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**Summary of the presentation**

**The European Plastic Waste Issue: Trends and Toppers in its**

**Sustainable Re-use**

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15 **Abstract**

16 The disposal of waste plastics has become a major worldwide environmental  
17 problem. In 2007, 25% of the world's plastic production capacity, which amounted  
18 to 260 million tonnes, was produced in the EU<sub>27</sub>, Norway and Switzerland. Only a  
19 small percentage of plastic solid waste (PSW) is recycled (approximately 20.4%)  
20 and the most common option for disposal is by landfill or (co)-incineration, both  
21 associated with major environmental burdens. Nearly all of the post-consumers  
22 PSW in the USA, Europe and Japan are commonly dumped in landfill sites, a non-  
23 sustainable and environmentally questionable option. The number of landfill sites  
24 and their capacity are moreover decreasing rapidly and in most countries the  
25 legislation on land nfilling is becoming increasingly stringent. Two sustainable  
26 alternative disposal routes are possible: i.e. primary and secondary re-use and  
27 mechanical recycling, or thermo-chemical and energy recovery respectively.  
28 Several European Directives concern the plastic waste issue and the requested waste  
29 management, and are briefly discussed in the paper.  
30 This paper reviews the waste management options for plastic wastes by re-use or  
31 recycling and by major thermal processing (pyrolysis, gasification, incineration with  
32 energy recovery).  
33 A combination of these various disposal routes remains necessary to achieve the  
34 most eco-efficient, effective waste management solution.

35  
36 **Keywords:** plastic waste, re-use, thermal valorisation, legislation

37  
38 **Non-technical summary**

39 The disposal of waste plastics has become a major worldwide environmental  
40 problem. The multi-million tons of post-consumer plastic waste which are generated  
41 annually were previously dumped in landfill sites, a non-sustainable and  
42 environmentally questionable option.  
43 New sustainable processes have emerged i.e. a mechanical treatment for recycling  
44 as virgin or second grade plastic feedstock, and a thermal treatment to recycle the  
45 waste as virgin monomer, as synthetic fuel gas, or as heat source (incineration with  
46 energy recovery). These processes are environmentally friendly and avoid the  
47 massive land filling, where the non-biodegradable plastics remain an environmental  
48 burden for centuries.

49 **INTRODUCTION**

50

51 The disposal of waste plastics has become a major worldwide environmental  
52 problem. The USA, Europe and Japan generate about millions of tons of post  
53 consumer plastic waste <sup>1</sup>.

54 These waste products were previously dumped in landfill sites, a non-sustainable  
55 and environmentally questionable option. The number of landfill sites and their  
56 capacity are moreover decreasing rapidly and in most countries the legislation on  
57 landfill is becoming increasingly stringent. Two sustainable alternative disposal  
58 routes are possible: i.e. re-use and recycling, or thermo-chemical processing and  
59 energy recovery respectively.

60 As plastics are hydrocarbons, they possess a high calorific value. They can thus be  
61 burned readily in e.g. a municipal or dedicated waste incinerator with heat and  
62 power generation; they can serve as a secondary fuel, replacing fossil fuels in  
63 production processes (e.g. cement industry). They can hence replace traditional fuels  
64 such as coal, natural gas and oil.

65 Whereas re-use implies the recycling of process scraps into the process itself  
66 (primary re-uses), recycling comprises alternative methods: (i) the secondary  
67 recycling or mechanical recycling, in which the waste product is reprocessed by  
68 physical means into new plastic products, generally of a lower quality; (ii) the  
69 tertiary recycling or feedstock recycling, in which the plastics are cracked into their  
70 constituent monomers, or in a hydrocarbon feedstock and fuel oil (This tertiary  
71 recycle process is gaining importance); and (iii) the energy use of the PSW to  
72 substitute for fossil fuels in highly endothermal processes (e.g. cement production).

73 It is of prime importance to have a separated, clean and dry plastic waste stream.

74 Therefore sectors where the quality of the waste product is high and the ability to  
75 clean the homogenous waste is present, have high recycling rates, e.g. in agriculture  
76 (> 50%) and distribution (48%) <sup>2</sup>.

77

78 The present paper reviews the current disposal and recycling options for plastic  
79 wastes. The technical possibilities as well as the current EU-legislation are  
80 presented.

81

82 **CONSUMPTION OF PLASTICS**

83

84 According to the Association of Plastic Manufacturers in Europe (Plastics Europe),  
85 a total of nearly 40 million tonnes of plastic were consumed in the European Union  
86 in 2003. This represents an increase of 5.6% versus 2001 <sup>2</sup>. The per capita  
87 consumption of virgin plastics was approximately 98.1 kg in 2003.

88 Thermoplastics contribute about 80% to the total plastic consumption, and are used  
89 for typical plastics applications such as packaging but also in non-plastics  
90 applications such as textile fibres and coatings. Thermosetting plastics are used in  
91 more demanding applications (e.g. for use at higher temperatures) and for non-  
92 plastics applications such as adhesives.

93 Packaging accounts for 37.2% of all plastics consumed. Moreover, plastics are  
94 increasingly substituting other more traditional materials, such as glass, because of  
95 the weight benefit, flexibility and ease of processing. Although over 50 % of all  
96 European goods are packaged in plastics, by weight these plastics account for only  
97 17% of all packaging.

98 The second largest consumer is the building and construction industry, with a  
99 contribution of 18.5%. Plastics are used for a range of applications from insulation  
100 to piping, window frames to interior design. The popularity is due to durability,  
101 strength, resistance to corrosion, low maintenance and aesthetically pleasing finish.  
102 8.5 % of the plastics are used in electrical and electronic equipment. Plastics are an  
103 indispensable material for this sector. It is a fact that many of today's new technical  
104 developments capitalise on the latest types of new generation plastics <sup>2</sup>.

105 Other important plastic users are the automotive industry (8%), where plastics  
106 reduce car-weight, thus reducing fuel consumption and reducing the environmental  
107 burden of traffic, agriculture (1.9%) and large industry (5.8%).

108 The remaining 20.1% of plastics are used in other household and domestic  
109 applications.

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## 115 **LEGISLATION AND PLASTIC WASTE MANAGEMENT**

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117 Several European Directives (binding for all EU member states) concern the plastic  
118 waste issue and the requested waste management, and will be discussed below.

119 Among the important legislation, the EC Directive (94/62/EC) on Packaging and  
120 Packaging Waste <sup>3</sup> has set a 15% material specific recycling target for packaging  
121 material by June 2001. This directive was revised in 2004.

122

123 Considering that prevention, recovery and recycling are key options in waste  
124 management, the European Plastics Industry is committed to promoting recovery  
125 waste management options. If the European Union is to meet the goals laid out in  
126 the EU Landfill Directive <sup>4</sup>, which obliges member states to progressively reduce  
127 the landfill-amount of recyclable waste to 35 % of 1995 levels within 15 years, it is  
128 clear from exhaustive research and practical experience from the implementation of  
129 the Packaging and Packaging Waste Directive (PPWD) and related eco-efficiency  
130 studies that neither recycling nor energy recovery options alone are sufficient.

131 Instead a combination of both is needed to achieve the most eco-efficient, effective  
132 waste management solution.

133 Post consumer plastics increased by over 10 % between 2001 and 2007. Improved  
134 collection and separation infrastructures instigated good progress in the amount of  
135 plastics recovered, with e.g. improvements in recycling contributing to an 11.2 %  
136 rise in recovery between 2001 and 2003. As a result, the amount of plastic waste  
137 going to landfill in 2003 was 61 % of total collectible plastics waste, down from 63  
138 % in 2001 <sup>2</sup>.

139

140 Another important source of plastic waste entering landfills comes from shredder  
141 residue (SR), and part of this plastic waste can also be targeted for recycling <sup>5</sup>. SR is  
142 the by-product of a process that reclaims the vast majority of ferrous and non-  
143 ferrous metals from post-consumer objects such as automobiles, fridges, washing  
144 machines etc. These waste products enter shredding facilities where they are size-  
145 reduced and metals are largely removed (> 90%) by over-band magnets and eddy  
146 current separators. The residual material is known as SR or 'fluff' (or 'light-fluff')  
147 and consists of a heterogeneous mixture of plastics, foam, rubber, tyres etc. <sup>5</sup>. The  
148 need to recover more of this material is partly driven by the EU End of Life Vehicle

149 (ELV) Directive <sup>6</sup>, and partly through a voluntary agreement by car manufacturers  
150 to incorporate a 25% level of recycled plastic back into automobiles <sup>5</sup>.

151

152 Plastic waste is especially problematic owing to the high volume/weight ratio: as  
153 such it is not an attractive material for collection and recycling, and costs of  
154 transportation, of reprocessing, and value of virgin feedstock all have an impact on  
155 the ultimate price of the recycled polymer material <sup>5</sup>.

156

157 Domestic waste remains the main source of waste plastics, about two thirds of the  
158 total generated. Distribution and industrial sectors are the second important source <sup>7</sup>.

159

160 One should remember that plastics are mostly non-biodegradable and will be present  
161 in landfills for a very long time (only 1-3% of the hydrocarbon content can be  
162 degraded during a considered time period of 100 years) <sup>7</sup>.

163

164 Several studies, including Holmgren and Henning <sup>8</sup> conclude that the best option for  
165 plastic waste treatment is recycling the plastics.

166

## 167 **MECHANICAL RECYCLING**

168

169 According to the European plastics industry <sup>2</sup>, the environmentally and  
170 economically most favourable recycling technique is mechanical recycling. This  
171 method is the largest recycling method, contributing for over 50 % to the overall  
172 recycling and is the second largest recovery technique for plastic waste after energy  
173 recovery. This technique directly recovers clean plastics for reuse in the  
174 manufacturing of new plastic products: the difficulties are mainly related to the  
175 degradation of recyclable material and heterogeneity of plastic wastes <sup>7</sup>.

176 Especially pre-consumer plastic waste is suitable for mechanical recycling. The pre-  
177 consumer residues only include the material generated in an industry, either in the  
178 companies who manufacture the polymers or in companies that use or transform  
179 them into the final product. The pre-consumer products generally consist of a unique  
180 feedstock, and are well identified, clean and homogeneous <sup>9</sup>.

181 In contrast, the post-consumer residues are a mixture of different plastics generally  
182 contaminated with dirt or other residues thus making recycling much more difficult,  
183 although feasible.

184

## 185 **FEEDSTOCK RECYCLING**

### 186 **Generalities**

187 Feedstock recycling comprises various advanced recycling technologies to turn solid  
188 polymeric wastes into high value feedstock that can be used as raw materials in the  
189 production of new petrochemicals and plastics, without any deterioration in their  
190 quality and without any restriction regarding their application. Feedstock recycling  
191 has in theory a great potential to boost plastics waste recovery levels <sup>2</sup>. These  
192 processes involve the use of moderate to high temperatures to break the structured  
193 bonds of the polymer. They can be carried out in the absence of air (pyrolysis), in  
194 the presence of a high partial pressure of hydrogen (hydrocracking), or of a  
195 controlled amount of oxygen (gasification) <sup>7</sup>.

196

### 197 **Pyrolysis**

198 A decomposition process which is carried out in the absence of air is termed  
199 pyrolysis or thermal cracking. It is a flexible process and thus especially useful  
200 when dealing with heterogeneous wastes such as commingled waste or automotive  
201 shredder residue <sup>10</sup>.

202

203 Using pyrolysis, the plastic waste is converted into pyrolytic oil and a solid residue  
204 (char). Since hydrogen and oxygen are absent during the process, usually high  
205 molecular weight and hence high boiling fractions are obtained. These are further  
206 processed and refined, resulting in petrochemical feedstock such as naphta. A  
207 summary of the obtained products after laboratory-scale pyrolysis of various  
208 polymers is presented in Table 1 <sup>11</sup>. These data reveal that within the group of  
209 analysed polymers, only PMMA and polystyrene (PS) can be considered for  
210 monomer recovery. The other polymers are sources of pyrolytic fuels (gas, oil,  
211 waxes).

212

213 Pyrolysis is carried out in a reducing atmosphere at temperatures up to 700°C.

214 Several technical designs have been studied in literature. Most authors, e.g. Arena  
215 and Mastellone <sup>12</sup>, Perugini et al. <sup>7</sup>, Kaminski et al. <sup>13</sup> conclude that a fluidized bed  
216 reactor is the most favourable option. This method possesses a number of  
217 advantages which yield a more uniform product and a higher conversion rate.

218

219 The reactor is generally filled with sand particles acting as a transport material.

220 When introduced in the reactor, the plastics quickly melt and coat the sand particles  
221 with a thin layer of polymer. This amalgam undergoes thermal cracking and  
222 produces lighter hydrocarbons which leave the reactor with the fluidizing gas <sup>7</sup>. This  
223 mechanism provides a uniform distribution of the polymers and excellent heat and  
224 mass transfer properties, resulting in a constant pyrolysis temperature and thus  
225 highly controlled polymer cracking and a minimisation of side reactions <sup>13</sup>.

226 According to Perugini et al. <sup>7</sup>, this process has an efficiency of nearly 80%  
227 conversion of plastic waste to petrochemical products, with an additional 10-15%  
228 used as fuel gas to provide the endothermal energy of the process itself.

229

230 When dealing with condensation polymers such as polyesters, polyamides,  
231 polyethylene terephthalate (PET) and polymethylmethacrylate (PMMA), it is possible  
232 to use a pyrolysis reaction to transfer the plastic into its original synthesis monomers  
233 <sup>14,15</sup>. This process is termed chemical recycling or depolymerisation.

234 Depolymerisation of addition polymers is more difficult, although some studies  
235 have shown its feasibility <sup>13</sup>.

236 The efficiency of these processes can be very high. Kaminski et al. <sup>13</sup> reported a  
237 recovery of 75% styrene and 10% oligomers when feeding polystyrene to a fluidized  
238 bed reactor and a recovery of 98% when using PMMA as feed.

239 The economical favourability of this process for PET is shown in an economic  
240 evaluation of a PET depolymerisation plant with a capacity of 900 tons/year by  
241 Lund <sup>16</sup>. This evaluation is summarized in Table 2. Depolymerisation is even more  
242 attractive when dealing with rather expensive polymers such as PMMA. Various  
243 processes for recycling PMMA are described in literature, e.g. Enyiegbulan <sup>17</sup>, Inaba  
244 and Kashiwagi <sup>18</sup>, Kaminski and Eger <sup>19</sup>. The most prominent ones are the extrusion  
245 system, the molten lead bath system and the fluidized bed process. Experiments of

246 Smolders and Baeyens <sup>15</sup> and Smolders et al. <sup>11</sup> concluded that a fluidized bed has  
247 superior properties as shown in Figure 1 <sup>11</sup>. The micro-pyrolysis by  
248 thermogravimetry measures an extremely fast depolymerisation rate. These  
249 conclusions were confirmed by Kaminski et al. <sup>13</sup>.

250

### 251 **Hydrocracking**

252 A second feedstock recycling process for plastic waste is known as hydrocracking.  
253 The plastic waste is hereby exposed to a hydrogen atmosphere at pressures in excess  
254 of 100 atmospheres. In this process, plastic waste is converted into fragments of  
255 hydrocarbons, in appearance and composition similar to crude oil.

256

257 In hydrocracking, heat fractures molecules into highly reactive free radicals  
258 (cracking) that are saturated with molecular hydrogen (hydrogenation) as they form.  
259 Cracking and hydrogenation are energetically complementary processes since the  
260 cracking reaction is endothermic while hydrogenation is exothermic. Thus the  
261 surplus of heat that is produced can be handled by employing cold hydrogen as a  
262 quench for this reaction <sup>10</sup>. The partial pressure of hydrogen must be high enough  
263 (about 200 bar) to suppress undesirable coking or repolymerisation <sup>7</sup>. Possibly, a  
264 catalyst can be used for enhancing the hydrocracking process <sup>20</sup>.

265

266 The advantages of hydrogenation include: (i) high-value products are obtained, (ii)  
267 the synthetic crude oil can be used without any difficulty in refineries (better  
268 feedstock than pyrolysis and gasification), (iii) troublesome hetero-atoms (i.e. Cl, N,  
269 O, S) are handled excellently and (iv) no toxic products such as dioxins are  
270 produced in or survive the process <sup>10</sup>.

271

### 272 **Gasification**

273 Gasification or partial oxidation of plastic waste is performed with the controlled  
274 addition of oxygen. The process essentially oxidizes the hydrocarbon feedstock in a  
275 controlled fashion. The primary product is a gaseous mixture of carbon monoxide  
276 and hydrogen. This gas mixture is known as syngas and can be used as a substitute  
277 for natural gas. Syngas is a valuable gas mixture which is used in the chemical

278 industry as feedstock for the production of numerous chemicals. The inorganic ash  
279 residue becomes bound in a glassy matrix and can be used as a component in  
280 concrete and mortar due to its high acid resistance <sup>10</sup>.  
281 A hydrogen production efficiency of 60-70% from polymer waste has been reported  
282 for a two stage pyrolysis and partial oxidation process <sup>21</sup>. Gasification is an  
283 attractive option since it prevents the formation of any dioxins and aromatic  
284 compounds. Gasification efficiently utilizes the chemical energy and recoverable  
285 raw materials inherent in unsorted domestic waste, industrial and special waste (e.g.  
286 medical waste), and is capable of transforming almost all of the total waste input  
287 into technically usable raw materials and energy <sup>10</sup>.  
288 Co-gasification of biomass with polymer has also been shown to increase the  
289 amount of hydrogen produced while the CO content reduced <sup>22</sup>.  
290 A 40 MW fluidized bed gasifier has been installed by Corenso in Varkaus (Finland)  
291 for processing polyethylene plastics with metallic aluminium recovery from  
292 recycling of liquid cartons.  
293 A typical circulating fluidized bed gasifier is illustrated in Figure 2 <sup>23</sup>.  
294

## 295 **INCINERATION WITH ENERGY RECOVERY**

296 Energy recovery remains the most common recovery route for post-user plastics  
297 waste in Western Europe with 22.5 % of total collectable plastic waste dealt with <sup>2</sup>.  
298 In the past, concern around the poor environmental performance and emissions from  
299 old incinerators meant that this form of sustainable re-use often met with opposition.  
300 However, strict legislation has ensured that energy recovery is now endorsed as an  
301 environmentally sound option. The incineration of plastic waste in the European  
302 Union is governed by directive 2000/76/EC on the incineration of waste <sup>24</sup>.  
303 The heat content of plastics compares favourably with that of traditional fuels such  
304 as heating oil and natural gas <sup>10</sup> and thus plastics can be conveniently used in work-  
305 to-energy processes, particularly if they cannot be mechanically recycled because of  
306 excessive contamination, separation difficulties, or polymer property deterioration  
307 <sup>7,25</sup>.  
308  
309 The plastic waste can be burned as such or can be co-fired as a mixed combustible  
310 fraction for use in solid fuel fired boilers and power plants when heat is recovered,

311 possibly with power generation <sup>10</sup>. The use of plastic waste as a fuel in cement and  
312 lime kilns is widely applied. (utilized as a partial substitute for coal or coke) <sup>26</sup>.  
313 The energy option is interesting when mechanical recycling is both economically  
314 and environmentally costly: due to the lightweight and diverse nature of smaller  
315 plastic products (such as films, pouches, yoghurt cups, blister trays etc.), collection,  
316 sorting and mechanical recycling is simply no viable option.  
317 Plastic waste incineration with energy recovery offers major advantages: (i) a  
318 reduction in the mass of waste by 90%; (ii) potentially harmful substances in the  
319 waste stream are destroyed; (iii) the inorganic fraction of the waste is essentially  
320 mineralized by incineration to an inert slag, which can be used as a raw material in  
321 the construction of roads; (iv) it is an ideal route for recycling mixed or heavily  
322 polluted polymeric substances and (v) it is the best and safest method for handling  
323 hazardous plastic waste such as medical plastic waste or hazardous-goods packaging  
324 <sup>10</sup>.  
325 Co-incineration of energy-rich plastic and low-calorific municipal solid waste has a  
326 positive effect on the incineration process where plastics are a benefit as a fuel that  
327 is low in ash and moisture, and an energy source for efficient destruction of  
328 pollutants <sup>25</sup>.  
329 Mono-combustion of plastic waste on its own is often used to produce steam for  
330 heat and power generation. Modern combustion technologies provide a high degree  
331 of combustion control and automation and are equipped with sensing technology to  
332 optimize air/fuel demands <sup>10</sup>.  
333  
334 Whereas mono-combustion requires specially designed boilers, co-combustion can  
335 be performed in existing (multi-fuel boilers). Burning 100% waste plastics in a grate  
336 fired boiler can be hampered by an uneven distribution of air in the bed and the  
337 occurrence of hot-spots, both of which are the result of the inhomogeneous nature of  
338 the plastic feedstock. As a consequence such waste incinerators require extensive  
339 flue gas cleaning systems to comply with the strict emission regulations. On the  
340 other hand, if the plastic waste is sorted and shredded and then evenly mixed with a  
341 primary fuel (e.g. coal or peat), the combustion is more efficient and no extensive  
342 flue gas cleaning is required <sup>10</sup>. This is also true when mixing plastic waste with  
343 other municipal solid waste before incineration.  
344

345 The presence of brominated fire retardants (BFR) could cause problems because  
346 during their incineration PCDD/F's and PCBD/F's are formed. Tange and  
347 Drohmann<sup>27</sup> demonstrated however that the production of these dioxins or dioxin-  
348 like products is not increased by the co-incineration of BFR-containing plastics and  
349 that the emissions remain within the legal standards for these processes.

350

351 The use of fluidised bed combustion is often advantageous. All advantages  
352 previously describes in this paper for feedstock recycling are also present when  
353 using the method for incineration.

354

## 355 **CONCLUSIONS**

356

357 This paper provided an overview of the waste management options for plastic  
358 wastes. Since landfill, which used to be the only disposal route for plastic waste, is  
359 no longer a viable option, alternative disposal or recycling options have become  
360 necessary.

361 Two sustainable alternative disposal routes are feasible: recycling and incineration  
362 with energy recovery.

363 In recycling, two major routes are possible. The mechanical recycling reprocesses  
364 the waste plastic by physical means into new plastic products. This option is only  
365 feasible when dealing with a homogeneous waste stream. When different sorts of  
366 plastics are mixed, a feedstock recycling is appropriate. This method converts the  
367 plastic waste into new feedstock which can be used as a fuel of in the production of  
368 new plastics or chemicals.

369 Another option is the incineration of the plastic waste. Since plastics possess a high  
370 calorific value, they can be burned readily.

371 A combination of all disposal routes remains necessary to achieve the most eco-  
372 efficient, effective waste management solution.

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444

445 **Table 1:** Pyrolysis of polymeric waste and hydrocarbon raw materials

446

| Feedstock                     | Pyrolysis temperature (°C) | Gas (wt%) | Oil (wt%) | Solid Residue (wt%) | Other products (wt%) |
|-------------------------------|----------------------------|-----------|-----------|---------------------|----------------------|
| Polyethylene (PE)             | 530                        | 7.6       | 50.3      | 0.1                 | 42 waxes             |
| Polystyrene (PS)              | 580                        | 9.9       | 24.6      | 0.6                 | 64.9 styrene         |
| Polyester                     | 768                        | 50.8      | 40.00     | 7.1                 | 2.1 H <sub>2</sub> O |
| Polyvinylchloride (PVC)       | 740                        | 6.8       | 28.1      | 8.8                 | 56.3 HCl             |
| Polymethylmethacrylate (PMMA) | 450                        | 1.25      | 1.4       | 0.15 C              | 97.2 MMA             |

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450 **Table 2:** Economic evaluation of PET depolymerisation

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|            |                   |
|------------|-------------------|
| Capacity   | 9000 tons/year    |
| Investment | \$ 2.5 million    |
| Purity     | 99.9% PET         |
| Price      | \$ 0.55 / kg      |
| Revenue    | \$ 5 million/year |
| Profit     | \$ 1 million/year |
| Net return | 20 %              |

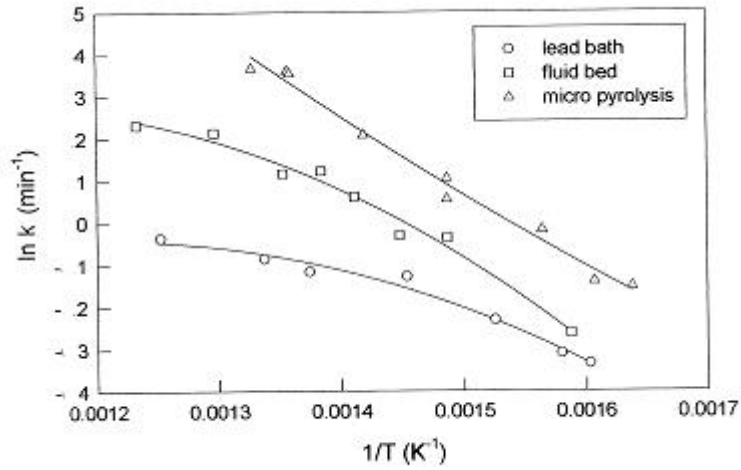
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455 **Figure 1:** Arrhenius Plot for experiments in (i) a lead bath, (ii) a fluid bed and (iii) a  
456 micro pyrolysis reactor.

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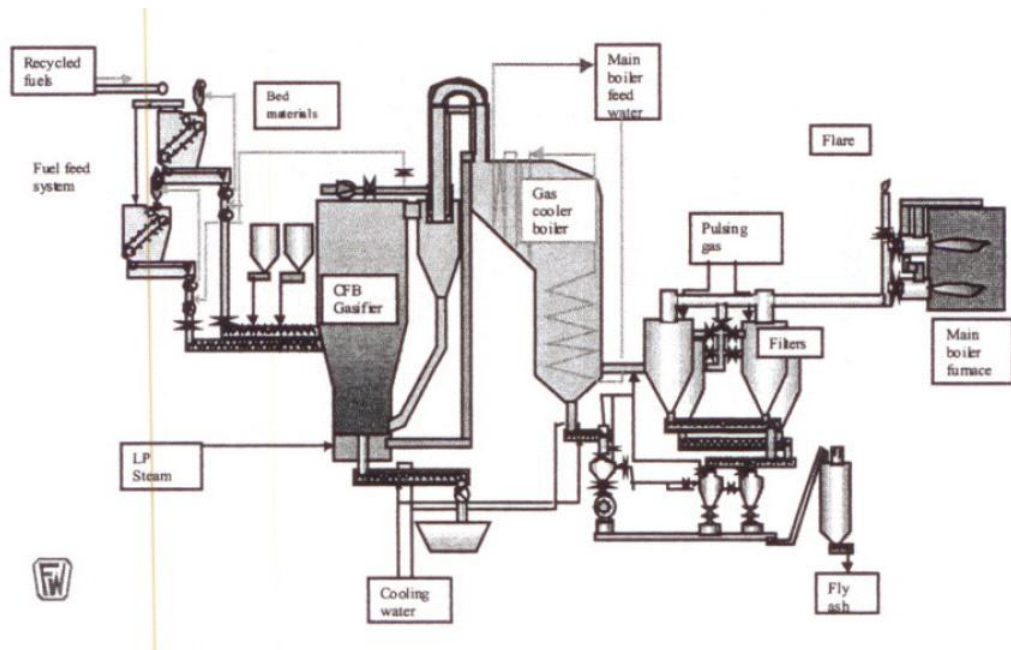
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461 **Figure 2:** Fluidised bed incineration plant

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