"Materials-Cycle Optimisation in the Production of Major Finished Materials"

CHAPTER 11: PACKAGING WASTES

by

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This chapter is part of a report made for the EC DGXII on a project entitled ***"Materials-Cycle Optimisation in the Production of Major Finished Materials"***. This project aims at facilitating the identification of longer-term R&D needs for materials-cycle optimisation, especially by using wastes, co-products, or by-products from one process as inputs to other processes. Book publication is envisaged. Following is the list of chapters:

All chapters are individually available as INSEAD Working Papers.

CHAPTER 11. PACKAGING WASTES[1]

11.1. Summary

Every package consumes raw materials. Packaging materials (for the most part) have notoriously short useful lives. Thus, while the quantity of raw materials (and energy) required to produce a singe bottle, can or carton are not very great, the numbers of such items produced are cumulatively very large.[2] The wastes and emissions generated by the production processes are correspondingly great. Moreover, the bulk and weight of packaging adds significantly to goods transportation requirements, thus amplifying the environmental impact.

This argument is especially pertinent with regard to aluminum cans and foil. Aluminum is extremely energy intensive to produce from virgin materials. (See *Chapter 2, Aluminum*). For this reason it is especially important to not to use aluminum for frivolous purposes, and to recycle that which is used. The Swedish experience verifies the feasibility of achieving very high levels of recycling. No new technology is really needed for this. The problem is clearly administrative and organizational.

Disposal of waste packaging materials is a growing problem. Old landfills are filling up and it is becoming very difficult to find new sites that are both physically and economically suitable, and acceptable to nearby residents. In effect, landfill space is becoming scarce. Packaging materials constitute 30% of municipal waste by weight but 50% by volume. Meanwhile incineration for energy recovery also generates significant emissions to the air, including heavy metals (e.g. mercury, cadmium) and dioxins. Incineration is currently unacceptable in some countries (e.g. Germany), although it is regarded as a source of energy in others (Switzerland, France).

The current situation with regard to recycling of packaging wastes in Europe is far from equilibrium, and probably unsustainable. The "green dot" program in Germany has created a major new avenue for waste disposal (by users), and a sharp increase in the available supply of recyclables. However, it is by no means clear that this program alone will lead to significantly more recycling. Recycling requires both supply and demand. The German program has been criticized justly for greatly increasing the supply of recyclables without doing anything to increase the demand for them. As a consequence, the added supply (supplemented by exports of recyclable paper from the U.S.) have disrupted existing markets and harmed existing enterprises in the recycling business.

Recycling of packaging wastes in general is not making much headway. In fact, re-use of glass bottles is declining, and recycling is still not economically feasible for most types of packaging materials (with the exception of glass and aluminum cans). For several reasons, more cost-effective and more efficient means of sorting and separating mixed municipal wastes are needed. There seems to be no fundamental technical barrier. However, most of the re-use and recycling options for waste materials cannot be justified economically in small scale applications.

A new and more systematic approach is also needed to facilitate energy recovery from municipal wastes (including chlorinated plastics). Assuming that chlorinated plastics will not be banned from use in packaging any time soon, the next best alternative would be to develop an effective low temperature gasification technology suitable for mixed municipal wastes.

What has not yet been given sufficient consideration up to now is an integrated system operating on quite a large scale, that could accept mixed wastes from a large region, and utilize the most advanced possible technologies for separation and beneficiation to produce a number of secondary materials, plus energy. The problem is cost, which can only be reduced by gaining experience and operating on a larger scale.

There is a need for much more innovation on the demand side to rectify the current imbalance between supply and demand. Having created the problem, in large part, governments will have to intervene to solve it. This can be done, in part, by mandating the use of recycled materials in certain applications. However that is a very blunt instrument, since bureaucrats are not the best judges of technical or economic feasibility. A much more appropriate form of intervention would be to subsidize R&D on new applications of recyclables. A less attractive, but possible approach would be for governments to offer tax relief for materials producers that convert virgin materials processing facilities to recycling facilities. This might be appropriate in the paper industry, for instance, where a new paper recycling plant costs $500 million and even a retrofit costs $50 million. At the same time, governments must begin the (admittedly difficult) process of cutting back on direct and indirect subsidies that favor the use of virgin materials, especially aluminum.

Goals of Public Policy: Reduce consumption of non-renewable raw materials; reduce energy consumption; reduce pollution associated with disposal of packaging wastes; increase recycling of energy-intensive materials, especially aluminum; develop new uses for mixed packaging wastes; develop improved means of energy recovery from mixed wastes.

11.2. Introduction

Packaging materials are extremely diverse. Major categories of packaging include rigid containers (glass, metal cans, plastic bottles), flexible containers (paper bags and cartons, plastic bags, toothpaste tubes) and flexible wrapping materials (paper, plastic film, aluminum foil) as well as bottle caps and seals, string, tape and wire. Each type includes several different materials and combinations, depending on the nature of the substance being contained. Liquids and dry materials constitute one major dichotomy, since packaging materials for the former must be airtight and impermeable. Food products and beverages must also be packaged in airtight (and, in some cases, lightproof) containers to inhibit contamination and spoilage. Toxic or hazardous materials, on the other hand, must be packaged in such a way as to prevent escape and/or corrosion. Some packaging materials should be transparent to allow the contents to be seen, as in the case of fresh fruits, vegetables and meat. Some packaging materials need to be very strong and tough, to facilitate handling, but need not be rigid. Some are needed only for a very short period (e.g. a grocery bag) while others should preserve the contents for a long time.

A material that is ideal for one application will not serve the purpose in others. Packaging materials compete against each other only in particular markets, e.g. alcoholic beverages, non-alcoholic beverages, prepared foods, detergents, paints and solvents, shipping containers (i.e. containers for other containers), and so forth. The potential for re-use and recycling depends very much on the specific application. However, by far the greatest share of used packaging materials end up in municipal solid wastes. This type of waste constitutes a particularly difficult challenge for re-use or recycling.

To compound the difficulties, published data on the supply side is scarce and inconsistent. On the other hand, market data from unofficial sources (mainly consulting companies) is voluminous but expensive and unverifiable. A significant degree of uncertainty is unavoidable. Nevertheless, there are several good reasons for considering possibilities for increased re-use and recycling.

The rate of paper recycling in the EEC was 38.3% in 1991 [CEPI, cited in Renaux 1992]. However, this is a little misleading, since paperboard packaging materials such as cartons are probably the chief consumer of recycled paper, whereas they themselves are not very suitable for recycling. On the other hand, used paper packaging materials themselves are not as easily recycled as printing grades of paper. Only in the cases of glass and aluminum is recycled material of comparable quality with the original, although the recycling rate for aluminum cans in Europe is still very low except in Sweden.

11.3. The Packaging Sector, in Physical Terms

Because of the diversity of package types, also, it is very difficult to characterize the packaging market as a whole in physical units. In monetary terms, paper products and plastics each account for about 30% of the total packaging market, while metals (tinplate, steel and aluminum sheet) account for 16%, glass for 7%, and the remaining 8% is divided between wood pallets and steel drums [EUROSTAT 1990]. See *Figure 11.1(top)*. We neglect the latter two categories hereafter, bearing in mind that they are virtually exclusively industrial. In tonnage terms, of course, the distribution among materials is somewhat different *Figure 11.1 (bottom)*.

Total paper and paperboard consumption in the EEC(11 countries) for 1993 was 54.5 MMT [COPACEL 1994]. A summary of available data on paper production, consumption, recovery and recycling is given in *Table 11.1*. Paper products and cartons used for packaging purposes in 1993 amounted to 23.574 MMT, or 43% of total consumption [ibid]. This included 2.542 MMT for Spain and Portugal. For 1991 the total was 20.482 MMT for EEC(9 countries), excluding the last two countries. Based on the overall growth rate for the larger group of countries, we can estimate packaging paper consumption for the two missing ones as 2.4 MMT in 1991, making a grand total of 22.882 MMT for EEC(11) in 1991. To include Austria, Greece, Ireland, Scandinavia, and Switzerland would increase the total consumption roughly in proportion to the additional population[3], or 12.5%. Thus, we estimate total paper and paperboard consumption for packaging purposes of 25.7 MMT in Western Europe in 1991.

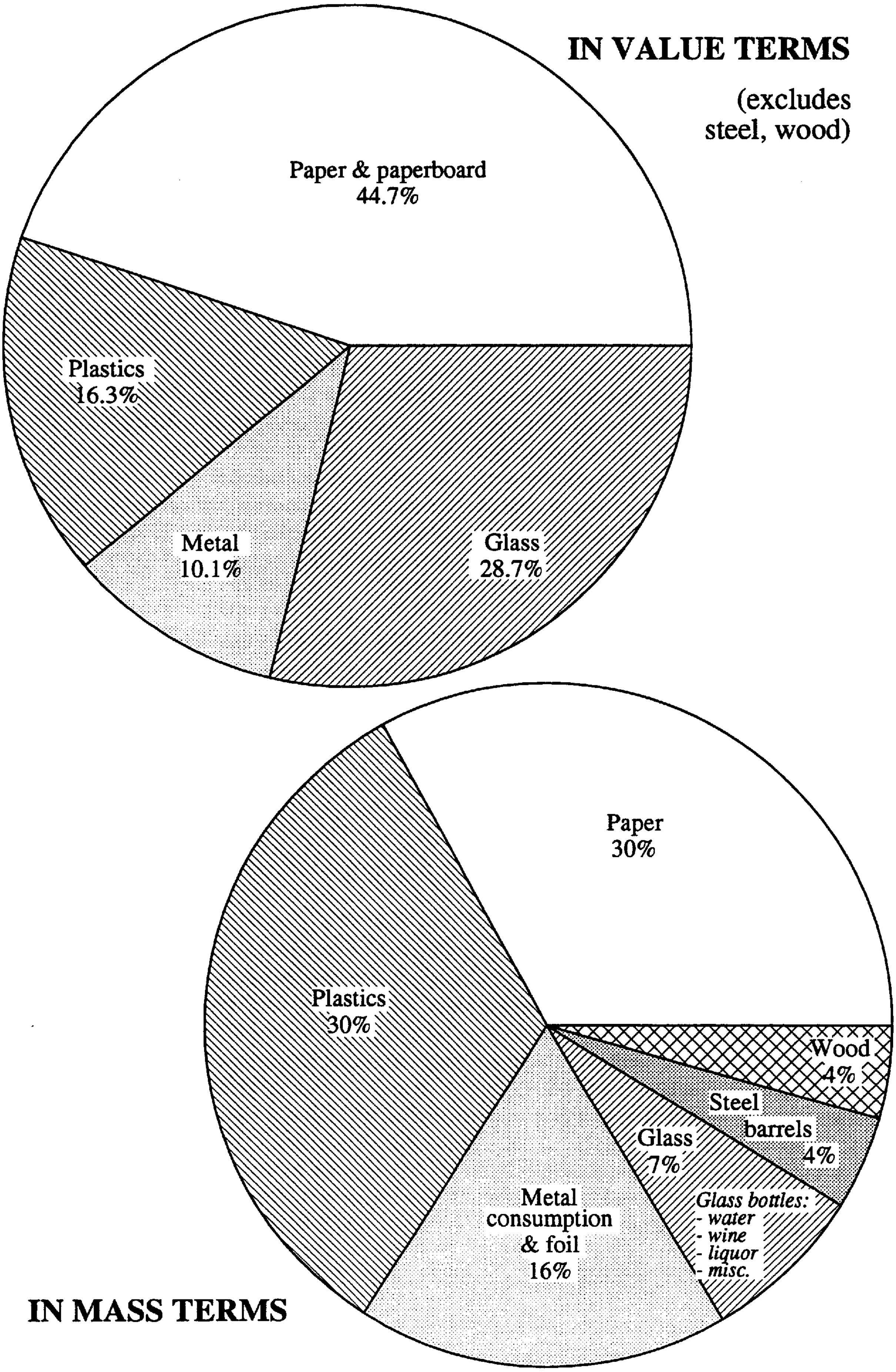

Figure 11.1. The packaging market in Europe, 1991 Source: [Renaux 1992]

Table 11.1. Western European paper, 1992

Country	Production (kMT)	Consumption (kMT)	Used paper cons. (kMT)	Recovery (%)	Recycling (%)
Belgium	1125	2180	286	31.4	13.1
Denmark	356	1105	307	39.1	27.8
France	7132	8870	3367	34.3	38.0
Germany	12132	15221	6109	47.2	40.1
Netherlands	2862	3273	1895	53.2	57.9
Portugal	865	778	339	40.4	43.5
Spain	3426	4582	2222	37.8	48.5
UK	4951	9393	2953	33.0	31.4
TOTAL	**32849**	**45402**	**17478**	**39.6**	**37.5**

Source: Confederation of European Paper Industries, CEPI

As regards plastics, total consumption in Western Europe (1991) was 24 MMT [Matthews, undated] as compared to 27.74 MMT in the U.S. [Modern Plastics, Jan 1993]; the total used for packaging purposes was 9.4 MMT, or 39% of total European plastics production [Matthews, undated]. See *Figure 11.2*. Unfortunately, detailed data on production and consumption are available in Europe, from the Association of Plastics Manufacturers in Europe (APME) only for 6 major tonnage resins (LLDPE, LDPE, HDPE, PVC, PP, and PS).

The Association Professionelle des Producteurs Europeens d'Acier pour Emballages (APEAL, cited by Renaux 1992) estimated the use of steel (mostly tinplate) for packaging at 4.87 MMT in 1990 and 5 MMT in 1991. The recycling rate for steel cans was estimated at 25% (ranging from 6% in Italy to 50% in Germany and the Netherlands. (It was 34% in the U.S., as compared to an overall recycling rate of 66% for the U.S. steel industry.) We have no information on the rate of recycling of tin (detinning) from used tin cans in Europe. However, this technology seems to have advanced considerably in the last few years. As a matter of interest, tinplated steel produced in the U.S. amounted to 2.47 MMT, with a tin content of 11,482 tonnes, or 4.7 kg per tonne [USBuMines 1991, "Tin", Table 4]. (This accounted for 23% of total tin consumption in the U.S. in 1991). Based on 5 MMT production in Europe, and assuming the same average tin content, tin consumption for this purpose in Europe would have been about 23,000 tonnes, virtually all imported.

Aluminum for beverage cans amounted to 780 kMT for western Europe in 1991. Aluminum captured 50% of the European beverage can market in 1991, with individual countries ranging from 100% for Sweden and Switzerland and 96% for Italy to 60% in the U.K. and only 12% for Germany [Renaux 1992]. The recycling rate for aluminum cans averaged 21% for Western Europe as a whole; it ranged from 93% in Sweden to only 7% for the average of the original six EEC countries, none of which had recycling programs in place as of the end of 1991 [ibid]. Tinplate still dominates the non-beverage market. (This is also true in the U.S., where aluminum cans have captured 73% of the total market of 130 billion cans shipped)

[USBuMines 1991 "Tin"]. Packaging materials — mostly cans — account for 31% of aluminum produced in the U.S.; we do not have a comparable figure for Europe.

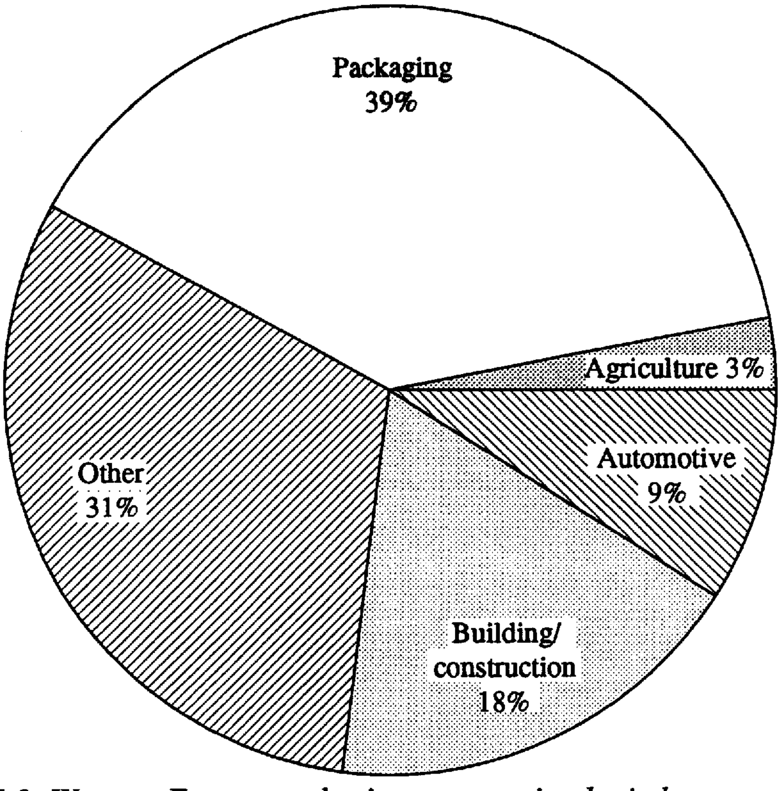

Figure 11.2. Western European plastics consumption by industry sector, 1991
Source [APME 1993]

Glass bottles were much heavier, adding up to 12.63 MMT, which is 65% of the total production of the EEC(9) glass manufacturing sector [ibid], and 80% in France [Briant 1990]. Again, one should extend the estimates to include the massing countries, in proportion to their population. In this case, the missing countries (including Spain and Portugal) add 31% to the base number. Assuming consumption and production are roughly equal for these countries, total packaging glass for Western Europe should be about 16.54 MMT. Adding up all the above we arrive at a total of 57.5 MMT for European consumption of packaging materials in 1991, not including any allowance for steel drums or wooden pallets used by industry.

Within each of the major materials categories there are significant differences in usage. For instance, glass bottles are overwhelmingly used for beverages, especially wine and beer, with a minor fraction going to food products (like baby-foods and jams and jellies). In the case of metal cans, 50% are used for foods, 10% for beverages and 30% for non-food products such as aerosols, paints, and motor oil [ibid]. The remaining 10% is aluminum foil, bottle-tops and closures. See *Figure 11.3*. Paper products are being increasingly used for drinks, especially fruit juice and milk, but most paper packaging products are cartons and wrapping materials for dry products other than food.

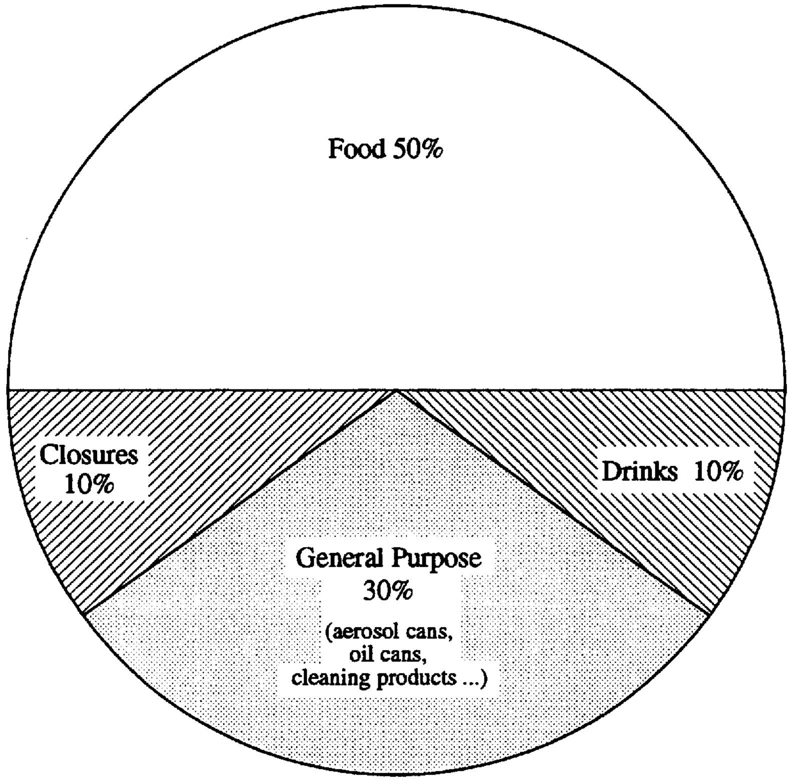

Figure 11.3. Western Europeans packaging uses of metal cans, 1991
Source [Renaux 1992]

11.4. Plastics in Packaging

Because of their diversity of composition, and the significant quantities of metals and other chemicals used for plasticizers, stabilizers and colorants, plastics cannot be aggregated for purposes of recycling. They therefore constitute a special case requiring more detailed analysis.

Plastic packaging materials are conventionally subdivided into four categories: (1) containers, (2) film and sheet, (3) coatings (mostly used in composite multi-layer materials and inside cans) and (4) bottlecaps or closures. Unfortunately, we do not have a detailed breakdown of European plastics consumption in a way that correlates directly with the above categories. The usual classification allocates plastics partly by process (e.g. blow molding, extrusion coating) and partly by material form (e.g. rigid sheet). See *Figure 11.4.* While containers are ipso facto "packages", neither film and sheet, nor coatings, are necessarily used for packaging purposes. In fact, in Europe a great deal of plastic sheet is used in agriculture and in construction. Similarly, while bottles are usually blow moldings or injection moldings, not all moldings are bottles.

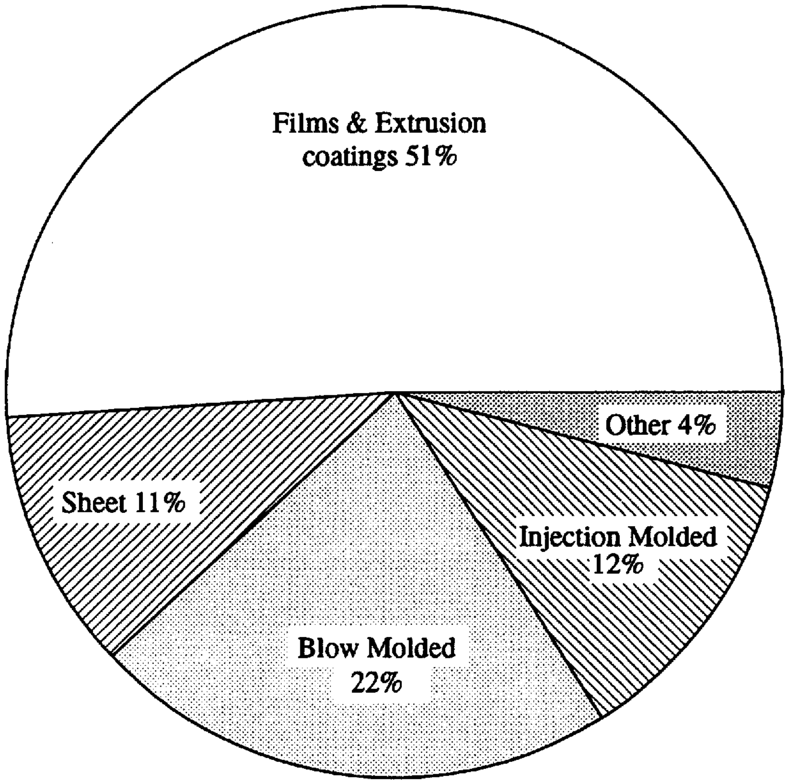

Figure 11.4. Western European packaging use of plastics, 1991
Source: Modern Plastics

A breakdown of plastic use within the packaging sector, as such, does exist for the U.S., for 1989, as shown below [*Modern Plastics* 1990]:

Containers	3393.5 kMT	(52.1%)
Film & Sheet	2354.5 kMT	(36.2%)
Coatings	393.8 kMT	(6.0%)
Closures	368.9 kMT	(5.7%)

The total use of plastics for packaging purposes in the U.S. in that year was 6.514 MMT, significantly less than the EEC total.[4] The largest subsector, containers, can be further subdivided by plastic, viz.

High Density Polyethylene	(HDPE)	1604.0 kMT	(47%)
Polystyrene	(PS)	602.0 kMT	(18%)
Polyethylene terephthalate	(PET)	451.5 kMT	(13%)

with the remaining 22% divided up among polypropylene (PP), polyvinyl chloride (PVC), low density polyethylene (LDPE and LLDPE) and "other". For film and sheet, LDPE and LLDPE are the main materials, followed far behind by PP, HDPE and PVC, and other. For coatings LLDPE is dominant and for closures PS and PP are the dominant plastics (see *Figure 11.5*) and *Figure 11.6*)

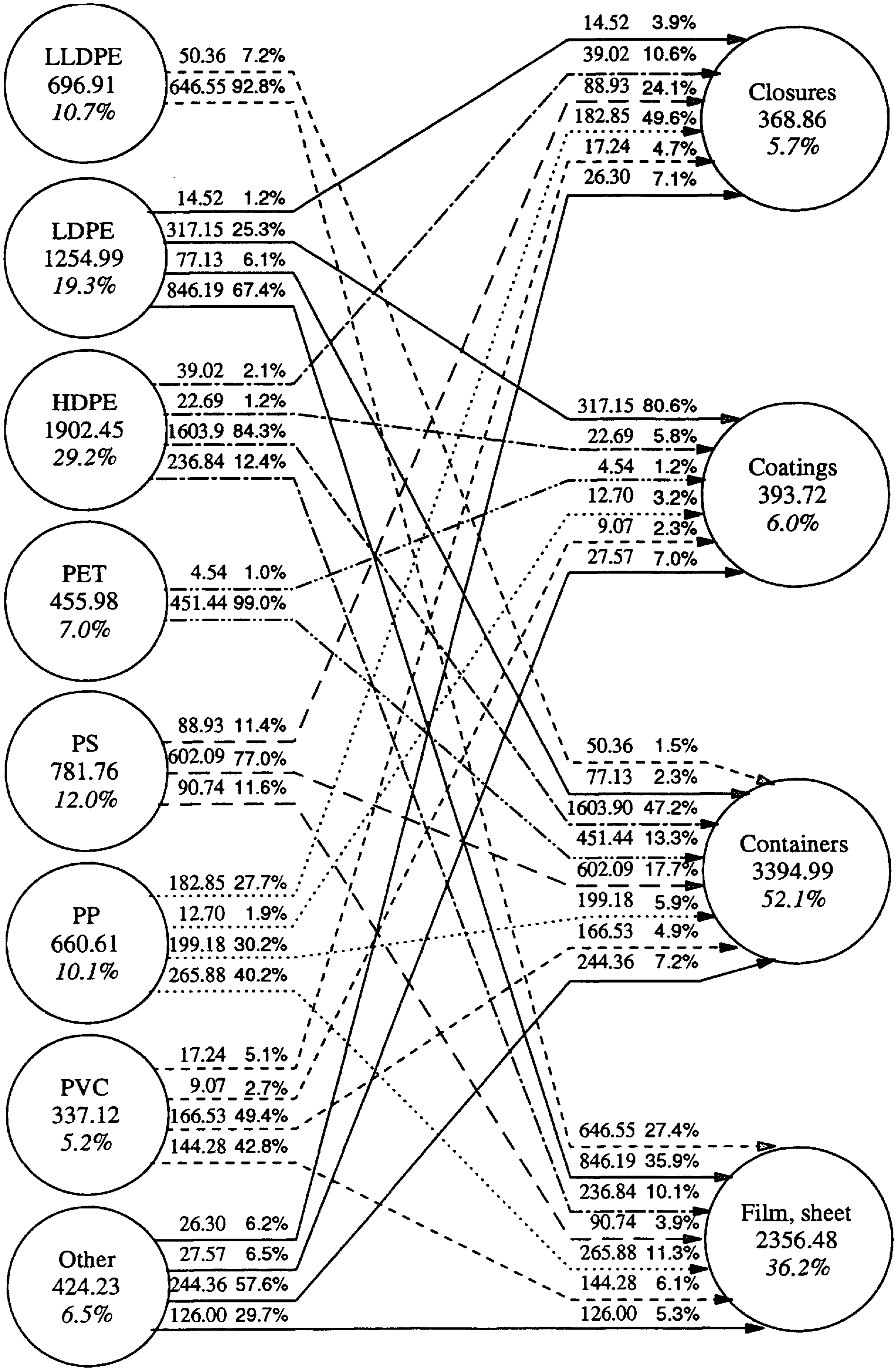

Figure 11.5. U.S. plastics use in packaging, 1989 (kMT)

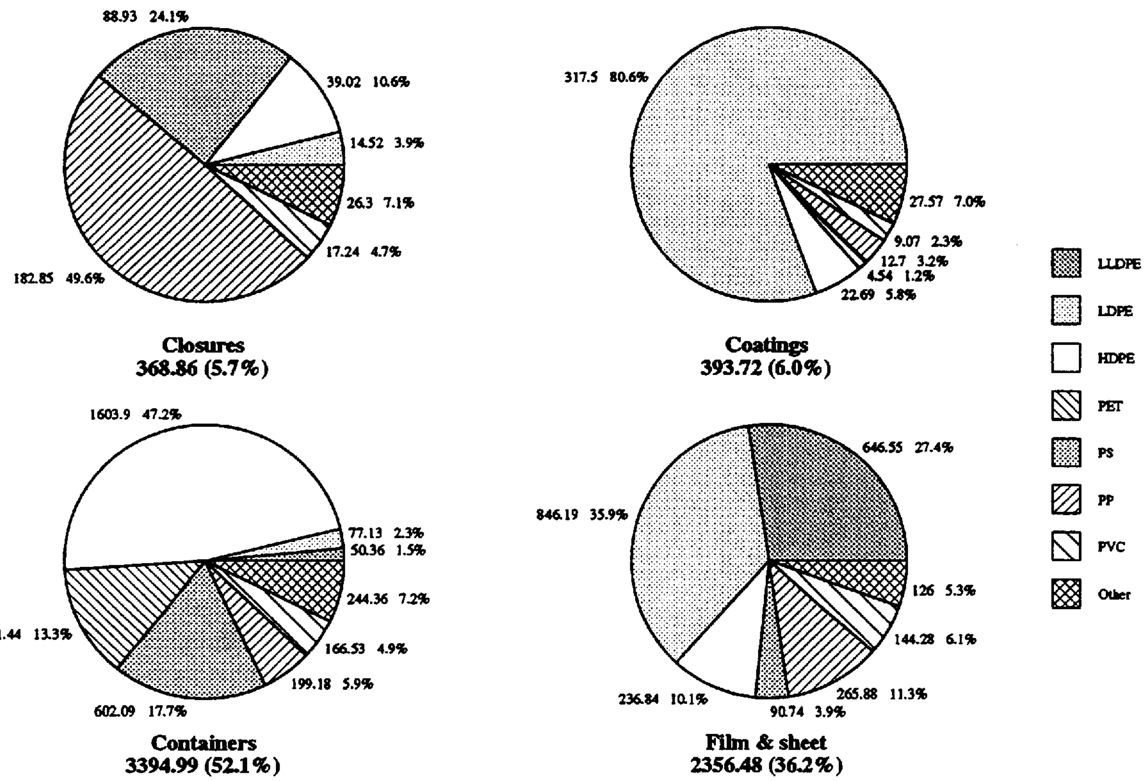

Figure 11.6. U.S. plastics use in packaging by end-use, 1989 (kMT)
Source [Modern Pastics, January 1990]

The European pattern is certainly fairly similar, given the internationalization of the brand-name packagers. There is one major difference, however. In areas where plastic and paper compete, the U.S. uses more paper for packaging whereas Europe uses more plastics. This suggests that the use of plastic film, in particular, may be considerably higher in Europe. Europe also probably uses more plastic bottles than the U.S., especially for mineral water. PVC is widely used for this purpose in Europe.

11.5. Packaging Waste

Packaging waste produced in Western Europe as a whole has been estimated as 154 kg/capita or 50.5 MMT for 1990 [OECD]. This total is subdivided as follows:

Domestic waste:	25.0 MMT	(10% recycled)
Commerce and Services:	15.0 MMT	(17% recycled)
Industrial Waste:	10.5 MMT	(43% recycled)
Total:	50.5 MMT	(19% recycled)

Based on the fact that packaging materials lifetimes tend to be very short, with little or no change in inventory, the sum total of materials apparently consumed for packaging purposes (57.5 MMT), should be very nearly equal to the annual waste flow. To be sure, some packaging materials are burned on farms or used for domestic heating purposes, thus never appearing in the "official" waste stream. Nevertheless, we suggest that the OECD estimate (admittedly incomplete) may be about 10% too low.

Table 11.2. Western European post-user plastic waste, 1990 (kMT)

Country	*Total post-users plastics waste*	*Agricultural sector wastes*	*Automotive wastes*	*Construction/ Demolition civil works wastes*	*Large distribution & industry wastes*	*Municipal solid wastes*
Austria	246	13	19	11	61	142
Belgium/Lux.	372	8	30	31	89	214
Denmark	208	6	10	11	46	135
Finland	164	2	11	11	40	100
France	2311	123	176	58	454	1500
Germany	2363	38	160	51	446	1668
Greece	272	8	9	6	54	195
Ireland	106	4	6	3	22	71
Italy	1996	139	118	54	465	1220
Netherlands	781	6	37	25	133	580
Norway	216	14	11	6	35	150
Portugal	283	7	8	7	66	195
Spain	1426	138	49	59	250	930
Sweden	326	11	22	15	68	210
Switzerland	325	16	19	10	55	225
UK	2199	52	161	73	513	1400
TOTAL	**13594**	**585**	**846**	**431**	**2797**	**8935**

Source: PWMI

A slightly more detailed breakdown of plastic waste, in particular, by country and major sector of origin is shown in *Table 11.2*. Detailed breakdowns of packaging waste by material are not available for all European countries, as we have noted. Data for the major northern European countries is given in *Table 11.3*. Details on the disposal of plastics wastes *per se* are not available for Europe as a whole. However, the Netherlands is probably reasonably typical of Northern Europe. In 1986 total plastic waste for that country was estimated at 763 KMT (1% of the total volume of solid wastes); of this 90% was incinerated or disposed of in landfills, and only 10% was recycled [Starreveld & van Ierland 1993]. By 1994 the quantity of plastics waste was expected to increase to 850 KMT absent additional waste prevention measures. Dutch authorities had hoped to reduce this by 6% (to 800 KMT) by means of effective waste prevention, with recycling up to 26% in 1994 and 42% by 2000 [ibid]. Yet, as of 1992, the recycling percentage remained at about 10% [ibid].

Municipal solid wastes are the main avenue for disposal of packaging materials, other than those generated directly by industry. In terms of weight distribution, we have at least three inconsistent sources to choose from, as summarized in *Table 11.4*. It seems to be agreed that municipal wastes in Europe (1990) averaged between 33.5 and 35.5 % packaging wastes.

Miscellaneous organic products (food and yard wastes) accounted for 25%-34%; paper and cardboard accounted for 28-39%; ashes and dust for 9.6%-16%; plastics 7.3%-10%; 8% glass, 8%-12%, metals 5%-8%, and textiles 2%-4%. Of the paper waste, a fairly large fraction is newspapers, magazines and advertising materials sent through the mail. The rest is packaging.

Table 11.3. Package material recovery & recycling rates, 1991 (%)

Country	Paper Recovery	Paper Recycle	Glass	Steel	Aluminum
Austria					24
Belgium	31.4	13.1	55	30	*
Denmark	39.1	27.8	35		
France	34.3	38.0	41	31	*
Germany	47.2	40.1	63	50	*
Greece			22		25
Ireland			23		8
Italy	27.8	37.3	53	6	10

The plastics and glass are almost all packaging wastes. In the case of metals, there are some non-packaging wastes. The major difference between the ANRED estimate (column #2 of the table) and the other two estimates (columns #3,#4) appears to be in the assumed split between packaging paper and non-packaging paper. (See, however, further discussion below).

Table 11.4. Municipal waste estimates for Western Europe, 1990

	ANRED (Renaux)	APME (I) (Matthews)		APME (II) (Anon)	
		source	(a)	source	(a)
Paper & board	5.5%	30.0%	17.5%	28.0%	15.5%
Plastics	10.0%	7.4%	7.4%	7.3%	7.3%
Glass	12.0%	8.0%	8.0%	8.0%	8.0%
Metals	6.0%	8.0%	2.5%	5.0%	2.5%
Packaging Subtotal	33.5%	53.4%	35.4%	48.3%	33.3%
Other paper	24.5%	NA	12.5%	NA	12.5%
Other metals	NR	NA	5.5%	NA	2.5%
Textiles	2.0%	4.0%	4.0%	4.0%	3.0%
Ashes, minerals & misc.	16.0%	9.6%	9.6%	9.6%	15.0%
Organics	25.0%	33.0%	33.0%	33.0%	33.7%
Total Municipal Waste	100.0%	100.0%	100.0%	100.0%	100.0%

NR = Not Recognized

(a): Original source did not separate packaging paper & metal from other paper & metal. These allocations have been made by the author (See also text).

Annual packaging waste generation should be in proportion to annual production of new packaging materials, adjusted for recycling and re-use. Glass appears to be under-represented in the municipal waste stream, compared to both metals and plastics. Extrapolating from EEC data, the weight of glass bottles manufactured and consumed in Western Europe as a whole in 1991 was about 16.5 MMT. This compares to 5.75 MMT of metal cans and 9.4 MMT of plastic packaging materials. Discards into municipal wastes should be roughly in the same proportions, other factors being equal. That is, the ratio of glass bottles to metal cans in the municipal waste stream should be about 3.6 to 1. In fact, glass and metals appear to be present in ratios of 2:1, 1:1 and 8:5 in the three cases cited above. Similarly, the ratio of glass to plastics should be roughly 16:9 based on relative consumption levels of glass and plastics. In fact, only slightly more glass than plastic is found in municipal waste. (In this case, all three estimates show similar ratios).

Two strong implications can be drawn from these disparate numbers. First, compare glass with plastics, since both are essentially pure packaging wastes. The fact that less glass is present than one would expect based on consumption levels, it follows that some glass bottles are being collected for re-use and recycling *outside* the municipal system, whereas plastics are not recycled at all. In fact, the numbers suggest that about 20% of glass bottles are re-used or recycled through external channels. This is consistent with general observation, though we have no precise confirming data. The second implication of the above numbers is that a considerable fraction of the metals going into municipal wastes are not packaging wastes (cans) but miscellaneous items such as wire, light bulbs, fasteners, pipe, small bits of hardware from domestic repairs, and so on. The non-packaging *fraction* would have to be around 1/3 (ANRED), 2/3 (APME I) or 1/2 (APME II) to make everything consistent. Interestingly enough, the end result in all three cases is that non-packaging metal accounts for 2-2.5% of total municipal waste.

The same logic should also lead us to an estimate for the packaging paper fraction. The proportionality principle implies that we should compute the ratio of paper consumption in packaging to plastics consumption in packaging, viz. (25.8/9.4) = 2.7. This is to be multiplied by the actual plastics percentage (10% or 7.4%, respectively). We thus estimate that either 10 * 2.7 = 27% or 7.4 * 2.7 = 20% of the waste stream consists of packaging paper and paperboard. Subtracting 20% or 27% from 30% or 28%, as appropriate, this implies that either 3%, 12.5% or 10.5% of the municipal waste stream must consist of "other paper", e.g. newspapers, magazines and advertising materials. There is a major inconsistency with the figures shown in the ANRED estimate (column #2), which allocate only 5.5% to packaging and 24.5% to "other paper". We cannot explain or resolve it except in terms of survey error.

11.6. Re-use and Recycling of Plastic Packaging Wastes

The potential for re-use of packaging materials *per se* is largely limited to re-use of steel drums and wooden pallets by the industrial sector, and re-fillable glass bottles. The former problem is one of organization and incentives; we need not consider it further. The situation with regard to refillable bottles is similar. There are minor technical difficulties, but it must be remembered that, in the case of milk, local delivery, collection and refilling was the norm at one time. It would not be unreasonably difficult to re-constitute a local delivery and pickup service for a wider variety of liquids in glass bottles, including mineral water, beer, wine and soft drinks. Again, the logistical details need not be considered here.

As regards recycling, the logic is clear if we compare the energy required to produce a packaging material with the energy recoverable by combustion (*Table 11.5*). It is clear that glass and metal (being non-combustible under normal conditions) contribute nothing to energy recovery. Paper and most plastics are highly combustible, by contrast.[5] However, it is worth noting that PVC, because of its high chlorine content, yields less than half the energy per kg than most of the other plastics. But even for polyethylene, 36-46% of the energy required to produce the plastic is irretrievably lost. In the case of PET, a very complex plastic, and PVC, not more than a third of the energy required to produce the material in the first place can be recovered as heat.

Table 11.5. Potential energy recovery from packaging materials

Packaging Material	*Energy Recovery Potential (Heat of Combustion per kg) kJ/kg*	*Production Energy kJ/kg*	*Recoverable Portion %*
Paper	17400	30102	57.8%
Glass	—	—	—
Steel	—	—	—
Aluminum	—	—	—
LLDPE	41000	63960	64.1%
LDPE	41000	76260	53.8%
HDPE	41000	72570	56.5%
PS	37800	68040	55.6%
PET	27600	82800	33.3%
PVC	14300	47619	30.0%

Source: [Gaines 1981]

There are two recycling cases to be distinguished. The first is recycling of materials to be used again as materials. Ideally, recycled materials should be comparable in quality to the "virgin" material and usable for the original purpose. In practice, this is possible for aluminum cans and may be possible for glass bottles. Tinplate can easily be recycled insofar as both the tin and the steel can be recovered. This is already done to a significant degree. The tin coating, however, is only recoverable by a special detinning process. To the extent that used tin cans are aggregated with other scrap iron and steel and used as feedstock for foundries, for instance, the tin becomes a minor contaminant of the steel and is lost.

In the case of paper, there is an unavoidable and significant degradation of quality every time a paper product is recycled. This arises from the need to re-pulp, remove various inks, coatings, and fillers (amounting to 10% or more of the product weight) and re-bleach. Cellulose fibers are shortened in this process, losing strength each time. Thus, while "100% recycled" paper is appealing some environmentalists, 100% recycling of all paper products is not technically feasible. An optimum mix of virgin and recycled pulp would probably require at least 30% new pulp on average, and the optimum "cascade" of products from high quality to lower quality uses is not yet clear.

The problem of recycling used plastics, for use as materials rather than for energy recovery, is even more difficult. Most plastic wastes are currently consigned to landfills (*Figure 11.7*). This is because most plastics appear in household and commercial (not industrial) packaging wastes, where sorting is difficult to do (and to enforce). Standardized markings, now being used by most packagers to distinguish various types of plastic, make it somewhat easier for householders to sort plastics. But voluntary sorting will not help much unless it is virtually universal, and it is very hard to imagine any effective enforcement system.

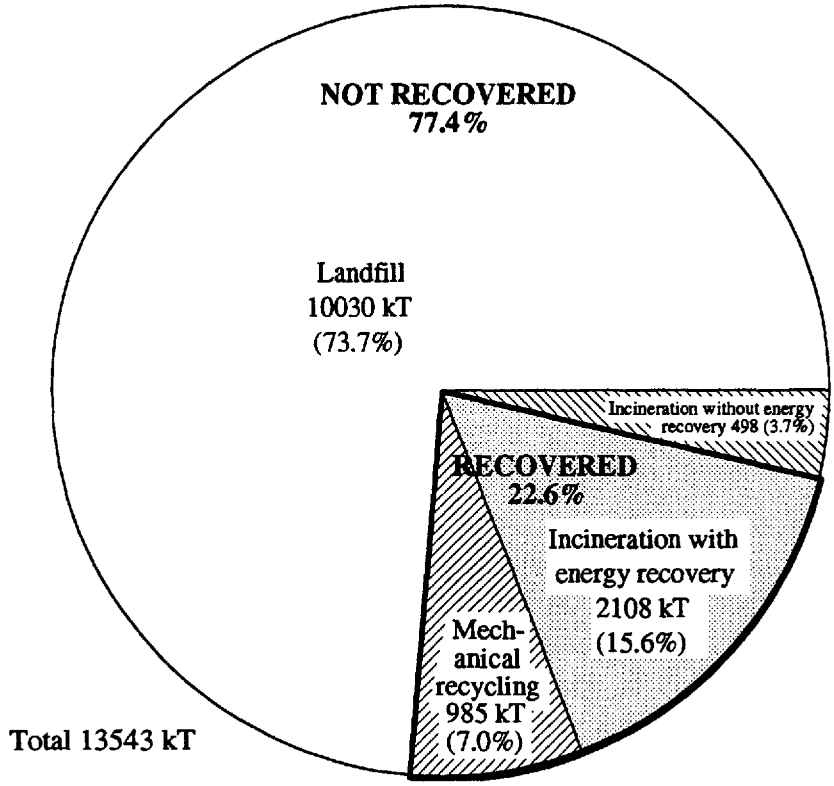

Figure 11.7. Destination of total post-user waste; Western Europe, 1990
Source: PWMI,APME

Recycling mixed plastic packaging materials is the final, and most challenging, aspect of recycling mixed municipal waste. It is comparatively easy to separate steel from other wastes by taking advantage of its magnetic properties. Other solids can be separated on the basis of their density or (in the case of glass) color. A generic sorting and separation system is shown schematically in *Figure 11.8*. Such systems are still relatively rare, but are becoming more common as the technology matures.

It is technically possible to separate different plastics, too, based on density and other characteristics. In particular, PVC is much denser than other plastics and is therefore rather easy to remove by gravity concentration, once the materials are broken up into small enough fragments. Electromagnetic scanners can also specifically identify PVC by recognizing the presence of chlorine [Manzone 1993]. This also permits automatic separation, for instance, of bottles within a given size range. A separation scheme for plastics (which would logically be an add-on to the system illustrated in *Figure 11.8*) is shown in *Figure 11.9*. Systems like this have been implemented in a few cases. PVC, in particular, is being recycled for mineral water bottles by Evian in France; other recycling programs exist, for instance the Tecoplast recycling plant in Italy, and Reprise in the U.K. [ibid].

PET is also recyclable as such. In the U.S. 30% of PET bottles are recycled [Rathje & Murphy 1992 p. 205]. Half of the total is attributable to Wellman Inc. of Shrewsbury N.J. Wellman currently recycles PET bottles at two locations, Johnsonville S.C. and Mullagh, Ireland. The process involves removing aluminum caps and paper labels, then cutting off the black HDPE base cups. The latter are crushed and sold as flakes to be recycled into plastic handles for irons and other items. The PET itself is recycled as stuffing for sleeping bags and

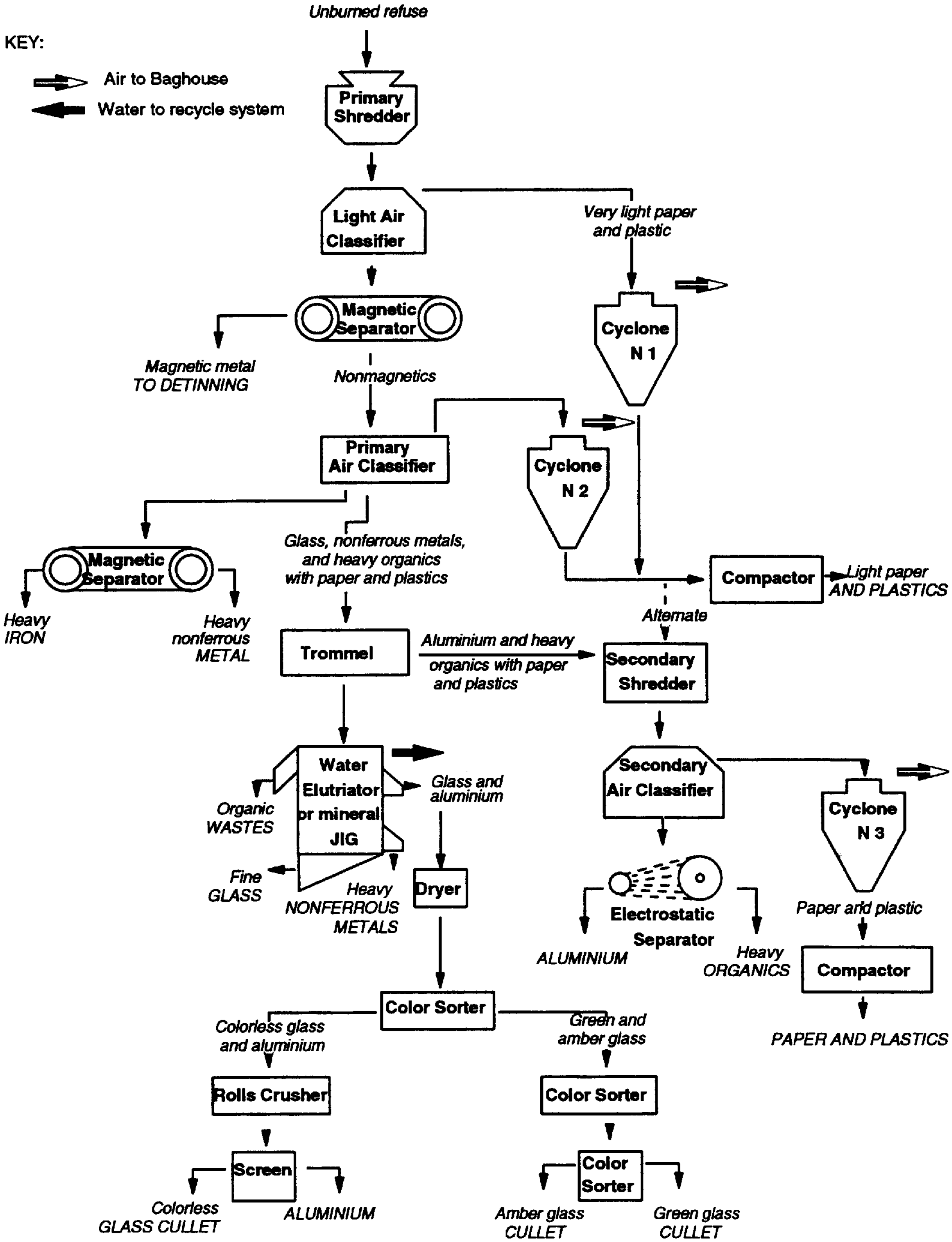

Figure 11.8. Raw refuse separation flowsheet

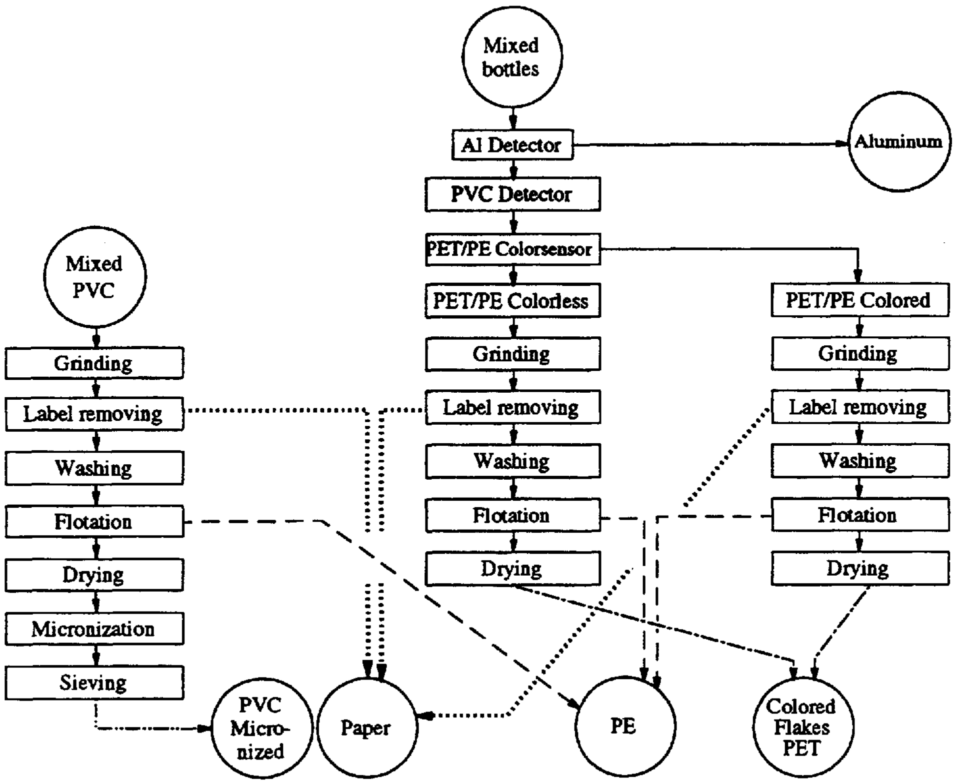

Figure 11.9. TECOPLAST recycling plant Source: [Manzone 1993]

ski jackets (e.g. Patagonia Inc.) or as fibers for polyester carpets [ibid]. In 1990. the ultra-conservative Food and Drug Administration (FDA) in the U.S. granted PET the first exception to its rule prohibiting the use of recycled plastic in food or beverage containers. Both Coca Cola and Pepsi Cola apparently plan to do this [ibid].

Polystyrene foam, one of the most controversial packaging materials, can be recycled. The process starts with collection and sorting, followed by (1) quality check, (2) washing to remove food residue, (3) compaction and grinding, (4) drying, (5) melting, (6) filtration, (7) molding into pellets and (8) cooling. The most expensive equipment involved — after sorting — is an extruder which incorporates steps (5-7). The recycled polystyrene pellets have approximately the same market value as pellets of virgin material [Kuo 1990]. Many polystyrene products are already made from mixtures of virgin and recycled material. One interesting product from Mandish Research (FLA), called "lightweight concrete" is actually 90% recycled polystyrene [Kuo 1990]

Polystyrene recycling was stimulated in the U.S. by the widely publicized "hamburger" controversy (between polystyrene foam and papier maché as containers for hamburgers and other `fast food'). When McDonalds, under pressure from environmentalists, decided in favor of paper, the polystyrene industry saw a major threat. In response, National Polystyrene Recycling Co. (U.S.) was created as a joint venture between several oil companies (Amoco, ARCO, Chevron, Mobil) along with several polystyrene producers (Dow, Fina, Huntsman, Polysar) in the late 1980's. The first operational recycling plants as of Dec. 1990 were located in Brooklyn NY, Leominster MA, and Portland ORE, with plants in Chicago, San Francisco and Philadelphia scheduled to follow by mid 1991 [Kuo 1990]. (We do not have more recent information). It is important to emphasize that polystyrene recycling is only practical in conjunction with an institutionalized collection and sorting system.

Table 11.6. Pollutants in plastics, 1989 (mg/kg)

Pollutant	Cd	Cr	Cu	Ni	Pb	Zn	Sn	Cl	F
PE-film									
.transparent	1	8	24	2	72	97	7	3412	11
. white	<1	13	35	5	60	427	2	2790	25
. yellow/red	20	347	55	4	1738	100	4	3182	28
. blue/green	1	81	93	3	591	403	5	1930	33
PE-hollow bodies									
. transp./white	<1	0	12	0	15	247	6	1070	5
. yellow/red	103	9	83	0	73	44	8	3397	7
. blue/green	10	4	26	0	50	154	4	2998	9
PP-cups	2	28	20	18	7	55	0	630	10
PP-cups									
. transp./white	2	0	44	0	11	694	0	1986	4
. colored	28	0	51	0	24	139	3	500	4
Polystyrene	2	0	32	0	21	151	3	7100	8
Laminated foil	6	19	94	8	93	143	91	98527	8
PE-nets	3	637	41	19	2425	672	17	1000	43
PVC									
. cups	1	0	20	1	13	46	371	454250	9
. hollow bodies	15	0	14	0	12	58	452	434000	10
. form pieces	2	4	47	10	22	88	362	418866	36
PE-caps									
. transp./white	4	69	66	59	14	381	4	750	12
. yellow/red	653	0	26	0	32	47	2	500	9
. blue/green	159	69	577	39	14	192	5	500	14
Other caps	40	0	245	0	17	370	2	750	11
Daily articles									
. PVC	420	156	26	13	1679	393	78	283250	35
. PE/PP	347	12	19	0	115	183	6	1812	16
. Others	88	4	555	104	48	2235	7	2000	

(after UBA report, January 1989)

Another approach to plastic material recycling is being explored by several European manufacturers of monomers. Depolymerization can be accomplished by "solvolysis" via certain alcohols (e.g. methanol) or glycols. Either methanolysis or glycolysis can be used to reduce polyesters, polyurethanes or polyamides to their constituent monomers. In particular, this approach is being investigated for PET by several major firms, including Hoechst-Celanese, Dupont, and Eastman Kodak [PWMI 1993].

There are fundamental limits to plastics materials recycling, however, arising from the fact that even plastics using the same resin (e.g. PVC) can also use a wide range of different additives. See *Table 11.6.* Recovery systems are inherently complex and capital intensive. They will not compete economically with either landfill or incineration under present conditions (unless these alternatives are strongly discouraged).

There are some possible uses for mixed plastics that do not involve separation. One such use is to produce a kind of synthetic "wood". In principle, a plastic based product similar to wood would be very attractive for many purposes, ranging from park benches and garden furniture to roof shingles, doors, floors and wall-panels. The plastic material would never rot, would never need to be painted (although it could be) and would not warp or twist. Minor technical problems need to be solved to make the material easier to cut, shape and fasten — like natural wood — but these do not appear to be serious. Such materials have already been produced and put to use. A vacation resort in St. Johns, U.S. Virgin Islands, not only utilizes such materials exclusively in the construction of its villas, but advertises the fact to attract "ecotourists". The major drawback to wider use seems to be market acceptance by consumers (and, of course, marketing by producers).

Nevertheless, practical difficulties must not be understated. The following story illustrates the sort of marketing problem that can arise:

> "Syacon was originally conceived using recycled poly-butylene terephthalate (PBT) aggregate from GE which was available in white, gray, or black. The marketing group wanted, and got, colors of aggregate which were virgin plastic, rather than recycled. The reasoning was that we could then better compete against terrazzo, which was available in a wide range of colors, but nothing like the potential colors available for plastics. Unfortunately, that nearly doubled the cost of already very expensive (by construction floor industry standards) aggregate in the product. Despite the cost, we were able to compete for, and get, jobs because of our ability to provide special colors. What caused the removal of the product from the market was that we experienced a few "popouts" of plastic aggregate in floors where spiked heels or other types of point loads were commonly found. The marketing group though aware of the potential for the problem before its introduction soon stopped promoting the product because of the combined price and popout situation..." [Mauerhofer, 1993]

An exciting variant of this idea is to use recycled plastic in the form of tiny solid balls to make synthetic "snow" and "ice" for ski-slopes and skating rinks that could be used in summer. This is a high-tech (and rather expensive) product that would not use much plastic material, but would help overcome the reluctance of consumers to accept recycled plastics.

A last-resort method for reducing mixed plastic materials to their component hydrocarbons is also technically feasible. Pilot plants to do this have been demonstrated by several petrochemical companies, including Shell and British Petroleum (BP). BP Chemicals has built a pilot scale pyrolysis plant for the conversion of mixed plastic wastes to hydrocarbon feedstocks [PWMI 1993]. The German utility VEBA has converted mixed plastic and household wastes to synthetic fuel oil by hydrogenation. This oil is then recycled back to raw materials for plastics in a neighboring refinery [PWMI 1993]. However the economics are very unattractive compared to the use of virgin materials and will probably remain so for decades to come.

An interesting study has been carried out recently by Dutch researchers at the Wageningen Agricultural University in the Netherlands [Starreveld & van Ierland 1993]. They constructed an optimization model for plastics recycling, based on relatively standard and non-controversial assumptions about technological alternatives and prices. The "base case" assumed oil prices at $20 per barrel, landfill dumping costs of $25 and incineration costs of $90 per metric ton of waste plastics. Four major plastics were considered (PVC, PE, PP and PS) which account for 85% of demand. Four categories of demand were considered, namely packaging, construction, transport and miscellaneous. Within each category, demand was further subdivided by quality levels, distinguishing "virgin" applications (such as food and beverages), "high quality" applications permitting a mix of virgin and recycled materials, and "low quality" applications for degraded or contaminated materials. Demand schedules and elasticities of substitution characteristics were estimated roughly, using 1986 as the base year. A standard linear programming software package was used. The model was used to explore the opportunities for recycling under various assumptions about disposal charges.

The most controversial assumptions in the model concern the options (and costs) for recycling plastic materials. Needless to say, the model considerably simplifies the reality. For example, it assumes the cost of "thermal conversion" of waste plastics for high quality applications (exemplified in the real world by the case of polystyrene, discussed above) to be $2400 per metric ton on a small scale, rising to $6500 per tonne as the scale of operation rises. Not surprisingly, the model does not select this option under any circumstances, regardless of the charge for disposal. Nevertheless, the results of many optimization runs are interesting. Most interesting of all is the fact that product recycling is clearly preferable to materials recycling, under all conditions. Beyond this, the level of recycling vs disposal is a strong function of the assumed disposal charge. For example, to achieve 25% recycling, the model calculates that a disposal charge of $300 per metric ton would be needed — extremely high in comparison with the assumed costs of dumping or incineration [ibid].

In some ways the model is clearly too conservative. For one thing, it probably underestimates the potential market for low quality applications of plastics by an order of magnitude, having no way to take into account the potential for product improvement and the potential impact of serious mass marketing of such products as synthetic wood. For another, it (admittedly) does not reflect the likelihood of major technological progress in materials recycling.

11.7. Energy Recovery from Packaging Waste

Incineration is the other form of "recycling", to recover heat energy, as noted above. This is clearly the preferred option in some countries (e.g. Switzerland), despite the relatively low efficiency of the process (*Table 11.5*) and even though 80% of the cost of a modern "high tech" incinerator may be invested in pollution controls.

There are two particularly vexing problems associated with the incineration option. One is the fact that many plastics contain significant quantities of metals which either volatilize (like mercury) and are dispersed with the combustion products, or are retained in fly-ash or bottom ash. Incinerator ash is notoriously toxic because of the high level of content of heavy metals such as cadmium and arsenic. Admittedly many of these metals are attributable to wastes (e.g. batteries) not associated with packaging materials. But significant quantities of cadmium, for instance, are used in inks and as plastic stabilizers. *Table 11.6* indicates the extent of contamination of plastics by metals, many of which are toxic.

The other vexing problem associated with incineration is specific to plastics, especially PVC and others that contain chlorine. PVC, in particular, constitutes about 22% of total Western European plastics consumption. Of this, about 10% is coatings, 7% is flexible film and 9% for bottles, especially mineral water. Packaging uses account for 18% of PVC use in Europe, but only 7% in the U.S. Films, in particular, contain over 50% filler and 16% plasticizer (mostly di-2-ethyl-hexyl adipate, or DEHP). DEHP has been declared a "probable carcinogen" in the U.S., but "not a carcinogen" by the EEC. This may account for the much larger use of PVC in packaging, especially of food and water, in Europe [MIT 1993]. The combustion of chlorine-containing plastics, like PVC, generates hydrogen chloride, HC. The chlorine industry minimizes the dangers associated with HC, pointing out that HC accounts for only 2% of acidification in Europe, and PVC only accounts for about 10% of this [e.g. Manzone 1993]. A second concern about combustion, of course, is the potential generation of carcinogenic dioxins and chlorinated PAH's.

This last issue is extremely controversial. Environmental groups, especially Greenpeace, have strongly criticized the use of PVC (and chlorine itself) on these grounds [e.g. Johnston & Troendl, 1993]. Not surprisingly, this was strongly challenged by the Vinyl Institute, which produced its own life cycle analysis and minimized the risks of PVC relative to other materials. The industry-sponsored MIT study also downplayed the dangers cited by Greenpeace [MIT 1993].

An independent life cycle analysis of alternative packaging materials, by the Tellus Institute, was carried out for the State of New Jersey, the Council of State Governments and EPA [Tellus 1992]. This study assessed direct and indirect emissions for all major packaging materials, weighted by toxicity and carcinogenicity relative to lead. The dollar values were computed as multiples of the average dollar cost of controlling various types of lead emissions ($1600/lb). Using this approach, dioxins received an extremely high weight, as did vinyl chloride monomer (VCM) and mercury emissions from chlorine manufacturing. These emissions adversely affected the valuation of PVC vis a vis other materials. In the Tellus study, PVC was evaluated as 12-16 times as costly (in the above sense) as other alternatives [ibid]. In fairness, however, it must be acknowledged that both the data base and the valuation methodology are open to question and need further refining.

The fundamental problem with conventional incineration is that to achieve effective destruction of complex toxic organic molecules, not to mention thermodynamic efficiency, high temperatures are needed. But, at high temperatures metals like arsenic, cadmium, lead and mercury are volatilized. They can be recaptured only by cooling the exhaust gases and inducing the metallic vapors to recondense on particulates that are subsequently captured by electrostatic precipitators (ESP's). The precipitator technology is quite efficient and reliable, but not inexpensive. Moreover, it takes a significant amount of the energy that is supposedly being recovered. This problem is fundamental. The difficulties are compounded by the presence of chlorine compounds, especially corrosive hydrochloric acid, in the exhaust stream.

The long term solution has to be to abandon conventional incineration altogether. It is a technological dinosaur. There are at least two generic alternatives, although neither has yet been taken seriously by either the electric utilities or the waste disposal community. The first is to apply low temperature thermo-chemical gasification technologies — similar, in principle to coal gasification technologies that have been under development for a number of years — to a mixed plastic waste input stream.[6] This would have to be followed by cooling (to condense metallic vapors), fly ash removal, desulfurization and hydrogen chloride removal of the gas prior to use as fuel for a two stage combined cycle. The first stage would either be a small aero-derivative gas turbine, such as the GE LM2500, or a heavy duty industrial gas turbines designed for stationary applications. Some turbines of the latter type already have operating experience with low-calorific fuels such as blast furnace gas. The second stage would be a conventional steam turbine bottoming cycle, using the gas turbine exhaust as one of its heat sources.[7]

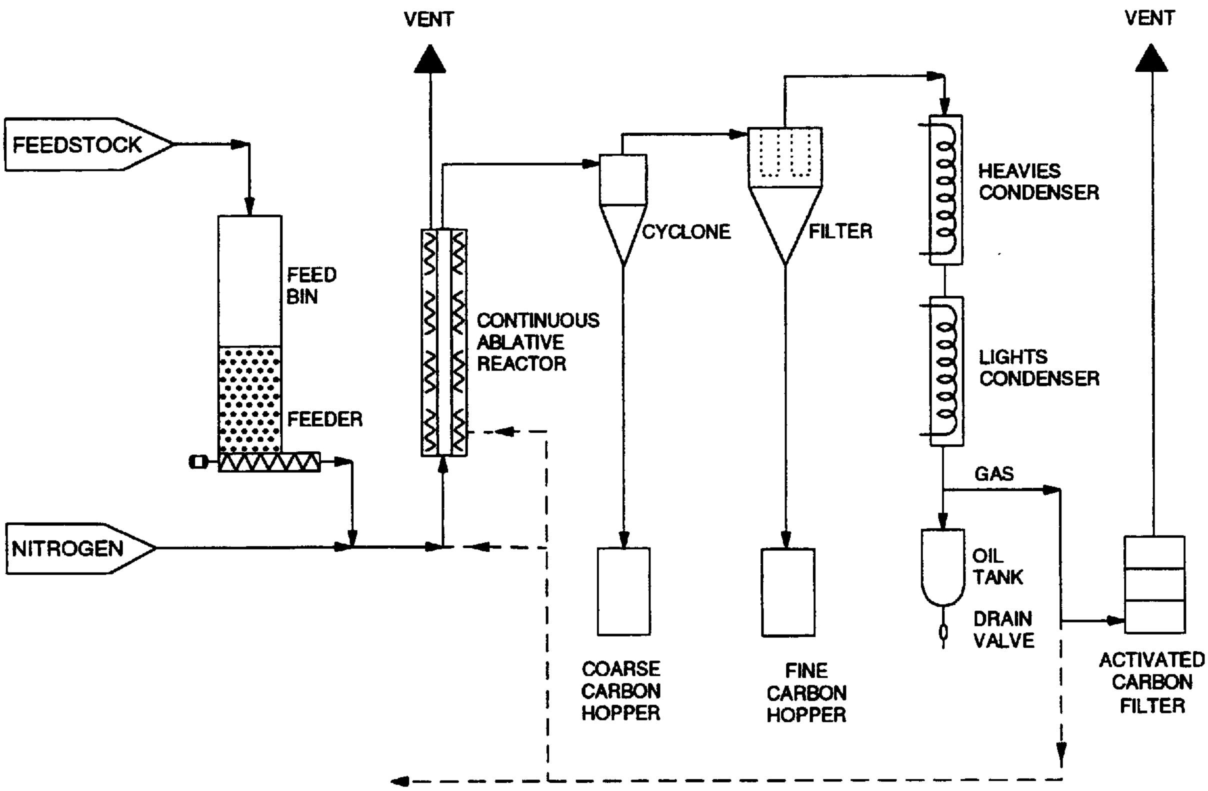

Figure 11.10. Scematic for a continuous ablative reactor (CAR)
Source: Castle Capital Ltd

Gasifiers are of two types. The first type uses heat supplied directly by partial oxidation of the feedstock to yield carbon monoxide; this is normally accompanied by a "shift reaction" in which steam reacts with carbon to yield more carbon monoxide plus hydrogen gas, along with nitrogen from the air. If pure oxygen is used (as coal gasification plants would do), the result is "synthesis gas", a mixture of carbon monoxide, carbon dioxide, water vapor and hydrogen; if air is used for oxidation purposes the product is diluted with nitrogen and is, essentially, "town gas" similar to the gas which was generated from coal to supply gas light and stove gas for cities before natural gas became widely available.

The second type of gasifier uses indirect heating through a heat exchanger. In this case the process is simple pyrolysis, at temperatures of 700-800 C with no oxygen present. The result, again, would be a mixture of carbon monoxide, carbon dioxide, water vapor, hydrogen, methane and tars. The amount of water vapor depends on the moisture content of the feed. Since municipal waste is quite dry in general, the resulting pyrolysis gas would consist mostly of carbon monoxide, carbon dioxide, hydrogen and hydrocarbons. Two indirectly heated gasifier designs have been tested to date: one uses circulation of hot sand as a heat exchange medium; the other uses a fluidized bed [Larson & Consonni 1994].

A third design is known as the Continuous Ablative thermolysis Reactor (CAR), which is being developed in Canada by Castle Capital Ltd. A schematic version is shown as *Figure 11.10.* It has been tested on a small scale on a variety of feedstocks ranging from shredded tires (see *Chapter 12, Tires*), sawdust, cow manure, sewage sludge, automobile shredder fluff, oil shale and municipal refuse. Here, too, the product would be a gaseous fuel to be used in a gas turbine along the lines described above. The CAR reactor is a proprietary version of the second type of indirect (heat exchanger) gasifier described previously. It achieves very high heat transfer rates in the reactor at pressures up to 100 atmospheres.

As applied to municipal wastes, the next step is gas cleaning and cooling. Aero-derivative gas turbines are very susceptible to erosion by particulates [Kurkela *et al* 1993, cited in Williams *et al* 1994]. Ash remains solid at these gas temperatures, and easily volatilized metals (like arsenic, mercury, sodium and potassium) can be condensed and removed with particulates at temperatures below 400 C. The particulates, in turn, may be removed by ceramic filters or liquid scrubbers.

Tars must be removed or cracked. The former can be done by further cooling. However this is a loss of chemical energy and another disposal problem, so the better solution would be to crack the tar in a catalytic cracking unit using dolomite as a catalyst. Hydrodesulfurization is a standard off the shelf technology. Hydrogen chloride can be removed in the liquid scrubber. Further discussion of the technical details of low temperature thermochemical gasifiers and gas cleaning technology would take us too far afield for present purposes, however.

References(11)

A number of general sources have been used in this section in addition to those cited in the text; they are included below.

[APME 1993] Association of Plastics Manufacturers in Europe. *Plastics Recovery in Perspective: Plastics Consumption & Recovery in Western Europe 1989-91*, Association of Plastics Manufacturers in Europe, Brussels, 1993.

[Briant 1990] Briant, Yvette, *Packaging in Europe: France*, Special Report (EIU 2046), The Economist Intelligence Unit, London, August 1990.

[Corradini 1990] Corradini, Roland, *Packaging in Europe: Belgium, the Netherlands & Luxembourg*, Special Report (EIU 2048), The Economist Intelligence Unit, London, November 1990.

[Duchin 1994] Duchin, Faye, *Household Use & Disposal of Plastics; an Input-Output Case Study for New York City*, Report to the AT&T Industrial Ecolofy Faculty Fellowship Program, Institute for Economic Analysis, New York University, New York, June 1994.

[Gaines 1981] Gaines, Linda L., *Energy & Materials Use in the Production & Recycling of Consumer-Goods Packaging*, Technical Memo (ANL/CNSV-TM-58), Argonne National Laboratory, Argonne IL, February 1981. [Prepared for the U.S. Department of Energy]

[Habersatter & Widmer 1991] Habersatter, K. & F. Widmer, *Ecobalance of Packaging Materials State of 1990*, Envionmental Series (132), Swiss Federal Office of Environment, Forest & Landscape, Zurich, February 1991.

[Johnston & Troendle 1993] Johnston, P. & S. Troendle. *PVC - An Environmental Perspective*, Greenpeace Exeter Laboratory, Earth Resources Center, University of Exeter, Exeter UK, May 1993.

[Larson & Consonni 1994] Larson, Eric D. & Stefano Consonni, *Biomass-Gasifier/Aeroderivative Gas Turbine Combined Cycle Power Generation*, Biomass Resources: A Means to Sustainable Development, BioResources 94, Bangalore, India, October 3-7, 1994.

[Lushington 1990] Lushington, Roger, *Packaging in Europe: West Germany*, Special Report (EIU 2047), The Economist Intelligence Unit, London, August 1990.

[Lushington 1991] Lushington, Roger, *Packaging in Europe: The United Kingdom*, Special Report (EIU 2157), The Economist Intelligence Unit, London, November 1991.

[Lushington & Mills 1987] Lushington, Roger & Rowena Mills, *The European Market for Rigid Packaging*, Special Report (EIU 1100), The Economist Intelligence Unit, London, May 1987.

[Manzone 1993] Manzone, R., *PVC: Life Cycle & Perspectives*, Comett Advanced Course, EVC, Urbino, Italy, 1993.

[Matthews undated] Matthews, Vincent. *Markets for Recovered Post-User Plastics Materials in Europe*, European Center for Plastics in the Enviroment (PWMI), Brussels, undated.

[Mauerhofer 1993] Mauerhofer, Fritz. Personal communication of letter from D. Factor, dated Nov. 24 1993.

[MIT 1993] Technology Business & Environment Program, Center for Technology Policy & Industrial Development. *Dimensions of Managing Chlorine in the Environment: Report of the MIT/Norwegian Chlorine Policy Study* Massachusetts Institute of Technology, Cambridge MA, March 1993.

[PWMI undated] PWMI. *Weighing Up the Environmental Balance*, PWMI (European Centre for Plastics in the Environment), Brussels, undated.

[Rathje & Murphy 1992] Rathje, William & Cullen Murphy, *Rubbish: The Archaeology of Garbage*, Harper-Collins, New York, 1992.

[Reeves 1990] Reeves, Teresa, *Packaging in Europe: Italy*, Special Report (EIU 2049), The Economist Intelligence Unit, London, August 1990.

[Renaux 1992] Renaux, Genevieve, *Packaging in the Single European Market*, Club de Bruxelles, Brussels, 1992.

[Starreveld & van Ierland c1994] Starreveld, P. Folkert & Ekko C. van Ierland, "Recycling of Plastics: A Materials Balance Optimization Model", *EARE*(327), c1994.

[Tellus 1992] Tellus Institute, *CSG/Tellus Packaging Study: Inventory of Material & Energy Use & Air & Water Emissions from the Production of Packaging Materials*, Technical Report (89-024/2), Tellus Institute, Boston MA, May 1992. [prepared for the Council of State Governments & the United States Environmental Protecion Agency]

[USBuMines 1991] United States Bureau of Mines, *Minerals Yearbook* [Series: ID=ORG] , United States Government Printing Office, Washington DC, 1991.

[Williams *et al* 1994] Williams, Robert H., Eric D. Larson, Ryan E. Katofsky & Jeff Chen, *Methanol & Hydrogen from Biomass for Transportation*, Biomass Resources: A Means to Sustainable Development, BioResources 94, Bangalore, India, October 3-7, 1994.

[Williams & Larson 1993] Williams, Robert H. & Eric D. Larson. "Advanced Gasification-based Biomass Power Generation", in: Johansson, T.B., H. Kelly, A.K. Reddy & R.H. Williams(eds), *Renewable Energy: Sources for Fuels & Electricity*, Chapter 17, Island Press, Washington DC, 1993.

Endnotes(11)

1. We wish to acknowledge valuable assistance from Vince Matthews of the European Centre for Plastics in the Environment (PWMI) in Brussels, Fritz Mauerhofer, President of MBT in Zurich, and Robert Williams of the Center for Energy and Environment at Princeton University.

2. In the U.S. per capita consumption of packaging materials in 1980 was over 275 kg/yr [Gaines 1981]. The production of packaging materials of all kinds directly consumed 3% of the national energy budget in that year, while the transportation of packaged goods (and packaging wastes) probably consumed a higher proportion of transportation energy (being disproportionately concentrated in the retail and wholesale trade sectors). Figures for Europe are not available, but they would be comparable.

3. The population of EEC(9) in mid-1993 was 349 million, while the other countries had aggregate population of 43.5 millions, or 12.5%.

4. It is difficult to explain the difference, unless it reflects the fact that the U.S. uses considerably more paper and paper products than Europe, presumably due to a price differential. As an example, grocery stores in the U.S. routinely package goods in paper bags, whereas in Europe the same goods are likely to be packaged in plastic bags.

5. Thermodynamic analysis shows that the "quality" (i.e. usability) of the (heat) energy recovered in incinerators is comparatively low. Incinerators are only efficient if built on a very large scale; but direct use of the heat (e.g. for district heating) is then virtually impossible because of distributional difficulties. To reconvert this energy to electricity, a further 60% to 65% is lost.

6. Shell Chemicals and Leuna Werke are jointly exploring the gasification of plastic wastes to synthesis gas [PWMI 1993].

7. A recent discussion of the application of low temperature gasification in the context of energy recovery from biomass by Williams and Larson describes the dimensions of the problem and gives numerous references [Williams & Larson 1993]. See also [Larson & Consonni 1994] and [Williams *et al* 1994].