Brunner, P. H.; Beckmann, M.; Born, M.; Merillot, J.-M.; Vehlow, J.: Research Needs for Waste Management. In: The Future of Waste Management in Europe, 07.10.-08.10.2002, Strasbourg (FR). Düsseldorf: VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen, 2002, S. 118-127

RESEARCH NEEDS FOR WASTE MANAGEMENT

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Summary
Increasing material flows have as a consequence high demands on the managing of waste. The residuals of our activities have to be directed to final sinks in a way which protects man and environment, saves resources and excludes any aftercare. The allocated strategies and processes are different in technical performance and environmental quality, and so are their products. The paper describes to what extent existing processes comply with the goals of waste management, and tries to identify future research needs. A rational evaluation of the various allocated or proposed processes requires a good understanding of the flow of materials, a transparent quantification of all emissions, a complete description of the quality and intended final sinks of all residues, and finally sound information about the total costs.

1 Objectives of modern waste management
The metabolism of modern economies is characterised by high growth rates of material flows, by huge and increasing stocks of materials, and by mainly linear material flows. In Europe, the material turnover amounts to more than 100 tons per capita and year, and is still growing; there are only weak signs of a decrease so far. The large input into the consumption process finds its counterpart in the output, namely wastes and emissions. While at the supply side, limits are not yet in sight, they appear at the back end of the system (CO_2 and climate change; CFCs and stratospheric ozone layer; nitrogen management and groundwater quality, and others). Some materials have short residence times (e.g. packaging materials, newsprint, food) and turn quickly into wastes, but more materials are used in applications with long residence times (buildings, networks, appliances). Due to today's increase in flows and stocks of materials, in the future the amount of wastes will rise and the composition will change as well. Hence, waste management will remain an important task. It needs to be integrated into materials management, resources management and environmental management.

In Europe, the historical mission of waste management to secure hygienic conditions in urban areas is fulfilled by now. In the second half of the twentieth century, new goals became important: Today, the purpose of waste management is threefold:

- First, to ensure that the "outputs" of the anthropogenic system are directed to appropriate "final sinks" such as landfills, soils and sediments that are environmentally safe for long time periods. "Final sinks" are of paramount importance because the strategy of dilution, which is appropriate for some substances, cannot be applied to all materials. Potentially hazardous substances such as halogenated hydrocarbons (CFCs) or heavy metals cannot be dispersed unlimited; they have to be transformed and stored in secure "final sinks".
- Second, to conserve resources by bringing potentially useful waste materials back into a production-consumption cycle. For recycling, it is a prerequisite that recycling products fulfil technical standards as well as environmental requirements, and that a market exists or can be created.
- And third, to supply information to the production sector so that designers can take into account the goals of waste management when creating new processes, goods and systems.

Today, the following goals of waste management are included in the legislation of most European countries:

- protection of man and environment,
- conservation of resources (energy, material, land), and
- aftercare-free waste management.

After-care free waste management can be defined as follows: First, it comprises "final storage" landfills that do not require long-term treatment. Thus, waste treatment processes are needed that produce inert residues by separation and immobilization of pollutants. And second, recycling activities must be designed so that contamination of secondary products is prevented and that problems of hazardous materials are not being transferred into future products that have to be taken care of by upcoming generations.

It is assumed that these goals can best be accomplished if waste management is based on the precautionary principle. In order to reach these goals, the following means are to be considered when establishing waste management systems: Prevention, recycling and safe disposal. In contrast to common public opinion this list does neither represent waste management goals nor stands for any ranking of the different actions. Decisions about prevention, recycling or disposal should be based on economic considerations such as local conditions and cost-benefit analysis: Which waste management approach fulfils the goals of waste management at the least costs?

An important prerequisite for successful waste management is public attitude, public understanding as well as public acceptance of waste management issues and decisions. It is necessary that scientific, technical, economic and environmental aspects of waste management are made as transparent as possible, and that traditional positions (e.g. "scapegoat" packaging; "the higher the recycling rate the better") are questioned in view of their technological and economic background.

2 The importance of waste management for resources conservation and environmental protection

Compared to the total annual per capita consumption of >100 tons and the amount of waste water of about 60 t/c.y, the 5-10 t/c.y of solid wastes are rather small. The largest fraction results from construction activities (figure 1) and comprises excavated soil as well as construction wastes. About one fourth of all wastes are combustible materials. Municipal solid waste (MSW) amounts to 0.2 - 0.4 t/c.y only. It represents less than 10 % of the whole waste mass and is thus, from a mass point of view, of minor relevance.

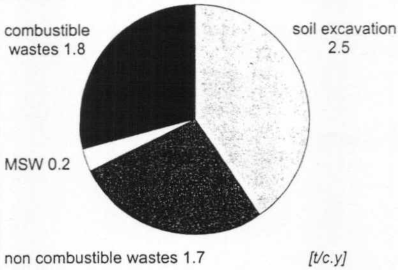

Fig. 1 Per capita waste generation

From a resource or environmental point of view, the situation looks different: wastes can be important carriers of potentially valuable as well as hazardous substances. Figure 2 displays the ratio of total material import to material in combustible wastes for carbon, chlorine, four heavy metals, and for energy. It is shown, that combustible wastes are important carriers for atmophilic heavy metals such as cadmium and mercury: Nearly half of these potentially hazardous metals are finally contained in the combustible waste stream. On the other hand, the contribution of combustible wastes to the national supply of energy, carbon, chlorine and lead is small and below 10 %.

This indicates clearly, where priorities have to be set in waste management: First, those goods and substances have to be identified that are of relevance in view of the goals of waste management. Second, the design of waste management processes and systems has to take into account the collection, recycling and safe disposal of these priority substances. Based on today's knowledge, atmophilic heavy metals are such elements of concern. It is important, that waste collection and treatment is tailored towards priority substances, and that these substances are directed to the appropriate recycling products and final sinks. It should be noted that many elements can be both resources and hazardous substances, depending on the concentration, the chemical speciation of the element, and the place of impact.

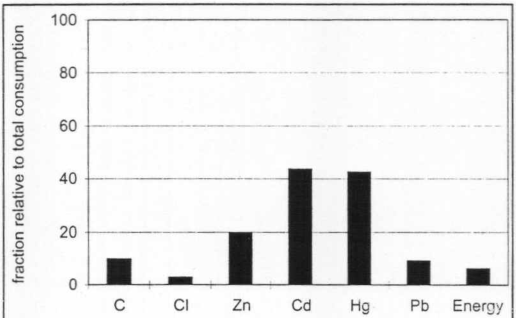

Fig. 2 Combustible wastes comprise more than 40 % of the totally imported mercury and cadmium and thus are important carriers of these heavy metals

In the future, the resource aspect is likely to become more important for wastes. Since, according to figure 2, large fractions of mercury and cadmium are contained in combustible wastes, treatment of these wastes should eventually lead to new recycling schemes for these and other substances. Separation is useful for both strategies, recycling as well as safe disposal. Separation, however, cannot focus on mechanical separation alone. A major fraction of heavy metals is present in the waste in various speciations, e.g. as additives or pigments in plastics and many of them, especially the above mentioned mercury and cadmium, form volatile compounds at high temperatures. Hence thermal treatment must also be used since it is a process which is well suited for the simple and effective separation of such uniformly distributed metals and their concentration in small mass streams.

In general, it is important to decide if the means of waste management are efficient to reach the goals of resource conservation and environmental protection, or if other means outside of waste management are more appropriate. Also, from a rational point of view, it is important to collect and treat those materials collectively that have uniform chemical properties. Thus some of the present waste management systems that focus on the function of a material such as packaging should be re-evaluated. The results of such evaluations should be compared to management systems focussing on the collection and treatment of the material itself e.g. plastics (figure 3), or paper, or aluminium. Taking into account that function based management systems so far collect about 10 % of a total material stream, it seems worth while to investigate how the other 90 % can be more efficiently collected and utilized. The efficiency of waste management could increase much if the focus is on total material flows instead of waste flows from individual economic branches.

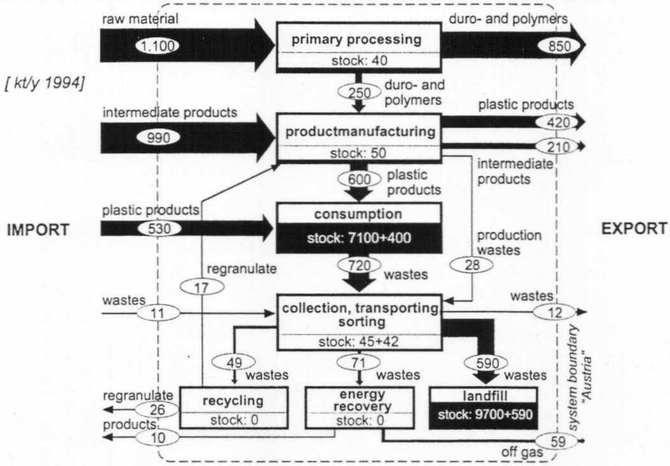

Fig. 3 Flows and stocks of plastic in Austria (the packaging ordinance controls about 5-10 percent of the total plastics consumed)

Since waste management of certain goods and substances is crucial for environmental protection and resources conservation, it is important to have sufficient knowledge about waste treatment processes and their potential to control material flows. Today, the availability of information about treatment processes is not uniform. While data about thermal processes is abundant and detailed, the knowledge about other treatments such as mechanical, biological or recycling processes is in general still rudimentary. For rational decision making in waste management, it is necessary that the level of information is more or less equal for all systems evaluated. The following information is indispensable for decisions regarding the choice of waste treatment processes: Material balance including transfer coefficients of the most important substances; energy balance; emission inventory (concentrations and flows); composition and quality of products and residues both in view of technical and environmental requirements; identification of long-term sinks for the residues and emissions of the process reliability; costs including disposal of residues and long-term emissions of landfills.

In summary, the purpose of waste management within a sustainable materials management is to produce recycling products for old and new markets, to direct materials as emissions or residues to appropriate final sinks with adequate carrying capacity, and to achieve this in a cost effective and transparent way that can be accepted by the public. Which research activities are needed to reach these goals?

3 Research needs

3.1 Thermal waste treatment

As mentioned above, waste incineration is today well understood in view of materials flows, environmental impact, quality of products, and it is characterised by high technical perform-

ance. The main objectives of the process are inertisation of the waste material, recovery of energy, and concentration of pollutants in small residue streams. A state-of-the-art waste incineration plant comprises a furnace, a boiler for energy recovery and an air pollution control system.
The combustion process causes the almost total oxidation of organic matter to CO_2 and guarantees the thermal destruction of infectious organisms and organic pollutants in waste. For inorganic substances it acts as a transformation and separation process, depending on the speciation of the material in question and the local chemical and physico-chemical conditions in the fuel bed. The energy recovery can reach up to 70 % in case of combined heat and power utilisation.

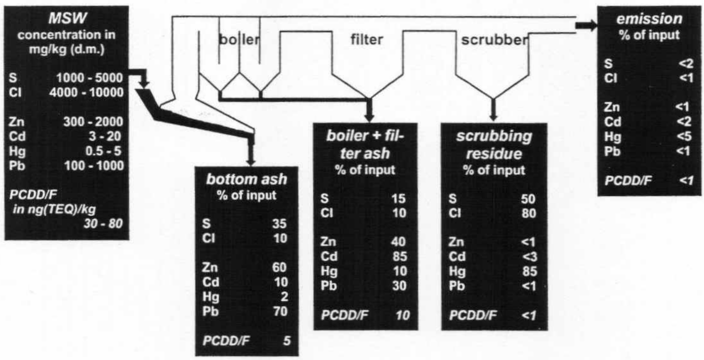

Fig. 4 Concentration ranges of selected elements and PCDD/F in MSW and inventory in MSW incineration residues calculated as percentage of input

Figure 4 illustrates the typical concentration range of selected elements in municipal solid waste and their partitioning in a grate fired waste incineration plant [IAWG 1997]. Non-metals like halogens, nitrogen, and sulphur as well as atmophilic metals like mercury, but also zinc, cadmium, or lead are preferentially transferred into the gas phase. Volatilised metal compounds – with the exception of those of mercury which has to be taken care of in the scrubbing stages - condense in the boiler section on the fly ash surfaces and leave the incineration plant along with the boiler and filter ashes. Lithophilic metals like titanium, manganese, iron, or nickel are mainly transformed into oxidic compounds and are incorporated and immobilised in the silicate/oxide matrix of the bottom ashes.

The graph in figure 4 contains also numbers for PCDD/F. The PCDD/F in the fuel are – like other organic species - almost totally destroyed in the combustion process and those found in the residues are re-formed by de novo synthesis.

Due to the high-quality gas cleaning stages implemented in modern waste incineration plants the emission into the air is extremely low for all elements and organic pollutants and complies easily with all legislative regulations in Europe. However, whether this low emission level guarantees the compliance with the first goal of waste management, the protection of man and environment, has been and is still questioned by environmentalists. Air emission limits are in principal set on the basis of (eco-)toxicological evaluation of the resulting immission. The actual standards are always compromises between knowledge of effects, available technology, and political interests. Eco-efficiency has yet not been a parameter of concern.

To get a view of the actual environmental effects of air emissions from a modern waste incineration plant, the impact of selected pollutants on the ambient air quality has been made on the basis of a dispersion model used by the South Californian regulatory board [SCAQMD

Table 1 Environmental relevance of the emission of some components

	stack emission	ambient air	contribution of stack to background air in %
HCl	5 mg/m³	30 µg/m³	0.5
SO_2	20 mg/m³	20 µg/m³	3
Cd	5 µg/m³	3 ng/m³	5
Hg	10 µg/m³	5 ng/m³	8
PCDD/F (TEQ)	0.05 ng/m³	50 fg/m³	3

1991]. The results compiled in Table 1 indicate that mercury causes the highest addition with approx. 8% and that the contribution of all emitted pollutants will be well below the range of the natural scattering of the ambient air quality. Hence it can be concluded, that the air is an adequate intermediate sink for the emissions from state-of-the-art waste incinerators.

Bottom ash is a silicate matrix which contains much higher amounts of several metals than the lithosphere. This fact makes it at a first glance not fit for final disposal on a landfill. In view of environmental impact, however, the mobilisation or leaching of potentially harmful constituents is of major concern. It regulates in most countries the requirements for disposal or utilisation of this mass stream. Bottom ashes from modern incineration plants have - after plain mechanical pre-treatment and aging - generally no major problems to meet the leaching standards set for landfilling or even those for utilisation in road construction. The high carbonate buffer capacity of bottom ashes guarantees a low release of heavy metals for thousands of years which can be modelled to predict the fate in a specific disposal or utilisation scenario [IAWG 1997].

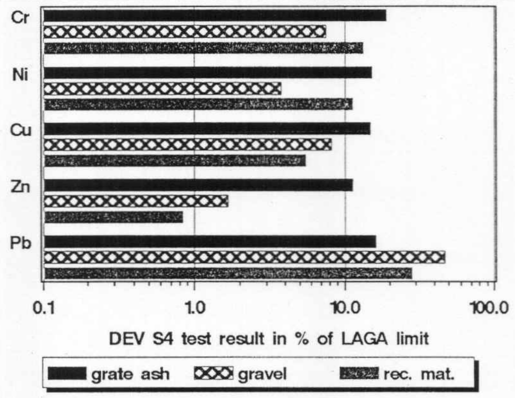

Fig. 5 Results of the German DEV S4 leaching test for selected metals from bottom ash, gravel, and recycled material as percent of the German LAGA standards for utilisation in road construction

To bring the environmental effects of bottom ashes into perspective, the German regulatory DEV S4 leaching test has also been run on other building materials like gravel from the river Rhine and material from road recycling. The results are shown for selected metals in figure 5: there is no significant difference in the leaching results from bottom ashes and from other building materials [Sauter 2000]. This implies that a landfill can act as a final sink for bottom ashes, but that also utilisation in special scenarios can be accepted and with that – although the available mass flow is low compared to the total flux in this sector - at least a small conservation of resources can be achieved.

Boiler and filter ashes with their high concentrations of heavy metals and organic pollutants are classified as hazardous waste and need to be either inertised or disposed of in special and safe sites, preferentially in the underground. A number of processes have been developed for immobilisation and also for separation and partial recovery of metals like cadmium, zinc, or lead. In Europe there is no market for such processes and a metal recovery does not pay today. It may however be considered to store such materials - e.g. by introducing a resource tax - in a way that allows future access in case economic conditions become more favourable.

If particulates are removed efficiently downstream of the boiler, the only heavy metal transferred to a significant extent into the chemical gas cleaning system is mercury. It should be mandatory to separate this metal from the scrubbing residues, if not for recovery than at least for environmental reasons. Respective processes have been developed. Else scrubbing residues consist mainly of alkaline or alkaline-earth salts. In case a large sewer system is available, these salts can be discharged – after cleaning and pH adjustment – and end up in the most adequate final sink for such materials, the ocean. Else, the salts have to be disposed of on sites excluded form any hydrological impact, again preferentially in the underground.

There have been made efforts to recover - aside of mercury - also HCl and gypsum from the effluents of wet scrubbing. In most cases, these attempts have proven to be not economic. Only a few plants in Germany recover them today.

This short discourse documents that waste incineration does meanwhile meet the goals of waste treatment with best technical performance and environmental compatibility. There are still some research needs, mainly directed to simplify the process and reduce its cost. A crucial factor in this direction is the maintenance, e.g. in view of corrosion of boiler tubes, grate bars, and the refractory cladding in the furnace. A further topic of interest is the development of small treatment plants at competitive costs. The development of simple and low cost plants is a key parameter to make thermal treatment of wastes available in emerging and developing countries, where a strong demand exists for the prevention of the contamination of water resources by waste disposal sites.

The findings allow also the conclusion, that bottom ashes need no further thermal treatment to improve their leaching stability. Fusion or vitrification can only be accepted if it is part of the primary thermal process or if it ends up in a higher quality which opens new markets. Else the consumption of energy for the melting process does not pay in view of eco-efficiency.

Although the time dependent metal release from bottom ashes can be modelled for centuries - which is suited to predict the fate in an utilisation scenario - there is still some lack in understanding the long-term fate of the bottom ash matrix on a disposal site.

Other thermal processes like pyrolysis or gasification - which may be promising in terms of size and for special waste streams - are less advanced in technical performance. After more than 30 years of development, they still require further improvement to reach the state of the art of waste incineration.

3.2 Mechanical-biological treatment processes (MBTP)

With the beginning of the nineties the objective of mechanical-biological treatment processes (MBTP) "production of an utilisable biological fraction (compost)" was replaced by the today's goals: "recovery of valuable material", "generation of a landfill suited fraction", and "production of solid recovered fuels (SRF)".

These contemporary aims are in line with the introductorily mentioned purposes of waste management, however, it is hard to say to what extent they are presently accomplished by the various MBTP, and what their theoretical potential is. The difficulties for such evaluations are - in contrast to thermal treatment processes mentioned before - on one hand attributed to the limited availability of data concerning the material and energy fluxes, and on the other hand to the lack in experience of long-term behaviour of so-called biologically inert fractions for landfill disposal.

To indicate the demands for further research and development, the above specified objectives of MBTP should be discussed in relation to the common purposes of waste management. Table 2 contains an overview with selected examples.

The consideration has of course to take the given situation into account, i.e. respecting the structures of waste management at present, the availability of resources etc.. Within the framework given here, the single topics can only exemplarily be mentioned.

Table 2 Overview of research needs in the field of MBTP (examples in brackets)

overall process chain		research needs	
MBTP	**succeeding processes**	**different processes**	**overall process chain**
recovery of valuable materials	utilisation in primary industry (steel, cement)	degree of separation product quality	material flows (diffuse emissions)
generation of fractions suited for land-filling	landfill	long-term behaviour - final sink	material and energy balances
production of SRF	energy production (power station, primary industry)	criteria for SFR quality assurance combustion behaviour (ignition, burnout, heat transfer, corrosion) distribution of pollutants (Hg)	required depth of dressing/complexity
residual fraction	thermal waste treatment (MSWI)	combustion behaviour (see above)	costs

The depth of processing (dressing) and thus the complexity of the processes is a substantial issue of mechanical-biological treatment respectively of the overall process chains[1]. Its quality has a strong influence on specific requirements of further valorisation of the generated fractions. Further more an increasing processing depth consumes more energy, it may need additional materials, it may cause pollution problems, and finally it increases the costs. Therewith the processing depth should first of all be adjusted to the quality profile of the generated fractions in order to allow utilisation or to comply with the demands of a final sink. These topics can only be discussed here exemplarily. For detailed explanations and investigations of different MBTP it has to be referred to specific reports [Soyez 2001].

Considering the objective „recovery of valuable material", metals (Fe, non ferrous), waste wood, glass and minerals are the fractions that could more or less easily be separated by MBTP. Depending on the effort, different qualities and mass fractions can be obtained. At first glance, such recovery and recirculation into the production cycle meets the aims of "conservation of resources". However, it depends on the overall concept whether the recovery of several fractions is effectively useful or not. Further activities should focus on the development of low-energy and low-cost dressing processes which enhance the sharpness of separation and thus improve the product quality.

The "generation of a fraction suited for land-filling" is the target of several currently ongoing research projects. For the time being, the residual fraction from MBTP cannot meet the same landfill criteria, such as loss on ignition, leaching parameter (esp. TOC) as bottom ashes from waste incineration. However, investigations on the landfill behaviour of MBTP residues revealed low landfill gas release, low leaching, and low sagging as a result of the biological processes and that gives hope that these materials may come up to satisfying landfill behaviour in view of respiratory activity, gas evolution and TOC of the eluate. The crucial question concerns the long-term behaviour of MBT residues in landfills: Whether the quality reached actually fulfils the demands for a "final sink" - especially in view of the long-term behaviour – needs further research. If it does, there is reason to give up today's mandatory thermal treatment of organic waste fractions prior to disposal and accept MBTP as inertisation process, too.

[1] The consideration of process chains, i.e., the inclusion of further processes for material and energy utilisation within the total balance, is an inevitable demand for the evaluation of MBTP.

Considerable uncertainties do still exist in view of the quality demands for the so-called SRF, the solid recovered fuels and of the assurance of such quality. Possible areas for the utilisation of SFR are cement kilns, power station firings and so-called energy utilisation plants. Latter are similar to MSW incinerators concerning process engineering. Basically two strategies could be applied if utilisation of SFR is envisaged. First of all it should be attempted to adjust the fuel engineering properties of the SFR to those of regular fuel. In addition it should be considered to adjust the thermal process to the properties of the SFR. There is still a considerable potential for both strategies which has to be explored in future.

High temperature processes such as calcination of cement clinker require high calorific substitute fuels to obtain low energy exchange ratio. Corresponding high calorific values of SFR produced from MSW could only be achieved by fractions like plastic, wood, and paper. Compared to hard coal such SFR exhibits different ignition and burn-out properties due to the remarkably higher content of volatile matter. This leads to different conditions for heat release and heat transfer and is e.g. of importance for the product quality of cement clinker as well as for the process behaviour of power stations. Next to the heat transfer conditions further attention should be given to corrosion problems, especially in power stations.

The inventory of harmful substances of SFR calculated as concentration per energy unit [mg/MJ] is typically much higher than that of regular fuels and power stations as well as high temperature processes for material treatment are generally less equipped with flue gas cleaning stages than MSW incinerators. Hence special attention has to be directed to the spreading or dilution of pollutants, first of all to that of mercury (see chapter 3.1). Also the incorporation of pollutants in products like cement should more be addressed as dilution and is far different from their concentration in small residue streams, as is aimed for in MSW incineration.

Hence if the production of SFR is considered, further investigations in view of the design and operation mode of the thermal process (fuel technology properties, corrosion and slagging behaviour, etc.) and also of the quality control of residues and products are substantial prerequisites for a continual development of MBTP.

Looking upon MBTP in the light of the introductorily discussed objectives of waste management, there is still an urgent need for sound and reproducible information about the material and energy fluxes of the overall process chain (inclusive of succeeding utilisation and treatment processes). While material and energy balances for the main components are available in special cases [IBA 1998], major uncertainties still exist concerning the fate of pollutants. The materials produced by MBTP must meet the requirements for utilisation in the following processes.

4 Conclusions

Considering the goals of waste management - protection of man and environment, conservation of resources, and aftercare-free waste management – it has to be stated that to some extent today's waste legislation as well as a number of practised waste management systems are already complying with these goals. Great progress has been made during the last decades in view of establishing integrated waste management systems. The rapidly increasing industrialisation accompanied with a dramatic urbanisation in parts of the world and a permanently growing rate in material consumption, however, have put high challenges for the development of waste management systems that reach the above mentioned objectives by simple technology at low costs. A high demand is also seen for processes to treat small amounts of waste at reasonable costs.

Regarding the major waste treatment processes, waste incineration is obviously the best investigated one. If the technology installed and the input composition are known, reliable estimates on the emissions to air and water as well as the residue quality can be made. The mass balances can be given for most elements and the fate of waste born organic pollutants can be predicted. Some research should be directed to simplify the process chain in order to reduce the efforts and make waste incineration economically more profitable. The medium- and long-term behaviour of heavy metals in bottom ashes can be modelled, the corrosion and eventual phase transformation of the silicatic-oxidic matrix, which during very long times may change the leaching properties, requires further research.

Compared to waste incineration, information about MBTP is still fragmented. There is a lack in material flows and element balances, the transformation of waste born pollutants is not documented in detail, diffuse emissions are difficult to measure, and reliable data on the long-term behaviour of residue fractions are missing. Hence major aspects of future investigations are the fate of pollutants, the quality of products, the long-term behaviour of fractions destined for disposal. The evaluation of the concepts by means of detailed mass and energy balances yields additionally clues for process engineering optimisation. The development of management systems to increase the overall efficiency is also a target for the next years.

Especially for the production of SFR there is a remarkable demand for research and development concerning the requirement of the fuel technology properties. SFR should replace regular fuels. In reply to this demand the overall process chain with consideration of the total effort and valorisation has to be regarded.

In order to be able to compare different concepts, the economic aspects must be regarded as well. The influence of existing structures of waste management could not be neglected in this evaluation process, e.g., the long-term maintenance and aftercare of landfill sites should be mentioned here. In the end it is important to point out, that evaluation as well as development of MBTP has to take local conditions into account. To avoid extensive and costly investigations of special cases, sound models, good data, and criteria with general acceptance are required.

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