conservative price of crude oil (US\$80 per barrel), exchange rate \$1.60 = £1.00, and the average energy content of a barrel of crude oil (6,120 MJ) it is possible to calculate a 'value of energy' of 0.8p/MJ. This figure, in combination with the calorific value of the products from the Enval process, leads to a value of £310 per tonne of hydrocarbons. This estimated value, however, cannot be realised in practice, since the high proportion of hydrocarbons (70%) is in gaseous form. In the financial analysis, the average value of the hydrocarbons from the process is taken as 50% of this estimate, i.e. £155 per tonne.

In practice, this fuel would not be sold on the open market. It would best be used as heat energy, or to generate power within the recycling centre, thereby substituting for imported power to the plant. Since the current price of intermediate fuel oil (which has similar characteristics to the oil produced in the Enval process) is in the order of US\$600, using the calculated value is considered to be appropriately conservative for the purpose of this analysis.

Here it is worth noting that, considering the amount of energy that the hydrocarbon products have, and given the high yields of non-condensable products from the process, these products could be used to produce electricity on-site, using common gas generators. This would substitute for imported electrical power to the plant which costs approximately 1.8p/MJ, which would, in turn, suggest a value from the gases of some £700/tonne. Whilst capital costs and losses in the generation plant would reduce that value, the figures again show that the energy value of the gases that is used in the financial analysis is conservative.

- **Value of the aluminium** - Correspondence with Alupro, based on discussions with their reprocessing members, states that the material might be valued at 80% of London Metal Exchange prices. Clearly this could only be confirmed following trials at the reprocessors when additional quantities are available from further Enval trials. Given the current price of aluminium (£1,650/tonne) and information directly obtained from metal recyclers (who declined to give a written confirmation of the price), the value of the aluminium obtained from the process has been conservatively established at £800/tonne.

- **Profit and Loss (P&L) Account** – Figures are based on the assumption that the water content of the feedstock is reduced during storage so that the percentage of laminated plastic is increased to 75% of feedstock weight.
- **Other assumptions**
 - The variable operating costs have been obtained by extrapolating the current costs of running the Enval pilot-plant. The figures have been obtained from the energy balance of the process, including all peripheral equipment, and the amount of nitrogen used; no other utilities are required. The values calculated and used were £10/tonne of waste for electricity and £3/tonne of waste for nitrogen.
 - Costs for the transportation of recycled products have been considered using quotations from actual industrial carriers. The values used were £10/tonne of aluminium and £15/tonne of oils. It is considered that the non-condensable products will be used on-site and no value has (conservatively) been assumed for these gases.
 - Costs for labour have been considered at £20,000/shift/year. A typical 2,000 tonnes per annum machine would require one operator for each of two shifts. These figures assume that the plant is developed prior to commercialisation to be sufficiently robust and reliable to be operated by a suitably trained semi-skilled operative.
 - The commercial plant will have a lifetime of at least ten years. The majority of the components are fixed vessels and pipe work in stainless steel. Some refurbishment and routine maintenance will be required on the moving parts, such as drive motors and valves, and the cost of this is estimated at 5.0% of the capital cost per year.
 - It has been assumed that by taking laminated packaging as a targeted material into a MRF, there would be a marginal revenue increase of £35/tonne in gate fees to the MRF.

It should be noted that the operating costs of a commercial unit are based on those obtained from pilot plant trials and therefore will be conservative, as no economies of scale have been taken into account.

7.4 Results

By integrating the above assumptions and data into the financial model built for the purpose, the P&L for the operations of the Enval process has been modelled and the results are shown in Table 10.

Table 10: P&L account for the operation of the Enval process (£ per annum)

<u>Income</u>		
Sales of aluminium	112,000	
Value of all hydrocarbons	211,000	
Saving on landfill	<u>70,000</u>	
Gross income		<u>393,000</u>
<u>Expenditure</u>		
Electricity	20,000	
Nitrogen	6,000	
Labour Cost	40,000	
Machine Maintenance	<u>32,500</u>	
Transport		
Feedstock supplies	50,000	
Aluminium	1,100	
Oil	<u>4,500</u>	
Total expenditure		<u>154,100</u>
<u>Net profit</u>		<u>238,900</u>

The calculations carried out for the Enval process suggest a payback period of approximately four years, once the licence fee is incorporated. The savings of landfill disposal costs, net of gate fees, by the collection authorities would be additional benefits within the total supply chain. It is important also to notice that, if cleaner laminates were to be mixed with post-consumer waste, for example coming from scrap generated within the industrial sector, the percentage of aluminium would increase substantially and therefore the return on investment would be greater.

Furthermore, following initial tests with separation equipment it has been established that the amounts of aluminium cans and other foils mixed with laminates during the segregation stages are likely to be considerably more than the quantity of cans added as 'contamination' during this project. Therefore the aluminium yield could be substantially increased.

8.0 Environmental analysis

8.1 Methodology

The results from the pilot-plant trials allowed an environmental assessment of the impact of using the Enval process for recycling laminated packaging to be undertaken by a Life Cycle Assessment (LCA) study. This section presents the results of a comparative LCA where the environmental impact considered is the global warming potential (GWP), expressed in kilograms of carbon dioxide equivalent (kg CO₂e). The GWP compares the environmental benefits of recycling the waste via the Enval Process and obtaining an aluminium ingot from the recovered aluminium with the production of the same mass of aluminium from a primary source. The assessment ignores the additional carbon benefit of surplus energy production from the hydrocarbons.

The technique of life cycle analysis was undertaken via the sequential stages of:

- objective and scope definition
- data collection
- impact assessment
- interpretation and reporting.

8.2 Objective and scope definition

Functional unit: The basis for comparison of the Enval process or the *functional unit*, was defined as one kilogram of aluminium as an ingot.

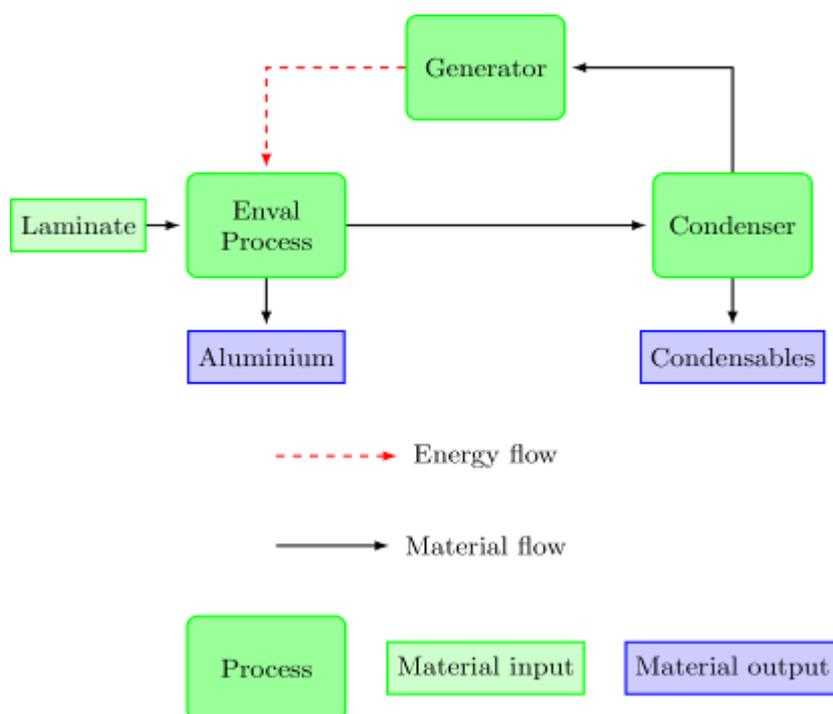
8.3 System boundaries

Laminate waste is not represented in the Product Category Rules (PCR) for LCAs and therefore system boundaries were chosen to comply with PAS 2050 (the UK standard for life cycle greenhouse gas emissions). The 'control volume' in this study encompasses:

- the input of laminate material without taking into account the collection or transport
- the provision and use of all energy requirements, e.g. electricity and nitrogen
- the operation of the Enval process.

The process map is shown in Figure 11.

Figure 11: Process map of the Enval process for purposes of the LCA



8.4 Data collection

The data quality rules specified by PAS 2050 were followed rigorously. The primary data used were fully representative of normal conditions encountered by the process being assessed. These data were used to draw up mass and energy balances, and to determine the overall raw material and energy requirements of the process. Operational parameters and primary data used are shown in Table 11.

Table 11: Operational parameters used in environmental assessment.

Process feeding rate	375kg / hr of laminate
Laminate aluminium content	9.7% in dry base
Nitrogen consumption	0.3 m ³ / hr (extrapolated from pilot-plant operation)
Electricity for motors	10 kW
Operating temperature	450°C
Aluminium recovery	100%
Water condensed	100%
Hydrocarbons condensed	80%
Nitrogen pressure	1 atm
Additional pumping power	5%
Microwave power	200 kW

Secondary data were used for emission factors to calculate the overall greenhouse gas emissions of the processes from the mass and energy balances. The GaBi 4.3 database was used to provide the secondary data required along with basic physicochemical calculations and common process efficiencies. The data used are compliant with ISO 14040 and ISO 14044. Data specific to the UK were used where possible, e.g. emissions associated with electricity usage. The data used to calculate the greenhouse gas emissions associated with electricity and transport are detailed on the next page:

- Electricity GWP: 0.6699 kgCO₂e / kWh.
- Data assumes a power grid mix of 39.3% natural gas, 32.1% coal, 22.7% nuclear, 0.4% blast furnace gas, 1.8% heavy fuel oil, 0.2% solid biomass, 0.8% gaseous biomass, 0.4% waste, 1.9% hydroelectric and 0.3% wind.
- Other secondary data used included:
 - gas electricity generator efficiency: 35% (from manufacturers data); and
 - cooling power required: 128 kW (extrapolated from the Enval pilot-plant).

When investigating disposal methods, to model the landfill route it was assumed that the laminate was made up of purely aluminium and PE, and to model the laminate for incineration it was assumed that the laminate comprised aluminium and plastic packaging in an MSW incinerator, where the energy from the plastic packaging was recovered.

Carbon emissions from the pyrolysis process, based on the foregoing parameters and assumptions, have been calculated.

8.5 Results

All values are in kgCO₂ equivalent per kg of aluminium.

Calculated Global Warming Potential (GWP) is as follows:

Production of aluminium ingot via Enval process:	6.30 kgCO ₂ e
Comprising:	
Pyrolysis process:	5.88 kgCO ₂ e
Production of aluminium ingot from new scrap:	0.42 kgCO ₂ e ⁴
Production of aluminium via bauxite process:	11.03 kgCO ₂ e ⁵

These results demonstrate that the greenhouse gas emissions from production of 1kg aluminium derived from laminated packaging via the Enval process are just over half of those emitted when producing primary aluminium.

As stated above, all the emissions have been attributed to the production of the aluminium only and not to the production of surplus energy from the hydrocarbons. If this was done, the GWP of the aluminium using the Enval process would be further reduced.

Similarly, the Global Warming Potential for disposal of laminate via incineration was calculated and the result showed that this would result in much higher emissions and without the recovery of the valuable aluminium.

Disposal of laminate via incineration with energy recovery: 19.9 kgCO₂e.

⁴ Value obtained directly from GaBi 4 software

⁵ Value obtained directly from GaBi 4 software

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