3 Recycling, Thermal Treatment and Recovery

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Waste paper, cardboard, waste wood, plastic and glass bottles, tins, not to speak of broken appliances etc. hardly appear in waste statistics of developing countries, although they are being used and discarded by the minority of the population who can afford them. The reason is that all these categories of materials represent the often exclusive income for a host of informal waste pickers and recyclers who collect them and turn them into marketable goods by making e.g. roof tiles from spent cans, fuel briquettes from cardboard, second-hand goods from broken and repaired appliances etc. These kind of “zero waste” systems are driven by the needs of the poor and do not need to be encouraged by appeals to save resources and to close materials cycles, nor does it require the complex legislation that has been issued to encourage recycling in industrialized countries. The informal scavenging is hard work for a small income and exposes those involved to great occupational health risks. The waste picking business only functions, if sufficient material is thrown away that can be recycled, i.e. if there is a social class above who can afford to waste. It relies on large social differences and, form this perspective, is hardly sustainable.

It is probably no coincidence that the strong zero waste vision proclaimed in section 3.1 of this chapter originates from California, the wealthiest part of the richest country of the world! The zero waste vision has been inspired by the fact that in natural ecosystems there is no waste, i.e. all refuse is recycled by specialized organisms in an ecosystem. While true zero waste is not literally possible, the idea of closed material cycles is convincing and an absolute need to counterbalance the impacts of over-consumption. Technologies are available for producing quality products from waste materials by mechanical sorting and processing of the retrieved fractions with a high degree of automation (section 3.2).

Recycling is not automatically the best solution in all conceivable cases. Recycling processes shoud always be assessed with respect to their ecological impact. As a rule, recycling is only advisable, if it produces less damage than disposal and production from virgin raw material. Limits to material recycling exist in particular for organic materials such as plastics, paper and biomass, especially if they are composites, physically mixed with each other and/or contaminated with toxic substances. For such materials, the energy content is the most valuable and accessible resource to be recovered. Recovering the energy from combustible waste requires the application of highly sophisticated technology to avoid negative environmental impacts of the combustion process. The contribution 3.3 covers the fundamental control options one has to optimize the conversion of the combustible fraction of waste on the traditional grate furnace and to minimize the formation of air pollution by primary measures in the combustion chamber. Together with the highly perfected air pollution control systems (electrostatic precipitators, dry or wet scrubbers, catalytic nitrogen oxide converters and charcoal filters) these primary measures have contributed to the present advanced state of incinerator technology, which can truly be regarded as a sink and not a source of pollutants.

It has been wide-spread practice to use the ashes from incinerators as a filling material in e.g. road construction, especially the bottom ash. 250 kg of bottom ash are on average produced from 1 ton of MSW and it seems to make sense to recycle this material in construction applications. The composition of bottom ash corresponds very closely to the composition of cement and traditional additives to cements (section 3.5). However, in contact with water, the ashes are not inert materials. Contribution 3.4 shows that especially the fly ashes, and to a lesser degree bottom ash, contain soluble heavy metal compounds, which can be leached out and contaminate the aquifers, if landfills are not managed in a way that collects leachate water for appropriate treatment. The investigations reported in section 3.5 show that further thermally treated ashes resulting from advanced incineration plants could be used as substitute construction materials for applications that are not too much demanding.

It shows one feature of recycling that must be kept in mind for all recycling operations: due to their heterogeneous origin, recycled materials tend to have inferior properties compared to materials produced from virgin raw materials. This drawback limits the market acceptance of certain recycled products. This is in particular the case, if used objects, such as for example plastic bottles or newspapers, are used for reproduction of the same product. The residence time of the goods in the anthroposphere could be substantially increased using modern recycling methods, but “down-cycling” produces waste, which ultimately cannot be avoided and needs further treatment. Today, the most common alternative to MSW landfills is incineration (section 3.3). “Down-cycling” is less of a problem for the recovery of raw materials. New advanced technologies, which aim to recover the values of the materials at the end of a “down-cycling stream”, are presented in chapters 4 and 5.

3.1 Reduce, Reuse, Recycle: The Zero Waste Approach

Richard V. Anthony

The notion of zero waste is as much as a principal of survival for the human species as it is a matter of fact in nature. A close examination of natural systems reveals that there is very little waste in nature. Everything is connected to each other. Every discard is an other’s feedstock. When the planet is seen as a finite sphere in space, there can be no *away* on planet earth. Everything that is sent away must go some place.

Zero waste references can be found throughout past and current mythology and religion. References to burning fires of garbage analogous to Hell are found in the proverbs of the Old and New Testament. There are many Biblical references calling for stewardship of the land and resources. The Native American Chief Seattle said it best: “We do not inherit the earth from our forefathers, we borrow it from our children."

Waste is a concept of privilege, for only the truly rich can afford to waste. If all the people of the world consumed and wasted resources like the upper 20 percent of the world population currently does, we would need several planets to supply those needs. The average inhabitant of the earth cannot afford to be wasteful.

The genesis of the zero waste movement comes from the realization that discarded materials are resources. These resources have been manufactured from a raw state with energy and labor. In the cases of metal and oil they are irreplaceable. The value of that energy and labor is still in the commodity, even after the user has discarded it.

A zero waste system is a resource management system. The population of the world at the turn of the new millennium has reached six billion. Futurists project that even with zero waste and world cooperation in the production and distribution of food and survival commodities, the planet can support a maximum of ten billion people [107].

As the world population increases, world resources generally increase as well. The impact of this increasing demand on the remainder of the planet’s finite resources like petroleum, metals, wild animals, birds and trees is leading to their depletion and in some cases, extinction.

The process of wasting resources is against nature. For humanity to survive over time on the planet, a balance of supply and demand must be attained that considers the whole biosphere. Extracting finite resources and destroying them after one use, while the population continues to grow upsets that balance. Therefore the ultimate option is to control population and recycle resources in order to survive.

In a zero waste system every thing has a place before, during and after use. In an ideal system, dismantling or de-manufacturing would be designed into the product. A society supporting a zero waste system would not subsidize wasting by paying for systems that destroy resources and create new sources of air and water pollution. Disposal funds would be used to collect and process resources. Existing disposal sites and systems would be used in transition but new facilities would be built for reuse, recycling and composting.

The system of extraction, manufacturing, use, and disposal to incinerators or landfill would be replaced by systems that capture the material and recycle them into a closed loop system of reuse, repair, recycle and redesign. Raw materials would be used as reserves.

The principle of the closed loop system requires that the consumer and the manufacturer buy recycled materials as well as recycle the product at its end use. A zero waste society would tax virgin and raw material use and give tax breaks for industries that use recycled materials. It would force the loop to be closed by making environmental dumping illegal or expensive.

Even though disposal by burning and landfill may be cost effective by today's standards, a legacy of depletion and pollution for our children will provide the basis for new standards. These new standards will take the future into much greater consideration concerning the planets' resources and will discourage waste.

3.1.1 Zero Waste Theory

A system design for the handling of discards from a household, business, institution, or city with a zero waste goal is theoretical. Recognizing that, scientifically, absolute zero is improbable, close counts. Any system that reduces wasting to ten percent of current generation rates would make a significant step toward sustainability and would be close to zero (90% successful). Pollution is measured quantitatively and a reduction of 90% is significant. In the area of discarded resources the remaining 10% may have to be dealt with through legislation, innovation and ultimately producer responsibility.

In a zero waste system everything has to go somewhere. Discards create jobs and products. In the cycle of use, reuse, repair and recycling close the loop to wasting. Discard management plans involve the transport and transition of discarded resources to a place where they will be used again.

In a perfect world this would happen logically. But the fact is that in many cases, the status quo of wasting is protected and encouraged by law. In many places in the world, tax laws and government funding for the collection and disposal of discarded materials encourage wasting over recovery.

Governments have the power to finance and implement discard management systems. Some systems are financed in such a way that they discourage the growth of recycling and composting industries. From a grassroots perspective, the individual has some influence on this process and can insist that the government include convenient recycling and composting programs in the disposal system.

If the natural forces of supply and demand were not subverted by subsidies for wasting, the consumer would place value on a product based on its reusability, reparability and recyclability, when making purchasing decisions.

When recycling and composting are considered a part of the disposal system in the analysis of costs, the revenue is used to reduce public subsidy for the proper handling of the discards. When adding the cost of long term disposal monitoring and considering the economic cost of taking land out of production forever, destroying ancient forests and polluting air and water downstream, planning a system to reduce or eliminate these future costs makes economic sense.

Zero waste discard management systems have political as well as technical considerations to take into account. The way each human being accounts for their daily generation of discards, and the way those discards are managed in a community are political and technical decisions. The future sustainability of the planet depends on people at the point of purchase, choosing products that can be ultimately composted or recycled and at the point of discard making a decision as to where in the system the discarded material should go. Aside from product design decisions and separation requirements, most of the decisions in the process are technical.

The consumer and the manufacturer are both responsible for the proper disposal of a product before, during and after purchase. The relationship between the consumer and the manufacturer should not be confused by government subsidies for the disposal of wasted resources. It is not fair that the entire population pay for the disposal of products enjoyed by only a few. The consumer should encourage the manufacturer to design products that can be repaired and eventually recycled or composted.

Manufacturers have a responsibility to the community to produce products that are designed for recyclability and/or compost-ability. Manufacturers should be encouraged to use recycled materials in their products. Products should be produced in a way that they can be repaired where wear and tear occurs and dismantled and recycled into new products when they cannot be repaired.

There is a hierarchy of use of materials that involves the highest and best use of materials in the areas of energy and resources [3, 4, 34, 66, 69, 92]: Source Reduction, Reuse, Repair, Recycling, Composting, Transformation and Landfill. In California in the early eighties, the “Three R’s” were used to teach pollution prevention. The first of the “Three R’s” (reduce, reuse and repair) refers to source reduction, or the area of discard management that addresses packaging and single use products. The 3 “R’s” have been taught as a means to demonstrate how product design can lead to decreasing waste. Consumers have been encouraged to consider buying products that can be reused and repaired.

To many, the key component in a zero waste disposal system is reducing the amounts of discards at the source. Products designed for a single use are used as examples of unnecessary over consumption. The debate over paper versus cloth diapers for babies addresses reusable washable cloth diapers as opposed to introducing fecal mater to landfill via paper diapers. Some other reuse issues include cotton versus paper napkins, double sided versus single sided copies, and refillable versus single use products.

Repair-ability in a product is another design criteria that can be omitted when subsidized wasting occurs. The notion that the manufacturer owns the product and rents it to the customer is becoming popular in the carpet and computer industries. As the product wears out or becomes obsolete the product is returned to the manufacturer for dismantling and recycling. Automobiles, appliances and computers are primary examples of situations where landfill and incineration are unacceptable disposal options. The materials used in these products can pollute water and air. The proper disposal hierarchy for these items is reuse, repair and recycle.

After reuse and repair, the next step on the hierarchy is to separate materials at the source for recycling or composting. Sorting discards into recyclable and compostable categories assists in a zero waste system by, for example, keeping wet materials from contaminating paper products. Plastic and glass are contaminants that are hard to remove from finished compost. Wet organics are contaminants to paper recycling. Material processing facilities (MFR) are used to classify materials into specific categories. These categories include reusable products, paper, metal, polymers, glass, ceramics, vegetative debris, putrescibles, soils, wood, textiles, and chemicals.

The hierarchy places mixed waste (not source separated) composting, transformation processes and sanitary landfill at the bottom. In a zero waste system, items that cannot eventually be composted or recycled are returned to the manufacturer through advance recycling fees or product deposits. The price of recovery and recycling is added to the product cost to cover the infrastructure needed to reintegrate this material back into use.

Thus zero waste theory calls for disposal systems that place disposal cost responsibility on the manufacturers, influencing them to redesign products for recycle ability. The discard management service provider, whether government or private contractor, is mandated to collect source separated material from clearly labeled and conveniently located storage containers and deliver them to processing centers that will sort, process and reintroduce these materials back into the use system.

3.1.2 Zero Waste Analysis

A waste stream assessment is used to determine the quantity, source and composition of the discard stream. This information is needed to make planning, design, contractual, financial and regulatory decisions. Managing resources means managing discards.

Quantity is measured in weight and volume. Materials are sold by weight; however, storage and trucking capacity are measured in volume. Knowing the annual and seasonal generation rates for the targeted populations' discards will aid in assessing capital, labor, operation and maintenance costs for the system. Equipment and structures include collection vehicles, storage bins, processing equipment, and buildings. Estimating quantities by discard type provides the basis for the estimation of potential revenue.

Source refers to the generation point at which the discards are aggregated. Sources include residential, commercial, municipal service, institutional, industrial, and agricultural generators. Residential sources include single and multifamily dwellings. Commercial sources include offices, retail stores, entertainment centers, restaurants, hotels and motels, and service stations. Municipal services include demolition and construction, street cleaning, landscaping, storm drains, parks and beaches, and wastewater treatment bio-solids. Institutions include schools, hospitals and prisons. Knowing the source of discards allows for the routing of specific collection vehicles to areas and which are appropriate to the type of discards generated.

Discarded materials can be segregated into twelve categories. The Twelve Master Categories as defined by Urban Ore of Berkeley California, a non-government agency (NGO) that developed this system, sort and aggregate discarded materials into market based categories. Items like TV sets are placed in the reusable category. After reuse the next step for the TV is dismantling for recycling. The goal is complete recovery through design and source separation; however, during the transformation to a zero waste system some material will be incinerated and land filled at the real cost through the current infrastructure. The following is an outline of the twelve categories.

1. *Reusable Goods* are discarded materials that are useful in their present form. Examples are doors, windows, furniture, lighting, household goods, clothing, bricks, live plants, etc. Reuse operators need enclosed or covered space and enough room to organize, display, and sell all reuse items coming to the facility. They will also need to dismantle, clean, upgrade and store unsaleable merchandise for recycling.
2. *Paper*, one of the largest commodity sub-flows, comes in many forms, from newsprint to cardboard, all valuable for their fiber content. Paper collection and processing requires warehousing and sorting facilities, a baler, a forklift, and trucking.
3. *Plant debris* is another large sub-flow; it includes tree limbs and tree rounds, brush, weeds, grass clippings, and leaves. Plant debris operators need room to store green materials until they are dry enough to be fed into a grinding process. After grinding, plant debris may be screened, windrowed, turned, watered, and eventually blended with other nutrients and minerals into various types and grades of soil amendments. Composting plant debris and tilling it into soil is a carbon sink, a potential remedy to global warming.
4. *Putrescibles* are similar chemically to plant debris, but differ in their high nutrient value, which makes them a magnet for scavenger species of birds, mammals, and insects. Special handling requirements may include rapid mixing and dispersing with plant debris, containerizing for aerobic or anaerobic decomposition and odor control.
5. *Wood* may initially be divided into three streams: reusable/resalable, recyclable/unpainted, and painted. Reusable wood includes, doors, cabinets, dimensional lumber, furniture and plywood. Recyclable wood is usually chipped or ground, manufactured into particleboard, or blended with other ingredients

into compost. Painted and treated wood may require special handling due to entrained metals and other toxins.

6. *Ceramics* are hard, brittle materials such as stone, concrete, china tile and asphalt.
7. *Soils* are generated by road and foundation construction and by dredging. Clean soils can be sold for fill or added to compost blends to produce a more mineralized product. Soils contaminated by petrochemicals can often be cleaned up through bioremediation.
8. *Metals* have been recycled for thousands of years; the metals recycling industry recognizes hundreds of subcategories, most based on complex alloys of two or more elemental metals such as iron, aluminum and copper. Metals have a very large and varied reuse component. Metals are also recycled extensively: most new steel, for example, is recycled from old steel.
9. *Glass* comes to disposal facilities in two major sub flows: plate glass and container glass. Plate glass may be used as is, if unbroken, or recycled into fiberglass or sand. Container glass may be color sorted, then ground up and made into new containers or simply made into sand.
10. *Polymers* are carbon-based compounds manufactured into films or rigid forms such as containers or computer cases. In comparison with other master categories, polymer recycling is a very young industry experiencing multiple growing pains. Resin complexity and incompatibility, contamination, and “heat” history are primary limiting factors.
11. *Textiles* are fabrics woven from natural or synthetic fibers into objects such as clothing, bedding, carpeting, draperies, and upholstery. The textile reuse and recycling industry is very old and well developed, with worldwide markets for everything from old Levis to wiping cloths and paper.
12. *Chemicals* include unused paints, used oils and solvents, cleaners, acids and bases and the like. Deemed safe for their designated used, they become major pollutants when land filled or burned. Reuse is a preferred disposal option for many chemicals. Recycling requires filtration, distillation, mixing, or other refining operations to produce useful products.

The following table displays the 12 Master Categories in a waste composition study for Del Norte County, a small rural community with 32’000 inhabitants living in just over 9’100 households on the coast of northern California. This information is required by law for cities and counties in California to be published in an Integrated Waste Management Plan for each County that is reviewed by the State of California on a regular basis.

Certain conditions can impact the quantities and types of materials discarded, including seasonal variations in weather and tourism, demographic differences in age and wealth, state of the economy, laws (container deposits, mandatory recycling rules) and natural or unforeseen catastrophes.

The United States Environmental Protection Agency publishes a waste characterization protocol to provide a standardized procedure for measurement of the types and quantities of discards from an established area. The process of defining the characteristics of a discard stream will assist in determining costs, and identifying key generators.

Table 3.1. Discard Composition Analysis (based on data from [50])

Categories	Discarded [tons/year]	Discarded %
1. Reusables	1,014	5.7
2. Paper		21.2
3. Plant Debris		2.6
4. Putrescibles		
Sludge		4.9
Other		21.2
5. Wood		1.8
6. Ceramics		9.9
7. Soils		5.9
8. Metals		9.3
9. Glass		3.8
10. Polymers		9.4
11. Textiles		2.8
12. Chemicals		1.3
Total		*100.0*

In a zero waste system all discards have a place. A zero waste characterization study that sorts discards for the above-described “clean dozen” categories is recommended. Definitions for each category should be established before sampling begins to ensure consistency.

3.1.3 Storage and Collection

Collection systems for recovering resources have matured in the last twenty years. Mandatory recycling rules in states and nations have encouraged the development of technology to meet the new rules. Collection systems that started out with the customer doing sorting for plastic, paper, metal, flint and colored glass, and organic material are being challenged by collection systems that collect material separated by wet and dry distinctions. Materials Recovery Facilities (MRF) use a combination of technology (magnets, balers) and hand picking off conveyor belts to create recycling materials with high market value. Wet materials like putresibles, vegetative debris and food dirty papers are collected in sealed compaction vehicles and ta1ken to composting facilities to be processed into soil amendment. New trucks have been introduced that collect wet and dry materials in the same vehicle by divided compartments within the truck.

Storage Containers are important for keeping materials separated. In the first phases buckets, baskets or barrels work. Today, automatic collection trucks pick up 60 – 90 gallon (227 – 341 liter) carts with wheels that are color-coded based on material type. The typical system uses blue for recyclable, green for organic and currently black for trash. Capturing the correct materials in the right container is most effective when containers are consistent in color and signage, convenient to the discard area, well marked as to what they are collecting, and large enough to handle all the designated discards between collection times.

3.1.4 Processing, Storage and Marketing

Just as the collection system feeds the processing plant, the commodity markets dictate the necessary processing systems. There exists a well-developed secondary materials market and there are uses and the corresponding demands for all 12 commodity types. International secondary fiber markets buy baled old newspaper, corrugated cardboard, high grade writing (ledger) paper, and magazines sorted grades and mixed paper. Metal smelters buy baled aluminum and non-ferrous, as well as ferrous metals (iron and steel). Sorted polymers can be formed into all kinds of product shapes and find markets. Glass must be sorted in order to have high value, but can also be used in aggregate. Organically composted materials are important feed-stocks for the agriculture industry as well as for urban gardeners.

Most of the transportation to market is done by truck and trailer rigs pulling load limits. Even if using rail, which typically is more economical for a large load, densification of the commodity is desirable. In the scrap industry, the baler is the primary technology used to densify loads for transport. Sometimes grinding is used to get more density in the bales. Still, most metal and fiber markets prefer the baled to the shredded material. Organic, ceramics and glass materials use grinding technologies to achieve transport densities as well as processing for feed-stock materials.

The processing area should have space to store load limit amounts of baled or ground material. Materials last longer under covered space. Ground up material can be stored in bunkers and loaded with a bucket-loading tractor.

Materials Recovery Facilities (MRF) are designed to recover source separated co-mingled materials. Trying to recover materials from mixed discards is problematic. The decomposing organic mater damages paper’s recyclability. Source separating materials by designated recyclables, papers and containers, or wet and dry materials will enhance the quality of the baled sorted materials.

At the MRFs the collector dumps the load on acement pad. The load is checked for hazardous materials or bulky items and then pushed onto a conveyor where somewhere along the line magnets retrieve the ferrous metals. Sophisticated systems use automatic sorting technologies (section 3.1.5), but manual separation is still the best. In the USA, these jobs offer better than minimum wage and include health insurance.

Most large cities have Independent Processing Centers that reclaim fiber, resins, textiles, metals, rock and aggregate, as well as humus. Communities, institutions and individuals can sell discards to these Buy Back Centers.

Whether they are called Scrap Yards, Paper Yards, or Reuse Yards, these commodity brokers guarantee the mill, smelter, or plant, the type and the purity of the material. They know the commodity specifications and value and are essential to the system as they are the market.

3.1.5 Appropriate Technology

Source Separation is the first step in reuse and recycling. The technology of using people to sort discards is known as low technology. There is a historical presumption that almost any material can be reused or recycled if kept free of contaminants and where inexpensive hand sorting for recovery is the dominant technology. After establishing a yard debris composting facility which is publicly available and reliable, banning such materials from landfill disposal reduces reliance on disposal while directing recoverable materials to appropriate facilities. Thus keeping both material and the related jobs in the local economy.

The following schematic diagram illustrates the current use of materials in our society:

As shown in the above figure 3.1, we do not "consume" materials; we merely use them and ultimately return them, often in an altered state, to the environment. The production of useful goods for eventual use by those people called "consumers" requires an input of materials. These materials can come from one of three sources: raw materials, which are mined from the earth and used for the manufacturing of products; scrap materials produced in the manufacturing operation; and materials recovered after the product has been used.

The industrial operations are not totally efficient, producing some byproducts, which are either disposed of or used as raw material in other processes. The resulting processed goods are sold to the consumers. After the product is used, there are three options: to reuse the material for the same or a different purpose without remanufacture; to collect the material in sufficient quantities for use in energy production or to recycle it back into a manufacturing process; or to dispose of this material.

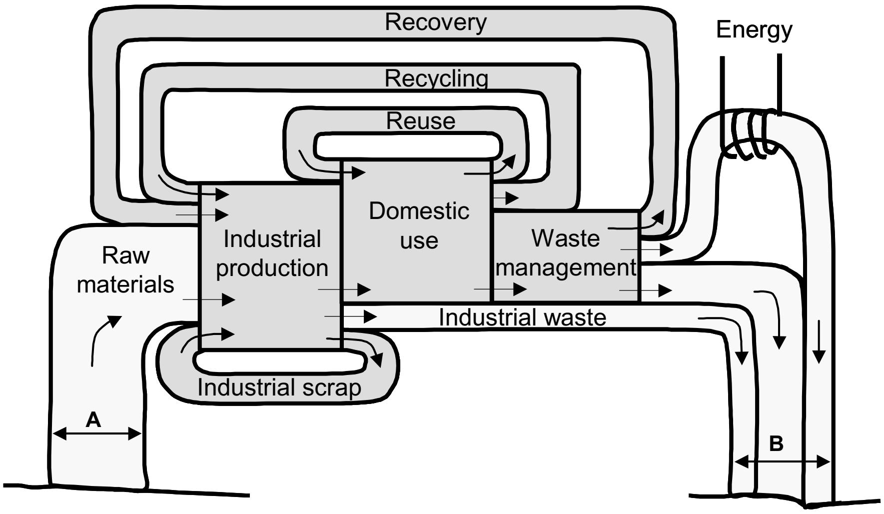

Fig. 3.1. Flow of material through society [106]

As shown in the figure, this is a closed system, with only one input and one output, emphasizing again the finite nature of our world. At a steady state, the amount of raw materials introduced into the process must equal the materials' disposal back into the environment. The closer the achievement of the zero waste goal, the less material is disposed of, thus raw material use is reduced.

The key to achieving the zero waste goal is having the appropriate source reduction, reuse, recycling and recovery programs. These programs must be supported by the applicable technology. In addition the programs must be accepted and used by the manufacturers and consumers.

Source reduction can be achieved in three basic ways:

- reducing the quantity of material used per product without sacrificing the utility of that product;
- increasing the useful life of a product;
- eliminating the need for the product.

As shown in Figure 3.1 source reduction results in a reduction in the size of the domestic use box and thus a similar reduction in the industrial production box.

Technology plays a role in each of these three options. For example, from 1972 to 2000 the amount of aluminum in an aluminum can significantly decreased. In 1972 an aluminum can weighed 0.74 ounces; by 2000 the same can weighed only 0.48 ounces or about 1/3 less. Another example is the advances in battery technology that have resulted in longer life battery. Thus one battery now lasts as long as two or three older batteries.

The preferred source reduction option is to eliminate the need for the product. This approach has been appropriately called voluntary simplicity. For example, when buying a single item at a store, it is usually not necessary to have the item placed in a bag.

Recycling involves taking material that has been used and sending it back to industrial production. The most important factor in the success of a recycling program is consumer participation. The centrally located recycling drop-off center is a low technological recycling solution which engages the public by having them do something about the wastefulness of contemporary society. A fixture of early (1970) recycling efforts to reach residential communities, these programs are quite appropriate for institutional, multi-family residential and small community recovery programs.

While a drop off site has low operational costs, it usually also results in low participation rate. Rarely do these programs engage more than 15% of the population unless the site is in a rural community and is near or adjacent to the dominant disposal site. The consumer has to be motivated to bring material to this site instead of disposing of the material in the garbage. In addition, the consumer must also sort the recyclables into various different categories.

A variation of a drop off site is a buy back site. At these sites consumers are paid for their recyclables. Because of the economic incentive, these sites have a higher participation rate. Curbside collection of residential recyclables is another option. In many cases recyclables are placed into containers, one for bottles and cans and one for paper products. Today's technology allows for paper and containers in one container. The key is to keep the paper dry. In addition, green waste, food and food dirty paper can be placed in a separate container.

Once the material is collected it is transported to a MRF. MRFs employ many different technologies for the sorting of materials. Many rely on hand sorting of recyclables. Others use automated equipment (see below). Once the material has been separated it is prepared for shipping.

Automatic sorting has been tried for mixed residential and commercial materials. In Italy there is a law that prohibits human beings from sorting mixed waste; they have therefore invented and assembled equipment for the sorting of mixed materials [9]. Currently, Germany has what is called the green dot take back program; they have assembled equipment that will sort source separated packaging materials [29]. Several generalities can be made regarding automatic sorting:

- Shredded materials make the size uniform so that other sorting techniques work better. Early experience in the US with shredders and municipal mixed materials resulted in explosions when sparks from the hammers ignited flammable materials.
- Magnets are reliable for ferrous metals. Eddy current magnets that send electricity through metals can effectively recover the non-ferrous conductible metals.
- Gravity is often used. A magnet hung high will allow non-ferrous metals to fall on the belt. Air knives, air classifiers, centrifuges, water and other kinds of liquid media are used to separate lights from heavies. Trommels are long cylinders with different size holes that allow separation by size when shedders are not used.
- Bounce adherence was demonstrated in the early nineties to effectively separate cylinders from papers. This piece of equipment, used in agriculture to separate tobacco leaf from the stems and seeds. The sytem uses a vertical conveyor under a trommel to bounce round things off on to another belt while the paper and plastic film adhears to the conveyor falls on another belt and is sent to a sorting area
- Bag breakers have been a problem. Plastic and broken glass are contaminants to compost. Spikes inside the trommels at the beginning of the line are effective in breaking the bags.
- Optical sorting with lasers is new and costly.
- Balers are state of the art in compacting materials for road load limits.

This equipment, it turns out, is very effective in sorting mixed materials that are in the same categories. Where compost from mixed municipal materials is contaminated with glass and plastic, and paper for recycling is contaminated by the food and vegetative debris in mixed material sorting programs, source separated materials enjoy the benefits of these technologies in conjunction with manual sorting. Most source separated material recovery programs use magnets and balers, while most source separated material composting programs use tub grinders and trommels.

Mixed waste technologies go against the natural flow of material use. In areas with no collection service recyclers divert discards by separating the twelve different categories of materials at the source into destination point clusters. An individual wanting not to waste would separate papers and containers (paper, metal, polymers, glass), load them into a private means of transport and take them to a buy back or drop off recycling center. Food, vegetative debris, and food dirty paper is collected in the home and taken to a composting area by the generator (resident) to an area which is usually on the property (sometimes near the vegetable or flower garden. Old broken furniture, appliances and other discards are loaded into a transportation vehicle and taken to a flea market or given to charity organizations. Chemicals, drain oil, and paint are stored and taken to the Household Hazardous Waste (HHW) roundup or center as needed. The destination points are the recycling center, compost heap, thrift store and HHW center.

Therefore an ideal system would have the public discarding the 12 categories of materials into destination clusters. These are: Paper and Containers, Organics (food, vegetative debris, food dirty paper), Discarded items (furniture, appliances, clothing, toys, tools, etc.), and Special discards (Chemicals, Construction and Demolition materials). An organized diversion program will use these clusters for developing processing centers and collection systems.

1. Co-mingled paper and containers clusters would be best processed when separated from other discards.
2. An organic materials processing center could be at the landfill or at a privately owned site.
3. A centralized Resource Recovery Park (RR park) can receive source separated recyclables, organics, construction and demolition debris and reusable goods to process, reuse, recycle and sell.
4. Household Hazardous Waste discards and construction and demolition materials are generated either in small amounts or at a specific time or event.

Two conceptual case studies are presented. They are the Resource Recovery Park for Reuse Repair and Dismantling for Recycling with a Paper and Container Recovery area and, the Organics Processing Facility. These examples are from the study for Del Norte County, California The earlier discussion on waste characteristics and the 12 categories shown are from this study. The County is still involved in siting and permitting the facility. Residuals will be shipped to a distant landfill so that the more diversion there is, the less the hauling and disposal costs will be.

Case Study: Resource Recovery Park for Reuse Repair and Dismantling for Recycling with a Paper and Container Recovery Area

In managing the Resource Recovery Park, it is important to let the market determine the details of where, how, and to whom materials move. Source separation principles should preside along with convenience, cleanliness, and satisfying the customer.

Table 3.2. Master categories, clusters and processing centers.

Twelve Master Categories of discarded materials	Clusters	Processing Centers
1.Reusable 2.Paper 3.Plant Debris 4.Putrescibles 5.Wood 6.Ceramics 7.Soils 8.Metals 9.Glass 10.Polymers 11.Textiles 12.Chemicals	*Paper and Containers* Paper, metals, glass, polymers *Organics* Food, vegetative debris, food dirty paper, paper, plant debris, putrescibles, wood *Discarded items* Furniture, appliances, clothing, toys, tools, reusable goods, textiles *Special discards* Chemicals, construction and demolition materials, wood, ceramics, soils,	*Recyclables:* Papers, plastic, glass and metal containers *Organics*: Food, vegetative debris, and food paper, putrescibles, untreated wood and sheetrock *Reuse & Repair*: Reuse, repair, dismantling, reconditioning, remanufacturing and resale of furniture, appliances, electronics, textiles, toys, tools, metal and ceramic plumbing fixtures, lighting, lumber and other used building materials *Metals*: scrap metals and auto bodies *Inert*: Rock, soils, concrete, asphalt, brick, land clearing debris, and mixed construction and demolition materials) *Household Hazardous Wastes*: Used motor oil, paint, pesticides, cleaners, and other chemicals

The Park is conceptualized as a central area where the public drops off discarded materials. The facility will have the capability and technology to 1. Sort discards for reuse, repair and/or dismantle for recycling; 2. process separately collected commingled paper and containers; 3. store bins for organics to be transferred to composting facilities; 4. store separated HHW materials for reuse and disposal; and 5. collect separated construction and demolition materials and transport if necessary (Table 3.3).

Types of services related to businesses located in a Resource Recovery Park include the following: drop-off or buyback recycling centers, food banks, repair services and retail store for resale of reuse items. Repair and reuse services include white goods (washers, dryers, refrigerators), brown goods (e.g., computers, TVs, electronics, and other small appliances), furniture, clothing, latex paint, vintage clothing, consignment, household item thrift shop, stove and porcelain refinisher, an antique restoration firm, Eco-artist, black smith, glass blower, etc. The Park would have collection points for the Composting Facility, C & D storage and/or Processing Area, and HHW storage and reuse.

Types of products recovered include the following: pipe, conduit, grills, gates, appliances, fasteners, patio furniture, tools, computer casings, toys, furniture, planter pots, discard collection receptacles, doors, fencing, furniture, cabinets, dishes, windows, lenses, glass blocks, lamps, toilets, sinks, dishes, plant pots, brick, block, stone, car parts, white goods, industrial scrap, dismantled structures, couches and mattresses, textiles, steel beams, equipment parts, metal fencing, metal building parts, and recovered dimensional lumber

HHW businesses include HHW material transporters and converters. Products and materials include left over paint, pool acids, fertilizers, pesticides, solvents and, other household chemicals.

Table 3.3. Process, Feedstock and Products

Process	Feedstock	Products
1. Sort discards for reuse, repair and/or dismantle for recycling	Discards	Materials, commodities
2. Process separately collected comingled paper and containers	Paper, containers	Newspaper, cardboard, ledgers, glass, steel, HDPE, PET, aluminum
3. Store bins for organics to be transferred to composting facility and	Food, paper, yard wastes, wood	Mulch, compost, wood
4. Store separated HHW materials for reuse and disposal	HHW	Reusable chemicals and paint, HHW
5. Collect separated construction and demolition materials	C&D	Wood, ceramics, inert, soil

Case Study: The Organics Processing Facility

Currently, more than half of the material disposed of in landfill is biodegradable or compostable. Paper is the largest quantity of organic material typically discarded for land filling. Mixed paper, when separated into paper stock grades, has a value as recyclable fiber for papermaking. The recovery of paper for recycling is discussed above. Only food contaminated paper (food paper) is considered as a potential feedstock for the Organic Management Program. Food paper includes food in wrappers, paper cups, waxed boxes, molded paper and pizza boxes. If aggregated, all these organics could be processed into mulch. The mulch could be composted by itself or with other organic nutrients into a high quality soil amendment.

There will be a large container at the Resource Recovery Park for organic material collection. This container will be transferred to the Organic Processing Center.

Businesses clustered around organics include collection and processing services for yard trimmings, food scraps, food-contaminated paper, wood, soils, and other putrescibles.

There are several levels of markets for organic material: lumber and wood recovery for reuse; live plants for reuse; mulched leafy green material for roadsides, garden beds and erosion control; mulched dense woody material for bio-mass based fuel burners; clean green and food compost; clean green and bio-solid mixed compost; and vermicompost, or worm castings, as a high grade potting soil.

Reusable lumber and furniture could be recovered and sold at the Resource Recovery Park. Mulched material can be used for roadside erosion control, or used as landfill cover. Clean green organic compost has a value for commercial farming and landscaping. Nitrogen enhanced organic compost has a higher value. There are local agricultural and nursery uses for soil amendment.

Construction and Demolition materials (C&D) can be separated at the source and brought to a materials yard and processed for resale. Businesses include collecting and processing C&D debris, deconstruction or dismantling. Products would include ceramics, concrete and asphalt, roofing materials, bricks, and mixed demolition debris.

Major potential end-uses for tires include producing crumb rubber for use in molded rubber products or rubberized asphalt.

3.1.6 Local Ordinances

In a zero waste system, rules need to be established, publicly accessible, and adhered to. Households and institutions can develop their own operating rules based on efficiency. The government or agency may by ordinance require the separation of designated recyclable and organic material just as hazardous or bulky materials require separate service. Health agencies can ban certain materials from burning and burying. It seems clear that metals, just based on recycle values for example, should never be buried or burned.

Where the government requires mandatory source separation, discarded material collection fees can be based on the types of materials collected (recyclable, organics, reusables). These charges are based on the collection and processing costs and resale value. Separate collection charges based on destination point make a lot of sense for both public and private collectors. The collector would ticket a container that is in violation of the separation ordinance. A member of the city would visit the generator and informs them of the rule violation and explain the separation procedure. A second violation can lead to a monetary fine.

Some governments require that packaging and durable products like electronic products be taken back by manufacturers. These programs require that the manufacturer add a deposit to the cost of the product that can be redeemed by a recycler when returned, or where the manufacturer pays a recycling fee to the government or a private agency to subsidize the operation of the recovery program [1, 3, 4, 34].

European law includes the Council Directive 94/62/EC of 15 December 1994 on packaging and packaging waste (Official Journal L 365, 31.12.1994). This directive covers all packaging placed on the market in the European Union (EU) and all packaging waste. The directive dictates that the Member States take measures to prevent the formation of packaging waste, which may include national programs and may encourage the reuse of packaging. The Member States must introduce systems for the return and/or collection of used packaging to attain a recovery target of 50% to 60% and a recycling target of 25% to 45%, with a minimum of 15% by weight for each packaging material. These targets are to be revised every 5 years (however, the first revision is still in process). The directive also regulates maximum concentrations of heavy metals in packages.

The Member States are to report regularly to the Commission on the application of the Directive. According to the reports from 1999, Germany, Scandinavia and Austria have been most successful concerning prevention/reuse. All member states met the overall recycling target of 25% of packaging material, the targets per material were met for all materials but plastic (these were only met in Germany, Finland, and Austria). Austria, Belgium, the Netherlands, Germany, Sweden, Denmark, and Finland have the highest recycling rates (around 45% or more).

The Directive on batteries 91/157EWG, Amendment 98/101/EG, regulates the use of heavy metals in batteries (especially mercury), thus making them more attractive for recycling. Several other directives are underway, e.g. concerning product responsibility for all electronic goods (take-back, obligation of member states to provide recycling infrastructure, recycling targets of between 60 and 80 % by weight, regulation of dangerous substances) (Directive on used electric and electronic goods 2000/0158 COD).

German law is the most advanced in the EU with regard to recycling and includes the German Packaging Ordinance [3], which regulates the waste hierarchy (reduce, reuse, recycle...) and product responsibility for all packages. This law obliges all manufacturers and distributors of packages to take back and recycle their used transport, secondary and sales packaging (recycling quota targets are established). According to the central recovery company, Dual System, the use of packaging declined from 96 to 83 kg per year and capita. A large fraction of this amount (78 kg per year and capita) is currently collected and most of it recycled [30]. The Ordinance was amended in 1998, reinforcing prevention and recycling targets and implementing the European Package Directive.

The Recycling and Waste Managing Act (Kreislaufwirtschafts- und Abfallgesetz) [4] introduced product responsibility for all goods circulated in Germany. However, this general law needs to be specified in further regulations. So far this has been done for old cars, electronic scrap, and batteries (full product responsibility: take back free of charge, recycling quota). A new law for old wood is on the way.

Industry established voluntary commitments for the take back of old cars and recycling targets (85% till 2002, 95% till 2015). The textile and carpet industry established their own reuse recycling system as a consequence of the Waste Managing Act. A large share of textiles are currently reused (40%) or recycled (50%), numerous carpet recycling facilities have been installed [31].

Producer responsibility take back laws are prevalent in parts of *Asia*. In Island Banking and Industrial Countries like Japan, Hong Kong and Taiwan, space is at a premium. Take back laws and recycling systems are prevalent in Taiwan and Japan. Taiwan has a series of take back laws that instruct manufacturers to residuals from the Island. In Japan, about 50 % of the discards are recovered for recycling, another 25% is burned for energy and volume reduction, and the residuals are buried. Much of the feedstock for the industries in these areas is recycled metal, paper or plastic. In Hong Kong, the government subsidizes wasting through a series of landfills and no disposal fees.

Several states in the *USA* have mandatory recycling laws. The States of New Jersey, Rhode Island and Pennsylvania have laws requiring the provision of recycling services. Some cites, such as Chula Vista and Poway California, require separation of designated recyclables from mixed discards. In California there are laws requiring that newsprint and plastics have recycled content, beverage containers are to have deposits and redemption centers, state agencies and cities are to have recycling plans with a 50 % reduction of waste generated, and advance recycling fees for oil, and tires. Currently the State legislature is contemplating a zero waste goal and take back laws for electronics.

United States federal law "The Resource Conservation and Recovery Act" is over twenty five year old and covers hazardous material collection, disposal and clean up, and sets basic standards for sanitary landfill operation. The Clean Air Act and the Clean Water Act control air and water emissions that are associated with typical disposal practices. The Federal government educates and funds programs that prevent pollution and promote recycling as a force against climate change.

3.1.7 Participant Education

Zero waste programs utilize source separation as a method to reclaim materials accurately and cost effectively. Involving the generator of the material in the program assures quality control at the point of separation. Program planners should include participants in the program planning process.

Whether the source of the discarded materials to be recycled is an entire city, an institution, office or home, participants in the generation of the discards need to be part of the process. In the city or office, a task force on zero waste could help provide direction to those in charge of implementing the program. Local coordinators in neighborhoods or at the business management level can work out collection location details and arrange for special pickups.

Promotion and education programs should be designed according to the needs of each generating group and maintained through out the year. Simple things like a quarterly newsletter tracking reclamation tonnage and explaining program details have a positive impact on those participating. Regular on time picks ups are the most important statement the program operators can make about their side of the program.

Planning for public education and involvement requires that program planners understand their audience, preparing formal plans, and establishing a method for evaluating programs. Using a task force made up of managers from collection, markets, and involved departments, the program goals and mission can thus be formed. Based on the goals, objectives to reach the goals for the short and long term are set. The plan is then put together on how to achieve the goals. A zero waste program is easy to monitor. Compare wasting both before and after.

Delivering an educational message, maintaining program participation, and funding activities are key challenges in making the program work. In a zero waste program the message is to eliminate waste by directing discards to reuse, recycling and composting programs. Participation in the program will vary based on the clarity of the message (What materials do you want?), and the participant's ability (Convenience) to take part (Where should I put them?).

One way to encourage participation is to explain how much wasting costs versus the costs of a zero waste program. The participant has a right and responsibility to understand the costs and liabilities of managing the discards they produce. In most cases, the citizen or employee has figured it out already. When the program is implemented , many will say "its about time."

Involving the participant in the planning, execution and evaluation of the program will help gather the data needed to make program evaluations, modifications and improvements. Participant involvement is necessary in the planning, education, execution and evaluation. Block leaders and program coordinators can provide value input as to types of material, generating areas, the necessary transport vehicles and competing interests.

When planning a Participant Education Program, a written document (plan) should be prepared using input from participants and program staff. The plan should identify the following:

- Main issues or challenges to be addressed,
- Short and long term goals to attain,
- Activities and events needed to accomplish each goal,
- Resources available for each activity and event,
- Timelines that coordinate public information with program implementation and take into account seasonal activities and events,
- A preset program to monitor and evaluate activities.

Most people are concerned about resources and the environment. In a volunteer program, participation can be anywhere from 15% to 80% depending on convenience. A drop-off recycling center will draw 15%, while a well promoted regular curbside pickup program will involve more than 80% participation.

Participation is always in the 90% range when the programs are (legally) required. Relatively few people refuse to participate in source separation programs, especially if it is the law (e.g., the packaging collection quota in Germany is currently 94% [30]. The usual reasons given for not participating in a required program include the following: inadequate knowledge, memory loss, being new in town, or temporary insanity.

3.1.8 Determining Costs and Benefits

The bottom line for most projects is the determining factor toward implementation. The bottom line must include the cost of wasting as well as the cost of recovery. Thus the cost of discard disposal starts when the material is source separated and includes the following: the cost of planning, storage, collection, and processing, as well as the reuse, recycling and composting revenue, and the cost of residual disposal in transformation facilities and landfill. The cost of monitoring and pollution mitigation at the transformation site and landfill must be included in the transformation and landfill disposal cost.

Households (numbers), container types, per unit costs (cost per ton), and land use categories, are all common denominators that can be used to calculate the cost of service or service fees. Annual costs are broken down into amortized capital (equipment and land) and operations (labor and materials). Revenue is broken down into annual material sales and service fees. In a cost benefit analysis, savings of land, resources and energy is factored in as a long-term benefit (revenue).

Using the twelve master categories, the following is a Cost/Benefit analysis of the 50-ton per day Discard System shown earlier in the waste characterization section and discussed in the recycling technology section. The clusters are based on destination points determined by markets and processing systems discussed earlier. The material is source separated and self-hauled to the center and placed into appropriate areas at the site.

Case Study: Cost/Benefit Analysis Resource Recovery Park by Cluster

Using the concept of a Resource Recovery Park as the processing centers and cost data developed by Urban Ore for The State of West Virginia to develop a reuse, recycle and organic Resource Recovery Park, the capital, operations and maintenance, revenue and total costs are estimated (Table 3.4). Note that avoided costs or disposal savings justify the project.

Table 3.4. Cost/Benefit Analysis of Resource Recovery Park by Cluster

Cluster	Capital [$/a*]	O&M [$/a]	Annual Costs	Trans/ Disp.** Savings	Sales [$/a]	t/a	Benefits (Costs) [$/Ton]
Reuse	34’817	432’311	467’128	106’425	413’700	1’419	+37
Recycling	58’475	169’928	228’403	323’925	108’410	4’319	+47
Organics	79’113	158’928	238’041	509’000	74’040	6’796	+51
Total	*172’405*	*761’167*	*933’572*	*940’050*	*596’150*	*12’534*	*+48*

* Amortization; 20 years land and structures, 6 years equipment and fixtures

** $75 dollar per ton savings from avoided transfer and disposal.

3.1.9 Measuring Diversion

One way to evaluate the success of a program is to measure the amount of discards generated. In order to measure the result of the prevention program source, reduction programs are quantified. For example, if before the prevention program there were hundreds of acres of lawns for public parks, golf courses and cemeteries that contributed lawn clippings, the prevention program implements a grass cycling policy. This policy would require mulching mowers that leave mulched grass clippings on the lawn instead of collecting them for disposal. The savings in material disposed is estimated and added to the diversion measurements as source reduced.

Other source reduction measurements include reducing paper use through two side copying and office e-mail, permanent drink cups for all employees, chemical diversion programs, etc. A substantial list can be obtained from the California Integrated Waste Management Board. Credit for reducing waste at the source provides support for prevention activities.

Transformation (burning, distillation, gasification etc) can also be calculated as diversion. Certain discards like forest slash, agricultural and hospital residue are best transformed by heat into a gas and/or inert materials. However, for the most part, the highest and best use for most discards is material recycling and composting.

The problem with a goal like “50% diversion” is, what do we do with the other 50%? If diversion of 50% of the discards is the goal for recycling, is the goal for wasting also 50%? Planners look 20 years into the future to estimate landfill needs. If 50% of the discarded resources are diverted and wasted resource generation increases at a positive number each year, in how many years will we need a new landfill?

A zero waste analysis would examine all materials currently discarded and then find a place for them. To the planner, the 20-year forecast will be zero waste. The existing capacity of the landfill is used as the zero target is approached. Materials that do not have a market must be sent back to the manufacturer with instruction that these materials are their responsibility. Ultimately violators will have their sales banned in localities where no recycling or composting options exist.

3.2 Mechanical Sorting Processes and Material Recycling

Bernd Bilitewski

The basic precondition of recycling is the separate collection of production wastes, used products and organic waste from residual waste. The form of collection and the logistics of the collected material have significant effects on the quality of the secondary materials, as well as on the economics and the environmental burdens.

- Primary material and primary energy resources can be replaced by secondary materials and secondary fuel only if the product and fuel quality is maintained.

The mechanical sorting process of separately collected waste fractions has, in spite of the development of new mechanical separation methods for MSW, still not succeeded in effectively replacing the method of handpicking. Because of this, the sorting plants still prefer hand picking. But it is a labor intensive and, therefore, expensive as well as slow method. Sorting machines have been developed to aid in handpicking efficiency and effectiveness.

The first automatic sorting plants for packaging and paper are in practical use. Because of their high investment capital needed and their large through-put, their applicability is limited to highly dense populated areas.

3.2.1 Glass Recycling

Waste container glass can be repeatedly melted without any quality loss. Separate glass collection, which began in 1992, has a recycling quota which amounts to approximately 85 % today. To achieve high glass quality, glass factories brought forth demands of low impurities and color sorted collection. The following impurities and glass qualities have been defined:

glass impurities

- glass from windows, lamps and special glass products are not suitable for the production of container glass
- wrong/mixed colors

impurities

- Ceramics and minerals
- top openings, cork, labels
- content matter

Ferrous and nonferrous metals disturb the melting process. Ceramics and minerals also have to be limited. Particles often cannot dissolve during the melting of glass, leading to inclusions, which make the recycled glasses more fragile.

The particle size distribution of shredded glass has an impact on heat transfer in the melting process. Table 3.6 shows the target demand of the glass manufacturing industries and the size distribution of two different types of shredder.

Figure 3.2 illustrates that semi-automatic glass separation has been the most frequently used method in the last twenty years [19].

To meet the new standards of color separated glass it is necessary to use an automatic separation unit to segregate glass into different colors and separate ceramics and minerals as well.

The automatic glass sorting machines – figure 3.3 –use opacity to separate glass into different colors and from fragments of non-glass material. The sensor used to distinguish the cullet functions using either infrared light or opto-electrical signals. As soon as the sensor identifies the cullets to be sorted out, a magnetic valve opens an air jet which blows off the particle(s).

Table 3.5. Impurities and quality demand by glass manufactures over time for container glass [20]

Year	**1977**	**1992**	**1994**
impurities max.	[g/Mg]	[g/Mg]	[g/Mg]
Ceramic, stones, porcelain	100	50	25
Nonferrous metals	15		
Aluminum		5	5
Lead		1	1
Ferrous metals	5	5	5
Organic matter	500	500	500
impurities max.	[%]	[%]	[%]
Water content	-	2	2
White glass:			
impurities of green	0.005	1	1
impurities of brown	0.01	2	2
impurities of colored white	0.02	-	-
Brown glass:			
impurities of green	10	3	3
impurities of white	5	5	5
Green glass:			
impurities of brown	15	10	10
impurities of white	10	15	15

Table 3.6. Particle size distribution of impact and hammer mill in comparison of the demanded target [59]

Particle size [mm]	Target [%]	Impact [%]	Hammer mill [%]
0 – 1.0	3	5	3
1.0 – 3.15	7	21	10
3.15 – 8.0	22	41	40
8.0 – 16.0	45	26	44
16.0 – 25.0	23	7	3

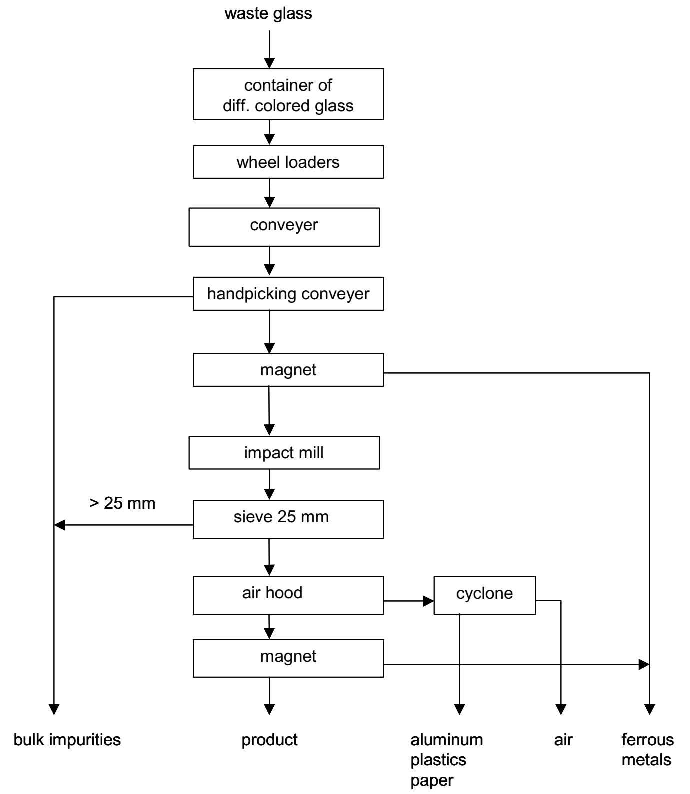

Fig. 3.2. Hazemags-separation plant for waste glass [98]

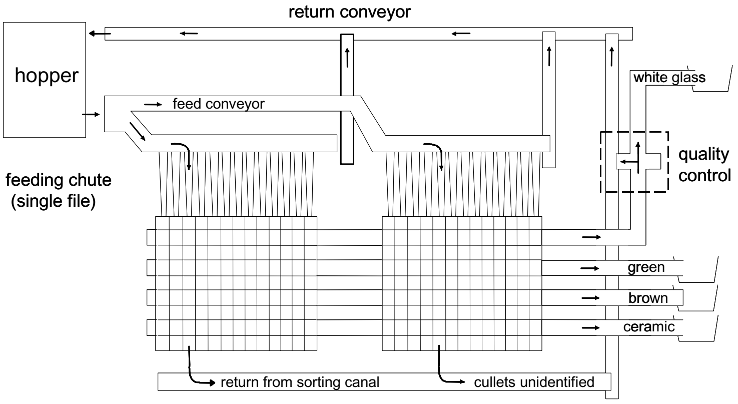

Fig. 3.3. Schematic picture of an automatic glass sorting machine [19]

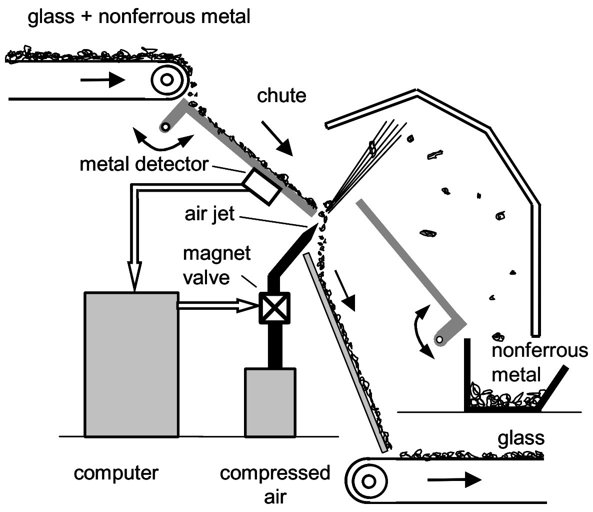

Fig. 3.4. Principle of eddy current separator [20]

The efficiency of the automatic glass sorting depends on:

- amount of impurities to be separated;
- particle size distribution (very small cullet are problematic)
- an exact feed in single file to the optical sensor
- successful (effectively sorted by color) collection at drop-off or curb side locations

The purity of an automatic separation unit for white glass is approx 99,7 % - 99,8 % [7]. To meet the target standard, the glass has to pass a second unit:

Eddy current separation for non-ferrous metal can be combined with the glass separation process. Eddy current separators have been used in the recycling processes of sorting packaging, electronic scrap and automobile shredder plants. Figure 3.4 shows the schematic principles of an eddy current separator of nonferrous metal. The eddy current induces a strong repelling current which can be combined with an air jet to make sure that the separation efficiency is almost 100 %.

3.2.2 Recycling of Paper and Cardboard

In the year 2000 in Germany, approx. 60 % of the input of produced paper, a total of 10,921 Mio tons, is secondary fiber. Table 3.7 shows the development of different recycling quotes of the main paper products. Roughly 85 % of the graphical paper and 75 % of the packaging paper used in German households are separately collected. To achieve these recycling quotas, it is necessary to collect paper in as clean a state as possible and to improve the separation process.

Table 3.7. Breakdown of the waste paper input of the paper production (1990 and 2000) [38]

Main paper products	waste paper reused [ton/y]		production [ton/y]		recycling quota [%]	
	1990	2000	1990	2000	1990	2000
packaging paper/cardboard	3’847’000	6’101’000	4’166’000	6’733’000	92.3	90.6
graphic paper	1’046’000	3’411’000	5’784’000	9’125’000	18.1	37.4
hygienic paper	455’000	750’000	828’000	1’017’000	54.9	73.7
technical paper	422’000	659’000	1’095’000	1’307’000	38.6	50.4
sum	5’770’000	10’921’000	11’873’000	18’182’000	48.6	60.1

The main separation process for collected mixed waste paper is sieving and handpicking. In a normal drop-off container, 35 % of the waste paper will be cardboard, 60 % deinking quality and approx. 5 % impurities. The productivity of handpicking is 0,7 – 1,2 Mg per worker and hour [19]

As soon as graphical paper and packaging paper are collected in separate drop-off containers, the quality content improves dramatically, so that graphical paper can be accepted without any sorting process, as shown in figure 3.5.

The used technology is based on a series of air classifiers, which will be used in combination with a shredder, producing a uniform particle size and making automatic separation possible.

Table 3.8 shows the performance of an air classifier in correspondence to the particle size in weight, thickness, form and area.

The deinking quality of the recovered paper has less than 2,5 % impurities. All metal, glass particle, sand, adhesive backs of books and waste components are separated. The second fraction consists of big cardboard pieces and the third fraction of a mixture of cardboard and (approx 4 %) of deinking quality paper of in respect of the input.

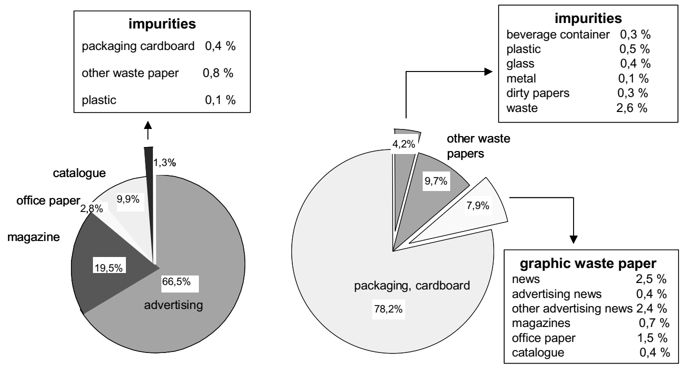

Fig. 3.5. Quality of waste paper containers by using separate collection systems for graphical paper deinking quality and card boards in Dresden [38]

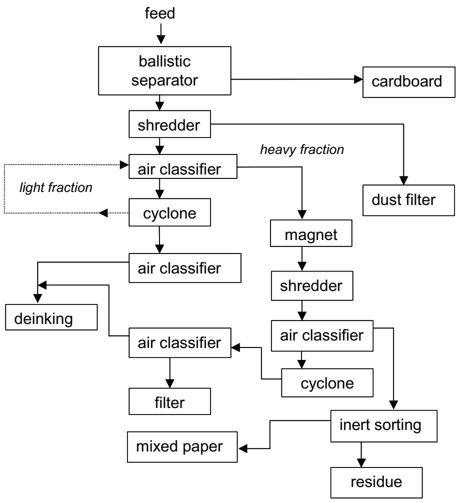

Fig. 3.6. Automatic separation plan for paper in deinking quality [73]

Table 3.8. Separation air velocity of card board particles in an air-classifier [73]

particle	form	weight [g]	area [mm^2]	specific weight [g/m^2]	thickness [mm]	volume [mm^3]	separation air velocity [m/s])
cardboard from deep frozen food	multi-corner	0.253	621	407.41	0.50	310.5	3.70
Tetra-Pack	trapeze	0.074	172	430.23	0.50	86.0	3.75
cardboard with torn side	trapeze	0.017	84	202.38	0.30	25.2	2.70
carton	trapeze	0.033	127	259.84	0.50	63.5	3.00

Deinking Technology For Recovered Paper

The flotation deinking technology for the removal of ink from a recycled pulp slurry was first established in Europe 1959. Since than the annual growth of production of DIP (De-Inked Pulp) has been 15 % p.a. Newsprint in Germany is only produced using secondary collected waste paper with a recovered paper utilization rate of 116 % [79].

Nevertheless, the utilization of DIP is a permanent challenge in the production of a constant quality, due to the variations of impurities and unwanted paper components in recovered paper deliveries, which are, for this purpose, still a mixture of newspapers and magazines mainly recovered from private households.

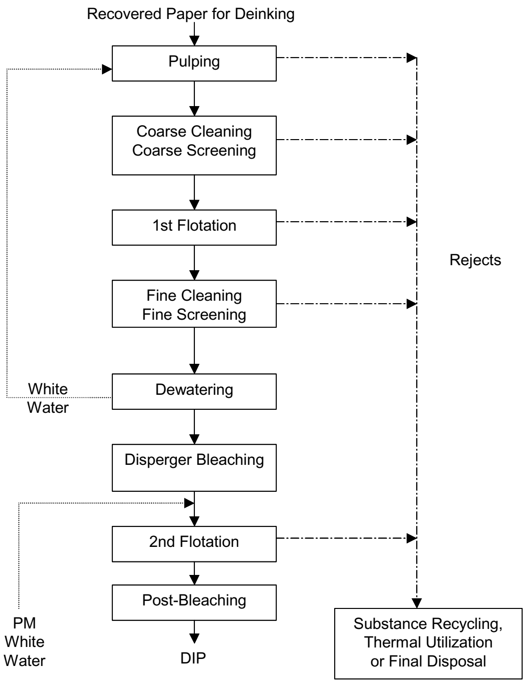

Fig. 3.7. Stock Preparation for Graphic Papers [79]

Finally, the composition of the recovered paper for deinking has changed in terms of the variety of printed matter; e.g. waterborne flexo inks, offset inks with natural binder systems, digitally printed papers, and adhesives such as self sealing envelopes, post-it notes and others.

Today´s flotation cells are mainly of a cylindrical shape, using injector aeration. For standard newsprint made from 100 % recycled fibers, today‘s deinking plants are commonly equipped with double flotation and a dispersion stage (Fig. 3.7). Processing based on double flotation and dispersion is intended to remove ink particles released from the fibers during pulping in the first flotation stage. For ink particles not detached from the fibers and for particles too large to be floated, the dispersing stage contributes both to the release and the break-down of smaller particles. In the second flotation stage these ink particles can be efficiently removed from the pulp.

In general, double flotation results in an improved DIP quality, not only in terms of brightness but also in residual ink content and visible ink specks. Additionally, variations resulting from the incoming recovered paper can be controlled better. In large stock preparation plants for newsprint manufacture up to 1’000 t/a DIP in one line with double flotation, the specific electric energy amounts to 350 to 500 kWh/t at a yield in the range of 75 to 82 % [79].

In general, the DIP processes need further improvements by increasing efficiency in terms of yield. This is only possible if the ink separation processes, flotation and washing, become more selective. Additionally, an advanced control of ash and stickies would be favorable for the utilization of DIP in all paper grades. The economic disposal of the rejects, energy recovery from them or their use for material recycling are pre-requisites for further DIP application in paper products. Finally, the composition of used recovered paper has to be controlled in a more sophisticated way in order to guarantee a more homogeneous raw material quality, resulting in smaller variations of important characteristics of the incoming stock as well as of the final DIP [79].

3.2.3 Recycling of Light Weight Packaging with the Green Dot System

The German business community founded the Dual System Deutschland (DSD) as a private organization. Under the DSD system, manufacturers apply for and pay DSD a fee to place their symbol, a green dot, on their packages to ensure that DSD will collect and recycle their packaging. DSD is not responsible for the actual recycling of materials; it is responsible for guaranteeing that recycling targets are met. Any product with a green dot signifies to the consumer that the package should be collected by DSD, and not returned to the retail outlet. At present, around 250 sorting plants in Germany are involved in sorting lightweight packaging collected by the Dual System.

The fully automatic SORTEC 3.0 process is divided into three steps: Dry mechanical pre-sorting, wet mechanical preparation and plastics processing (Fig. 3.8). The yellow bags are first opened mechanically. Then the lightweight packaging passes through various sieves which sort the waste according to size. After this, the fractions are transported past an air separator which blows out light plastic films and pieces of paper. This so-called lightweight fraction is forwarded directly to the central hydra-pulping step. The heavy fractions are transported past a magnet separator, which lifts out ferrous metals such as tin cans. PET bottles and beverage cartons are identified by means of near-infrared spectroscopy. All shapes, sizes and colors of beverage cartons and PET bottles are identified with the aid of spectral analysis. The unit establishes their position on the conveyor belt and compressed air valves blow them into appropriate collection containers.

The remainder of the heavy fractions is conveyed to a second pulper. Any adhering dirt and paper fibres are suspended in water in this unit and the plastics and packaging containing aluminum are washed clean. During the water treatment step, the paper fibres are removed and any pollutants are flocculated before being discharged as solid sludge. The purified water is returned to the hydrapulping process, thus forming a closed cycle.

The remaining material, primarily plastic and aluminum packaging, is subsequently shredded. Then it is routed to two series-connected sorting centrifuges containing water or a saline solution as separating medium. These separate the plastics according to their specific density. This method permits the recovery of basically homogeneous polystrene as well as polyolefine fractions [74]. The heavy material that has sunk to the bottom is subjected to eddy current separation for re-

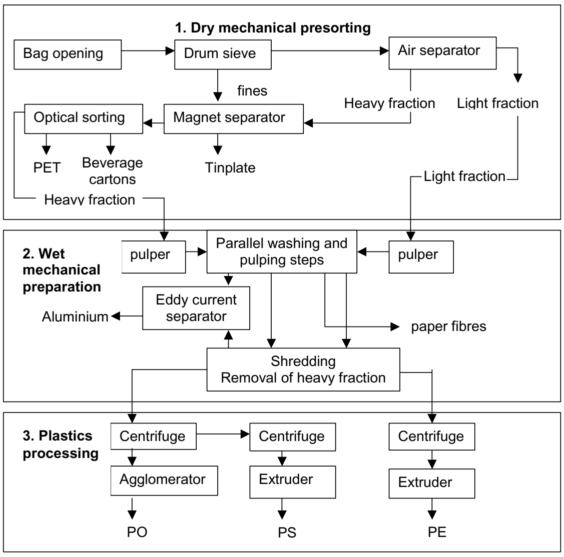

Fig. 3.8. Flow sheet of the SORTEC 3.0 [74]

moval of the aluminum components. In the subsequent plastic processing step, the homogeneous plastic fractions are melted in extruders and processed into granulate (Fig. 3.8). The material balance is shown in Table 3.9.

Table 3.9. Secondary raw material and residue in a material balance [74]

Tinplate	23.5 %
Beverage cartons	5.0 %
Paper fibres	8.0 %
Aluminum	4.0 %
PE granulate	13.0 %
PS granulate	3.5 %
PET	1.5 %
PO-Agglomerate	23.0 %
Residue (wood, textiles, stones)	18.5 %
Total	100.0 %

New Optical Sorting of Household Waste with Optibag

The contemporary concept of waste collection is the multi-bin, one used for organic waste, one for paper and cardboard, one for packaging; in large housing areas, three bins are use for glass of different colors.

The Optibag-System uses plastic bags with a thickness of al least 35 µm and a different color for each fraction. The sorting system is based on a color sensor that recognizes the color of the bag. Each color corresponds to a fraction. The system

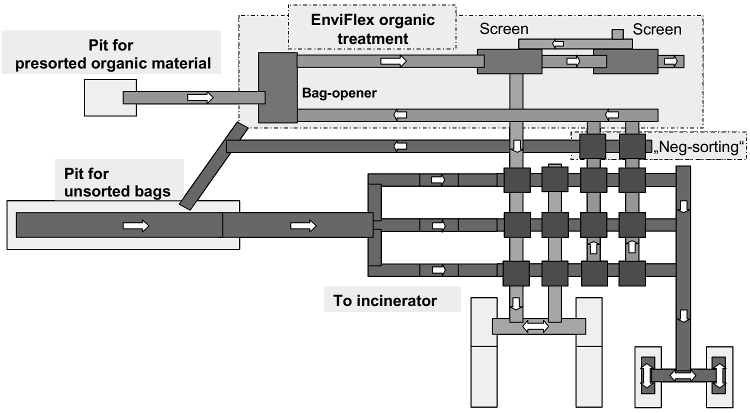

Fig. 3.9. Optibag plant in Sweden

has a capacity to handle up to 6-7 fractions. The bags are dumped into existing waste chutes or containers. A single truck collects the colored bags.

In the recycling plant, the optical system identifies the color of the bags and distributes them onto a receiving conveyer. If a bag does not match any of the color criteria, it will continue on to the end of the conveyer, together with material that is not contained in any bag and will be sent to landfill or incineration.

The sorted bags are delivered to bag openers and containers or directly to an incineration plant or biogas plant, and one or several fractions of recyclable material to sorting plants.

The Optibag-System ensures that separation at the source takes place and that transportation costs and environmental burdens are minimized. In Europe, 16 plants are in operation connecting 1.4 million people with system.

3.2.4 RDF-Production from Household Waste

Up to now, the market for substitute fuels has developed slowly. It is essentially influenced by three participating groups: the producer of substitute fuels, the users of substitute fuels and the approving authorities. The existing dissent in interests between these groups is clearly reflected in the discussion about quality standards for substitute fuels. While the authority represents primarily ecological interests and therefore judges quality standards by the emission standards and the transfer into different environmental compartments, the producers of substitute fuels maintain the role of waste processors. They define quality standards on the basis of waste as a raw material and its associated pollutant load. For the user, rather technical aspects are at the centre of interest, especially concerning operational reliability and aspects of product quality.

Table 3.10. Survey of quality standards for substitute fuels

	LAGA (proposal) [a] LAGA, [55]	BUWAL [b] BUWAL, [24]	BGS (proposal) [c] Püchel, [78]
Element	mg/MJ	mg/MJ	mg/MJ
As	1.9	0.6	0.5
Be	0.13	0.2	0.13
Cd	0.3	0.1	0.5
Co	1.2	0.8	0.75
Cr	3.7	4.0	15.09
Cu	3.7	4	35.21
Hg	0.02	0.02	0.05
Ni	3.5	4	7.55
Pb	n.a.	8	12.58
Sb	0.07	0.2	3.02
Se	0.2	0.2	0.5
Sn	0.4	0.4	7.55
Te	0.04	n.a.	0.4
Tl	0.15	0.12	0.15
V	6.7	4	1.51
Zn	8	16	n.a.
Cl	1 % by weight	n.a.	n.a.

n.a. not available. Basis for conversion of mg/kg(dry) into mg/MJ is LHV(dry) [d] equals 18’000 kJ/kg.

[a] Working Group on Waste by the German Bundesländer: Criteria for energetic utilisation in cement kilns.

[b] Federal Office for Environment, Forest and Landscape: Swiss guideline of waste disposal in cement kilns.

[c] German Quality Association for Secondary Fuels: Quality standards for substitute fuels.

[d] LHV denotes Lower Heating Value.

These contrary interests are also reflected in the ongoing discussion about the assurance of production quality and use of substitute fuels. From the different positions, standards for substitute fuels are presently suggested.

Mechanical processing techniques must be sufficiently selective to produce defined fuels. Different RDF-production facilities were investigated with respect to separation efficiency and their mass balances were determined for each element. Therefore, the input and output streams were sorted and the mass distribution of waste fractions connected with the fraction-specific concentrations. This mathematical model was useful for the understanding of the relative contribution to each output stream. Sankey diagrams offer a descriptive method for displaying material and energy flow balances. Additionally, Figure 3.10 shows the impact of the considered elements by individual waste fractions combined into four differently shaded groups. The grey tones represent the classification into

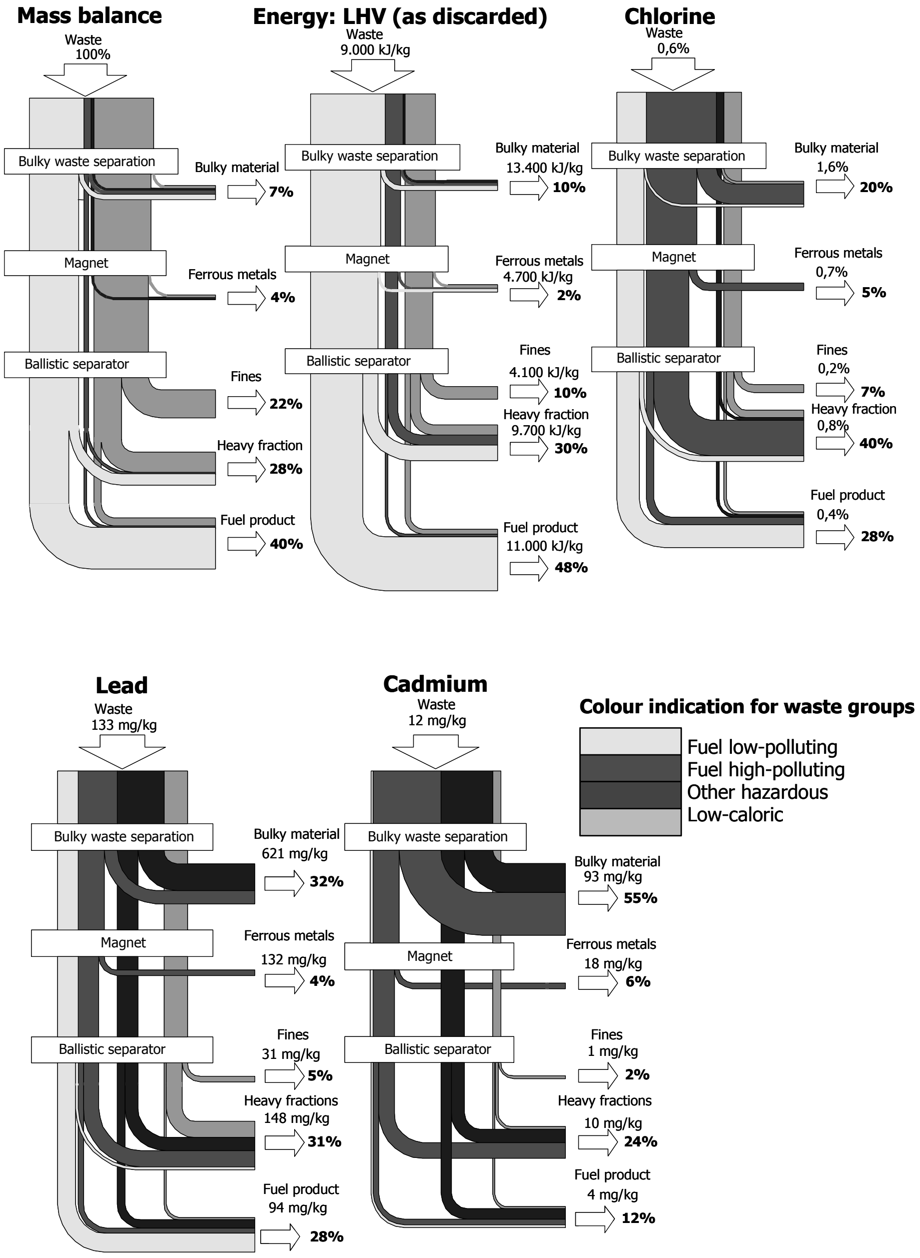

Fig. 3.10. Energy- and material flow balance of mechanical waste processing by ballistic separation, displayed as Sankey diagram; raw material is waste from urban areas [52]

- high-caloric fractions of small pollution impact (wood, paper/cardboard, plastic foils and - packaging);
- high-caloric fractions of high pollution impact (non-packaging plastic products, shoes, leather, rubber, other composites);
- low-caloric or inert fractions (organic waste, minerals, metals, fines);
- hazardous fractions (batteries, luminous tubes, electronic waste, household chemicals etc.).

From the examined mechanical processing of household waste (e.g. sizing, air classifying, automatic plastic detection), only the separation in the ballistic separator is used to ensure a sufficient recovery of paper and cardboard. The desired selectivity of the separation process was indicated by the reduction in concentration for the three regarded pollutants, while the caloric values increased compared to the input. Only small proportions of fuel with low pollutant contents in the household waste are lost with the heavy fraction group. In the heavy group selective pollutants are enriched. The example clearly indicates another pollutant sink. The high proportion of bulky waste in the household waste at the practical test was notable. The material balances show that an effective separation of bulky fractions is an important part in the production of quality-secured fuels [52].

3.3 Conventional Thermal Treatment Methods

Michael Beckmann and Reinhard Scholz

3.3.1 Introduction

Various processes, which integrate pyrolysis, gasification and combustion fundamental structural units, are currently being applied and tested in the field of the thermal treatment of municipal waste and similar industrial waste. The main thermal processes can be broken down into two units:

- First, for the conversion of the solid and pasty waste
- Second, for the treatment of the gas, flue dust or pyrolysis coke produced in the first unit (Table 3.11).

The conventional thermal treatment of residual waste, also often called “classical combustion of residual waste,” represents a tried technology. The processes for thermal waste treatment can be classified into the so-called main thermal processes and processes or plants for flue gas purification, energy conversion, ash treatment, production of supplementary agents, etc. Classical waste combustion can be viewed as a combustion-post-combustion process with a grate system in the first unit and a combustion chamber system in the second unit. In relation to the classification in Table 3.11, Figure 3.11 shows the profile of a complete process as an example.

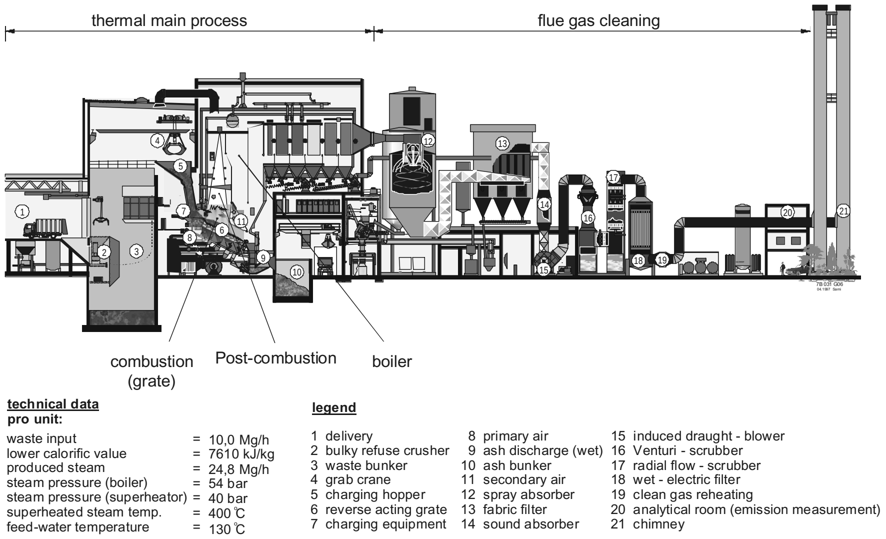

Fig. 3.11. Schematic representation of a waste power plant (classical municipal solid waste combustion plant) [100]

Table 3.11. Systematic description of main thermal processes [87]

	Unit 1	Unit 2	Processes and Examples
A	combustion[1]	combustion	combustion - post-combustion-process (e.g. standard waste incineration) [27, 51, 56, 67, 77, 81 83, 89, 100]
B	thermolysis[2]	combustion	thermolysis - post-combustion-process (e.g. Schwel-Brenn-Verfahren by Siemens KWU) [18]
C	gasification[3]	combustion	gasification - post-combustion-process (advanced standard waste incineration) [17, 82]
D	thermolysis	gasification	thermolysis - post-gasification-process (e.g. Konversionsverfahren by NOELL [36], Thermoselect-Verfahren [94] etc.)
E	gasification	gasification	gasification - post-gasification-process (e.g. gasification and gas decomposition by LURGI [6])

[1] Includes the processes drying, degasification, gasification and combustion

[2] Includes the processes drying, degasification and pyrolysis

[3] Includes the processes drying, degasification and gasification

The flue gas purification (so-called secondary measures) of the ‘classical’ process in particular has been improved in recent years. Plants equipped with state-of-the-art technology meet the statutory specified limits for the emission of pollutants into the air, water and soil.

The current priority is the development, modeling and optimization of the process control (so-called primary measures) of the main thermal process. A considerable potential for development is present in the areas of grate and post-combustion in order, for example, to

- reduce the flue gas flow (flue gas purification plants, emission loads);
- improve the energy utilization;
- influence the characteristics of the residual material.

Considerable progress has been made in development with regard to the 'classical' processes with grate systems. The optimization of the design for the combustion chamber [27, 56, 77, 100], flue gas recirculation [83, 89], enrichment of the primary air with oxygen [51], water-cooled grate elements [56], further development of the control (e.g. IR-camera, [67, 81]), etc. should be noted as examples.

In addition, new, altered process controls with grate systems, such as e.g. the gasification with air on the grate, and the connected independent post-combustion of the gases produced are being tested on the pilot plant scale for future developments [17] and, recently, also on small industrial scale [8]. The desired improvements toward the above-mentioned objectives are then even more pronounced.

In the following section, general points of the process control in grate systems will be illustrated briefly. Then examples of process control practically implemented in plants and results of experiments in industrial and pilot plants as well as on the laboratory-scale will be discussed.

3.3.2 Process Control in Grate Systems

The efficiency of the thermal process for the treatment of waste is primarily determined by the process control of the main thermal process. The possibilities available for the reduction of pollutants and flue gas flows through primary measures must be exploited. The expenditure necessary in the range of secondary measures, e.g. the flue gas purification, is then adjusted accordingly. Classical waste combustion can, as mentioned at the beginning, be divided into two units. Combustion on the grate takes place in the first unit. Then, the gases and flue dust arising from the grate are combusted in the post-combustion chamber in the second unit.

When discussing the partial steps of the solid conversion and the combustion of the gases generated, the main influencing parameters mentioned in Figure 3.12 (e.g. [87]) must be considered. This is of particular value when regarding the individual reaction mechanisms (e.g. formation and degradation of pollutants). The various control possibilities along the reaction pathway are of particular importance for the optimization of the process.

Solid Conversion in Grate Systems

The solid conversion on a grate can, more or less, be divided into the following partial processes in the direction of the reaction pathway (Fig. 3.13): drying, degassing, gasification and residue burn-out.

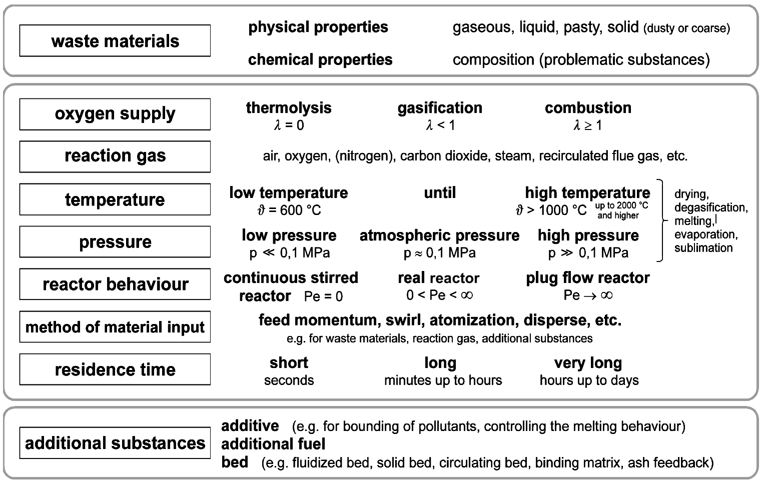

Fig. 3.12. Main influential parameters [87]

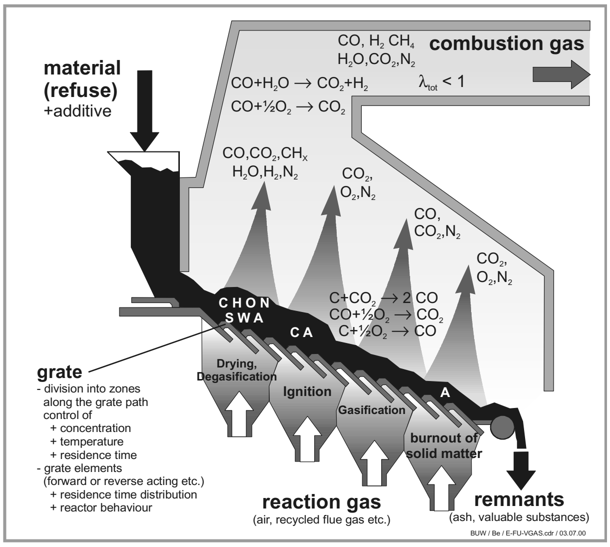

Fig. 3.13. Schematic representation of the solid conversion in grate systems during the combustion process. (CHONS: elements, W: water, A: ash).

Since the oxygen supplied to the grate (usually air) relative to the waste leads to over-stoichiometric conditions (e.g. $\lambda \approx 1.3$), it is termed “combustion on the grate.”

In order to be able to discuss process-engineering options, the most influential parameters and their distribution along the reaction pathway must be considered. There are many different options for the control of the main parameters in grate systems that can selectively influence individual partial processes along the reaction pathway (Table 3.12). These control options are particularly advantageous when dealing with variations in the reaction behavior due to fluctuations in waste composition. The following representations of process-engineering options are also depicted in the overview Table 3.12 and the flowchart in Fig. 3.14.[1]

Quench reactions at the surface of the wall should be avoided by maintaining high wall temperatures using the following:

Suitable refractory lining should be guaranteed for both units (grate and post-combustion). This also means that the heat transfer must be carried out separately from the solid conversion and the post-combustion as far as possible, i.e. combustion and heat decoupling are to be connected in series as shown in Figure 3.14.

The two partial steps, solid conversion on the grate and post-combustion process, can be optimized more easily, the more decoupled they are. In order to achieve this, either a geometric separation is possible, or, as will be explained in connection with the post-combustion process, a fluid dynamic decoupling.

The division of the grate area into several grate zones, which are separate from one another with respect to the reaction gas supply must also be taken into consideration when evaluating the control options of grate systems. This makes it possible to control the amount of oxygen available and the temperature in the bed along the reaction pathway through variation of the supply of reaction gas so that the individual steps can be matched to suit the characteristics of the starting material, even with fluctuating composition.

An additional leeway with regard to distribution of oxygen and temperature is achieved when inert gas, recycled flue gas or additional oxygen is fed instead of air. A preheating of the reaction gas can also be considered for waste materials with low heating values.

By the variation in distribution, the oxygen content and the temperature of the reaction gas, the burn-out of residues from waste with varying heating values and mass flows in particular can be optimized.

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[1] In this case, the main focus is on the process control for solid input material in grate systems. When considering the process control possibilities, the incineration of gaseous, liquid and dust-like feed material must first be discussed since generally only one unit is necessary for these. Then, using this information as a basis, one can shift to the process control for lumpy and pasty materials which generally require two units. Since the systematic representation would take up too much space, the procedure and references are mentioned here (e.g. Scholz und Beckmann [83, 87, 88]).

Table 3.12. Characterization of grate systems [85]. Process engineering options

Starting materials	
	Lumpy, also pasty when in connection with a solid or inert bed
Amount of oxygen available	
Level	Usually overstoichiometric (combustion), understoichiometric (gasification) possible; making independent post-combustion possible; oxygen exclusion (pyrolysis) not customary
Control along the reaction pathway	Very well adjustable (e.g. air/oxygen gradation, flue gas recirculation, etc.) when separated into individual zones; the partial steps of drying, degassing, burn out of the solid can be influenced in connection with temperature control
Temperature	
Level	Bed surface temperatures of up to ca. 1000 °C and higher; average bed temperature lower
Control along the reaction pathway	Very good possibilities through separation into several zones as with the control of the oxygen concentration (preheating of the air, flue gas recirculation, water/vapor cooling)
Pressure	At standard pressure, generally only a few Pascals underpressure due to the plant construction
Reactor behavior	
Solid	According to the movement of the grate elements, the individual zones can approach continuously stirred reactor characteristics (e.g. reverse-acting grate), or a plug flow reactor characteristic (e.g. traveling grate); over the entire reactor length, a plug flow reactor characteristic results
Gas	a) Oxidizing agent etc. is forced to flow through the bed and is distributed evenly over the bed surface, resulting in very good contact between gas and solid b) Flow control over the bed is possible as counter and parallel flow, gas treatment in the following process step is necessary (e.g. post-combustion)
Residence time	
Level (average residence time)	In the range of several minutes to hours; adjustable through grate speed and mass flow and can be influenced in the project design through total length and width
Control along the reaction pathway	Very good adaptation possible through separate speed regulation of the grate elements in the individual zones; control through discharge roller if necessary for additional improvement of the burn out at the end of the grate
Additives	Additives for the binding of pollutants into the solids and influence of the characteristics of the residue (ash, partly fused ash, slag); inert bed e.g. matrix for possible easily melted substances (e.g. plastic)
Functional range (examples)	
	For the solid conversion in the first step in municipal solid waste combustion plants; separation of metals from the composite at low temperatures and simultaneous understoichiometric conditions

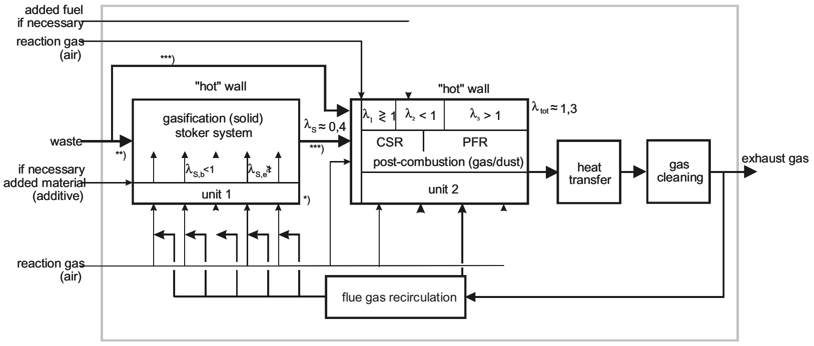


Fig. 3.14. Schematic representation of the separated process control; combustion/gasification-post-combustion process with grate and combustion chamber system [83, 88]

The gas flow over the bed can be controlled by applying parallel, center or counter flow. In parallel flow, post-combustion of the gases emitted from the beginning of the grate occurs first. In the counter flow, the hot gases from the end of the grate convey heat to the drying and degassing zone at the beginning of the grate. The post-combustion of the gases can be optimized independent of the application of parallel or counter flow regimes if separated process control of the grate (1^{st} unit) and the post-combustion process (2^{nd} unit) is available. This makes it possible to implement primary measures for the reduction of NO_X and at the same time to optimize the burn-out. Similarly, the temperatures in the drying and degassing stages do not depend on the flow control. The heat transfer rates can be influenced by the so-called secondary heating surface effect, i.e. by radiation exchange between the surrounding refractory-lined hot walls and the surface of the material.

An additional degree of freedom in the optimization of combustion is obtained by the individual movement of the grate elements in the different zones. This means, on the one hand, an increased construction expenditure, but on the other hand, the residence time and bed height can be controlled independently in the individual reaction zones.

By additional water-cooling of the grate elements, the reaction gas distribution, oxygen concentration and temperature can be varied over a wider range. Using the above-mentioned measures, the excess-air coefficient, the flue gas and flue dust flows can be reduced. The temperature in the burn-out stage can be increased to the point that ash sintering occurs, which leads to a marked improvement of the elution behavior of the residues [94, 105]. Furthermore, the water-cooled grate results in a lower risk of thermal damage for waste materials with high heating values, and reduced ash sifting through the grate (low thermal expansion permits little clearance between the grate elements).

The control of the combustion process on the grate using an infrared (IR) camera for the detection of the temperature at the bed surface has been mentioned. The position of the main reaction zone can be identified and controlled by redistributing the primary air. Through selective change of the primary air (reaction gas input), a fast adjustment to fluctuations in the waste composition, an avoidance of gas blow-through and streaming, an improvement in the residue burn-out and the avoidance of emission peaks can be expected.

Post-Combustion Process

The main parameters controlling the post-combustion process (Fig. 3.12) can be discussed in the same manner as for the solid conversion process. An overview is shown in Table 3.13.

The residence time is an important parameter in connection with the formation and decomposition of pollutants. In chemical engineering one differentiates between two limiting cases with respect to the residence time behavior: the ideal continuously stirred reactor (CSR) and the plug flow reactor (PFR) [58]. Figure 3.15 shows the decomposition of CO as a function of the residence time for these two reactor types, together with a real reactor. It can be seen that the PFR exhibits the best characteristics for CO oxidation. In the post-combustion process, a CSR must be connected to ensure mixing of the gas before entering the PFR (Fig. 3.14, second unit, first stage).

Mechanical structures generally cannot be applied for mixing due to high temperature, corrosion, etc. Two fluid dynamic stirring mechanisms can be used:

- so-called supercritical swirl flow with linear recirculation or recirculation of hot gases [25, 57] for plants with low capacity or
- single or multiple jets arranged above or next to each other which act as injectors to draw in and mix the surrounding gas [83, 84].

The installation of an intense mixing zone (CSR element) at the entrance of the post-combustion leads to the above-mentioned hydraulic separation as represented in Figure 3.14. A relaxation zone (PFR as suitable reactor type for complete oxidation) is situated above the mixing zone.

High intensity in the mixing zone must be achieved in order to guarantee optimum burn-out (CO, hydrocarbons, dust). Plants with greater capacities are generally equipped with injector jets.

The amount of oxygen available along the reaction pathway can be controlled by air staging, fuel staging, flue gas recirculation, oxygen supply, etc.

Sufficient options are available to optimize the process control with respect to the mechanisms of formation and decomposition of pollutants. At this point it should be noted that extensive experience and knowledge exists for the reduction of NOx and the improvement of the burn-out of gaseous, liquid and powdery fuels. This experience should be transferred to the post-combustion.

Table 3.13. Schematic representation of the separated process control; combustion/ gasification-post-combustion process with grate and combustion chamber system [85]

Starting materials	
	Gaseous, liquid, dust-like
Amount of oxygen available	
Level	Overstoichiometric to understoichiometric; variable over wide ranges; if overstoichiometric at reactor discharge: called “combustion chamber”; if understoichiometric at the end: called “gasification reactor”
Control along the reaction pathway	Very good through gradation of oxidizing agent and fuel along the reaction pathway (introduced over stirred reactor elements)
Temperature	
Level	Different combustion temperatures in the range from 1000 °C to 2000 °C or more; range is very variable
Control along the reaction pathway	In addition to the staging of oxidizing agent and fuel along the reaction pathway, intervention by flue gas recirculation, spraying of water etc. possible; indirect heat coupling and decoupling through corresponding heating or cooling systems; many possibilities
Pressure	At standard pressure, generally only a few Pascals underpressure due to the plant construction; high-pressure combustion rare; pressure gasification more common
Reactor behavior	
Dust/gas	Hydraulically, stirred reactor as well as plug flow characteristics can be approached for dust and gas
Residence time	
Level (average residence time)	In the range of seconds (longer at higher pressure); adjustable through load conditions and can be influenced in the project design through geometric dimensions
Control along the reaction pathway	Very difficult; residence time distribution can be controlled over the reactor behavior
Additives	
	Additives, in particular, introduced over the stirred reactor elements, in order to bind pollutants (e.g. sulfur dioxide, nitroxides) as well as to influence the slag characteristics and melting points of the dust
Functional range (examples)	
	Combustion of liquid residues; post-combustion of gas and dusts in the second step of the thermal treatment process; high temperature gasification of residues for the production of process gas (low and high temperatures); certain combustion processes (e.g. recirculation of chlorine as hydrochloric acid in the production cycle etc.)

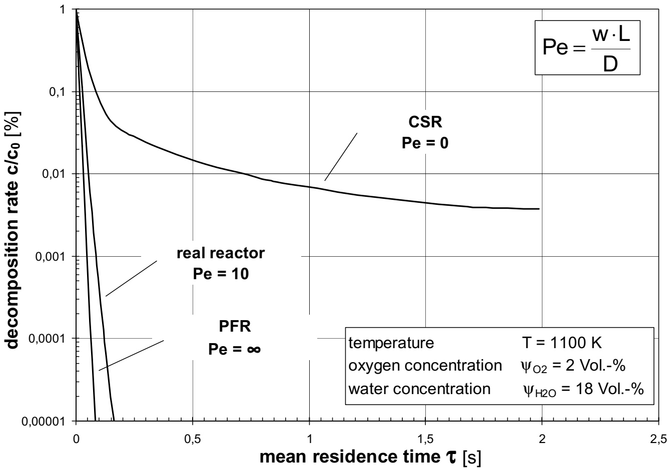


Fig. 3.15. Dependence of the CO decomposition on the average residence time and the mixing conditions in the reactor [32, 87]

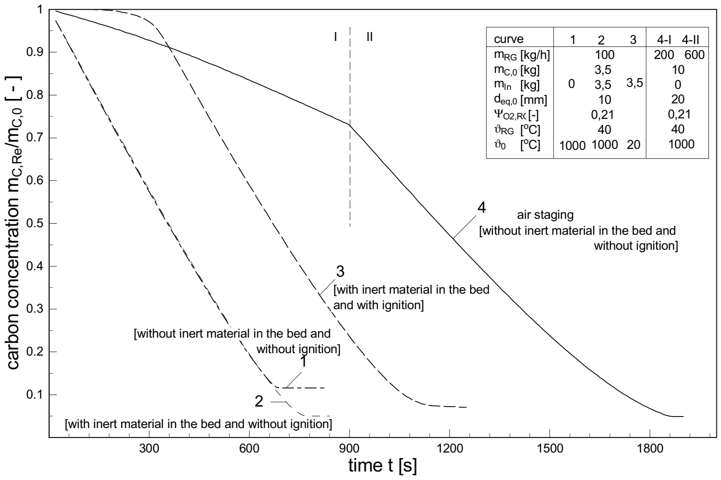
3.3.3 Examples and Results

The following discussion of the effect of given process controls is important to the understanding of the processes taking place during waste incineration. However, no estimation of the total concept of the plant can be derived from the evaluation of the individual aspects.

Solid Conversion on the Grate

The main goals of the solid conversion on the grate are the achievement of high ash burn-out (low residual carbon content) and a low concentration of heavy metals and salts.

These objectives are influenced, aside from by the composition of the waste, mainly by temperature, oxygen concentration and residence time as well as reactor type with respect to residence time. A distribution of 'ignition cores' [67, 68] and stabilization of the temperature in the bed is achieved by intensive mixing using the reverse-acting grate system. Due to the early ignition of the bed in reverse-acting grate systems, the addition of primary air generally already reaches its maximum in the second primary air zone. The maximal temperature in the bed is also reached in this section. Reverse-acting grates can be approximated in the individual sections as CSR elements [12] [13]. A forward-acting grate system can be considered as a PFR element. The input of the primary air into the drying and ignition phase must be regulated carefully in order to avoid a break in the ignition front. The main air is generally added in the middle of the grate. The primary air



curve	1	2	3	4-I	4-II
m_{RG} [kg/h]		100		200	600
$m_{C,0}$ [kg]		3,5		10	
m_{In} [kg]	0	3,5	3,5	0	
$d_{eq,0}$ [mm]		10		20	
$\Psi_{O2,RG}$ [-]		0,21		0,21	
ϑ_{RG} [°C]		40		40	
ϑ_0 [°C]	1000	1000	20	1000	

Fig. 3.16. Calculated carbon concentration vs. time for a given bed [11]

in the burn-out zone must be adjusted carefully for high burn-out. A too high primary airflow in the burn-out zone can lead to a ‘blow cold’ (extinguish) of the bed and a corresponding high carbon content in the ash. The inert material acts as a heat reservoir which takes up heat at high temperatures in the main combustion zone. Due to this heat reservoir, the risk of ‘blow cold’ in the burn-out zone is reduced. This positive influence of the inert material should be considered in discussing pre-treatment of MSW before incineration, such as mechanical-biological processing: Reducing the amount of thermal mass in the bed might be contra-productive.

The influence of air staging and of inert material on the burn-out can be clearly shown by calculations using mathematical models for the solid conversion [11]. The calculated normalized carbon content in the bed over time for various boundary conditions is shown in Figure 3.16. A comparison of curves 1 and 2 in Figure 3.16 clearly shows the influence of the inert material as described above. A significantly better carbon conversion is achieved with inert material than without. Curve 4 shows the influence of air staging for a fuel without inert material in which the residual carbon content is as low as that of case 2 (no air staging).

To ensure an even distribution of primary air, the pressure loss in the grate element must be much higher than that in the waste bed, independent of the type of grate.

For forward-acting grate systems, a control of the independent grate speeds in several grate zones is generally possible. However, for reverse-acting grate systems, such a differentiated control of the residence time is not carried out. A so-called discharge drum for the additional control of the residence time in the burn-out zone is used more often in reverse-acting than forward-acting grates [68].

The course of combustion is influenced, in addition to by the distribution of the primary air, by the temperature and oxygen concentration of the primary air (reaction gas). The primary air is generally preheated to temperatures of $\vartheta = 140$ °C, which is particularly advantageous for the drying and burn-out phase. Higher bed temperatures are also reached in the main combustion zone by preheating the air. An increase in the oxygen concentration of up to 35 vol.-% in the reaction gas has been carried out in e.g. the "SYNCOM Process" [51]. This guarantees good burn-out [2] and causes a reduction in the flue gas flow (see below). In addition, the reduced gas flow through the bed leads to decreased entrainment of dust particles.

The temperature of the bed is influenced by the gas flow regime applied. The temperature in the drying and burn-out phases is influenced by the design of the combustion chamber geometry (secondary radiation surface). This so-called secondary heating surface is more important in the burn-out zone of a counter-flow combustion than a parallel-flow combustion.

The advantages of using water-cooled grate elements have been discussed above. In addition they can result in further improvements with respect to the ash quality (increase in temperature and reduction of the oxygen concentration), as pilot plant experiments have shown [22, 37, 105]).

The primary air supply, grate speed, waste feed, etc. are controlled in order to ensure an even course of combustion and highest possible burn-out [100]. This firing power control can be supported by appropriate temperature detectors increasingly including methods such as e.g. IR cameras [67], pyro-detectors [81], 'heating value sensors' [103].

Whereas process control for a good burn-out is state-of-the-art in the practice, the optimization of the process parameters with respect to the selective release or immobilization of heavy metals in the ash (primary measures for the improvement of the ash quality) is still a current research topic. Approximately 300 $\text{kg/Mg}_{\text{waste}}$ grate ash remain after waste combustion, from which ca. 40 $\text{kg/Mg}_{\text{waste}}$ scrap iron can be separated. Currently, ca. 3 million Mg/a grate ash accumulate in Germany, of which ca. 50 % to 60 % are used as secondary building material in road construction and the rest is deposited in landfills [104]. The aim of future developments must be the improvement of the ash quality by primary measures in order to make a high-grade utilization possible.

Depending on the combustion conditions, heavy metals, chlorine, sulfur and fluorine, etc. are released from the fuel bed and bound by the ash.

Investigations in a pilot plant using various waste compositions have shown that the evaporation of heavy metals (e.g. Cu, Zn and Pb) correlates to the bed temperature and chlorine content (Fig. 3.17, Fig. 3.18; MW = municipal solid waste, reference fuel; CSR = car shredder residue - light-weight fraction; ES = plastic scrap from electronics; PVC = polyvenil chloride) [105].

An additional parameter governing evaporation is the oxygen partial pressure. Results from experiments with radioactive tracers (^{69m}Zn) in a pilot plant [22] clearly show the differing behavior for the release of zinc under reducing and oxidizing conditions. The measured zinc evaporation for three different operation conditions is shown in Figure 3.19. The two parameters which were varied on the grate were the oxygen partial pressure and temperature. The redox conditions of

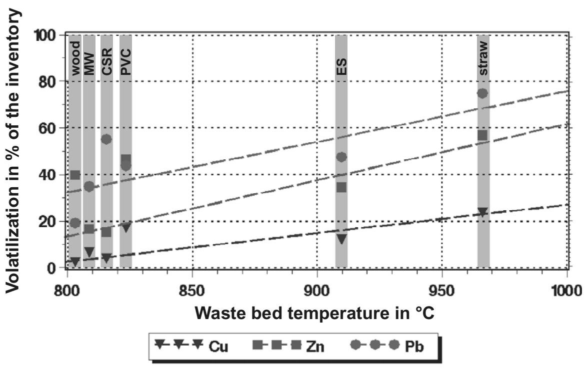


Fig. 3.17. Relationship between volatilization and waste bed temperature [105]

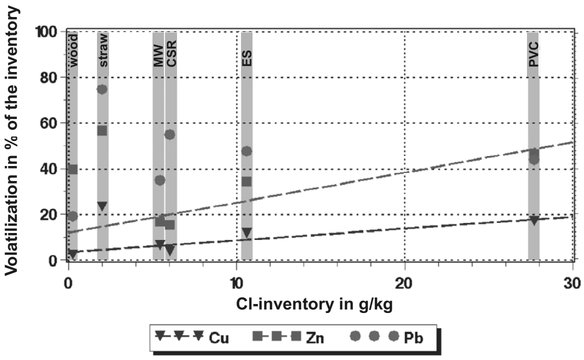


Fig. 3.18. Relationship between volatilization and chlorine (Cl) inventory (abrev. see text) [105]

the incineration process were changed from combustion to gasification operation by decreasing the flow rate of primary air to one third. It must however be noted that even in the so-called combustion operation mode, reducing conditions dominate in the solid bed in the first primary air zone. The temperature variation was achieved by adjusting the water content in the waste material. Figure 3.19 reveals that the trend of zinc evaporation is independent of the operating conditions and the amount of evaporated zinc. The evaporation takes place very fast, i.e. in a narrow area on the grate. However the location at which the evaporation takes place on the grate depends on the operating conditions. Complete evaporation occurred at locations with sufficiently high temperatures and with reducing conditions. For the experiment in which only 50 % evaporation of the radio tracer was observed (wet, oxidizing), the location of evaporation was shifted further down the grate. This was due to a delay in reaching the necessary temperature.

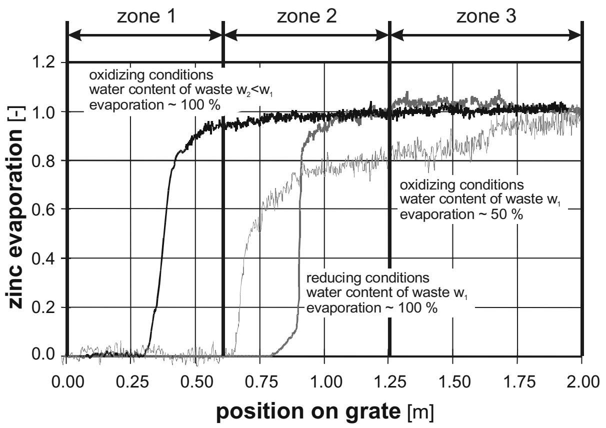


Fig. 3.19. Normalized Zn amount detected in flue gas scrubber after the pulsed addition of Zn tracer at position 0. Accumulation is monitored while tracer is transported along the grate (0.0 m to 2.0 m). oxi.: oxidizing conditions; red.: reducing conditions (gasification); w: water content of waste; evaporation: % of tracer transferred to flue gas [22]

The shift in the temperature profile brings the evaporation zone for zinc into the region where oxidizing conditions prevail (air zone 2). Increasing amounts of zinc oxide were produced which were not volatile and, therefore, complete zinc evaporation was not possible. The hypothesis that a thermal mobilization of heavy metals at high temperatures is supported by the reducing effect of the hot carbon in the fuel bed is referred to in [105].

It should also be mentioned that a marked decrease in the extractability of pollutants from ash can be achieved by sintering, and that the transition from sintering to melting achieves only relatively small further improvements [105].

Post-Combustion

As outlined in the previous section, the main objective of the post-combustion process is primarily the degradation of CO and organic trace elements as well as the burn-out of fly dust (a total high burn-out). The minimization of NO_X by primary measures is also being investigated for practical implementation and is state-of-the-art in burners for gaseous, liquid and powdery fuels [49, 65, 109, 110, 111].

The most influential parameters in the achievement of this objective are temperature, oxygen concentration, residence time and residence time behavior. These parameters are determined by a series of individual aspects of the process control and not only by the flow form, which is often discussed in connection with an initial post-combustion of the gases (e.g. parallel flow) or with the minimization of NO_X in the combustion chamber above the bed.

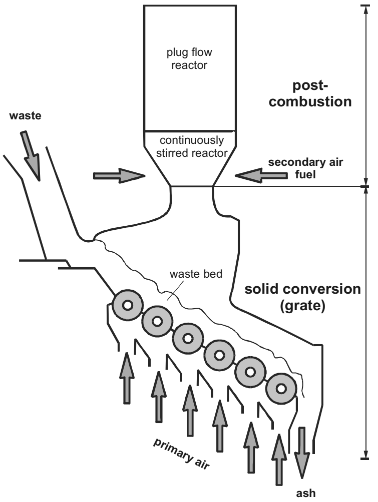


Fig. 3.20. Schematic representation of the grate and post-combustion zone [86]

The separation of the post-combustion from the grate as shown in Figure 3.12 is discussed in more detail in [87]. The separation does not have to be geometric; it can also ensue by fluid dynamic means. A fluid-dynamic separation (Fig. 3.20 and 3.21) can also be very effective when, for example, a good overlap of the cross-section, adequate suction of the residual stream to be mixed and sufficient penetrating depth of the injector jets are achieved. Optimization of these injectors generally leads to fields of jets. The positioning of the injection along a narrowed cross-section in the post-combustion zone assists the mixing (Fig. 3.21 and 3.22). This fluid-dynamic separation also leads to the formation of the important CSR element. The settling section is then located above the fields of jets (Fig. 3.21 and 3.22) (PFR zone).

The average velocity w_x of an injector stream which penetrates the combustion chamber above the secondary air jets with a speed of w_0 decreases hyperbolically with the penetration depth of the stream x. In the combustion chamber, the stream is diverted in the direction of the up-streaming gas y. The flow rate ratio of the up-streaming gases w_y to the exit velocity of the stream at the jet w_0 is proportional to the square of the penetration depth x^2. Achieving high-quality mixing in plants with large cross-sections is a problem that can be solved by the installation of a so-called prism in the combustion chamber (Fig. 3.22). In this system, first installed in the MSW-Incineration plant in Bonn, the flue gas from the grate is divided into two partial flows “A” and “B” by a membrane-wall construction in the shape of a prism. The prism is water-cooled and protected with refractory materials. Secondary air is injected into the divided flue gas streams “A” and “B” as indicated in Figure 3.22, reducing the necessary jet length correspondingly. By the installation of the prism, a much shorter and more clearly defined burn-out of the flue gases just above the prism could be achieved [77].

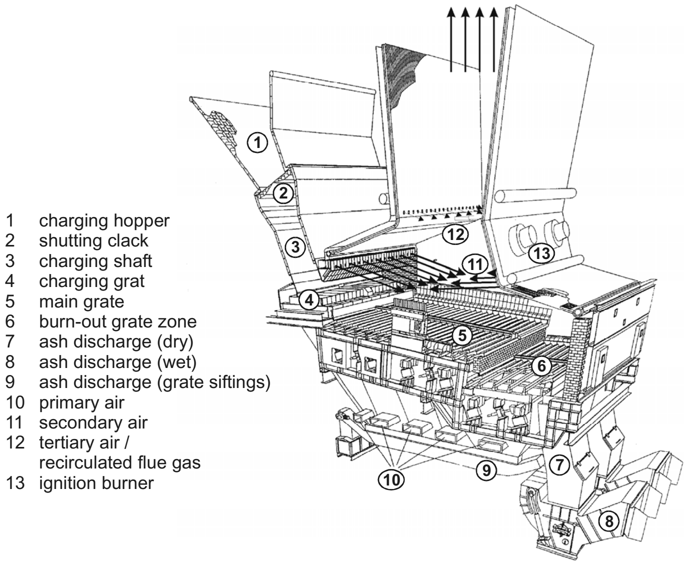


Fig. 3.21. Schematic representation of the forward acting grate and separated post-combustion zone [56]

The injection of secondary air should be minimized as much as possible. The substitution of secondary air by recirculated flue gas reduces the total flue gas mass flow at the chimney, and at the same time prevents temperature peaks in the post-combustion zone if the injector jets are positioned properly.

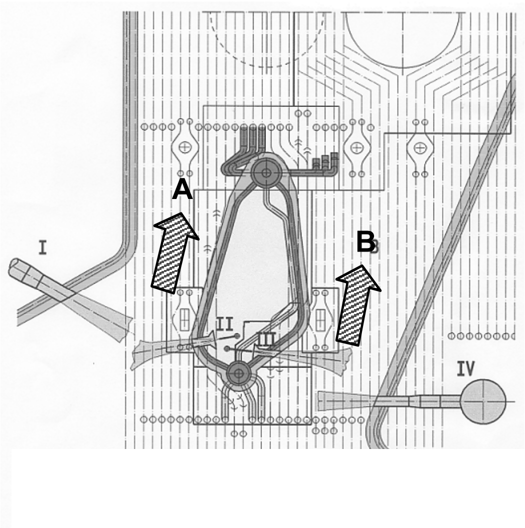


Fig. 3.22. Cross-section prism [77]

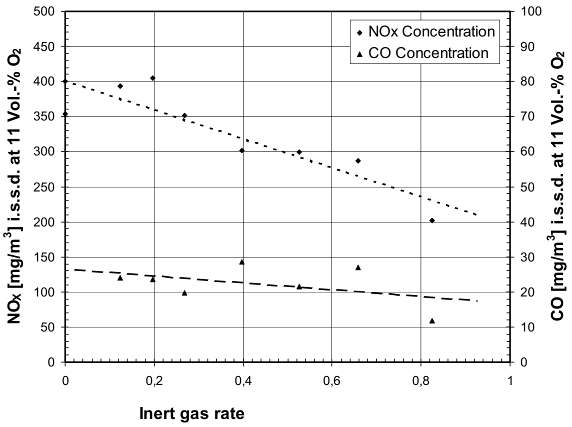


Fig. 3.23. NO_X and CO gas concentration dependent upon the inert gas rate [89]

This leads to a decreased formation of thermal NO_X. The influence of the flue gas recirculation in the post-combustion process of a waste combustion plant is shown in Figure 3.23 [89]. In these investigations, the flue gas recirculation was simulated by adding nitrogen. The mixing of the flue gas originating at the grate was carried out at a high inert gas ratio with injector jets. Overall, a decrease in the NO_X concentration was achieved. The constant low CO concentration, with regard to the inert gas ratio, shows that the CO conversion does not depend on the oxygen available in this case.

A different separation between grate and post-combustion is shown in Figure 3.24. Here, the stirred reactor element for the post-combustion of the gases emitted from the grate is situated above the first half of a drum grate. The post-combustion zone now only consists of the „calmed burn-out zone“ (PFR zone).

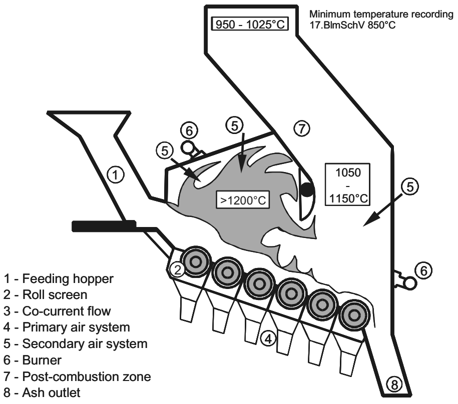


Fig. 3.24. Drum grate with ‘Feuerwalze’ [27]

The European Combustion Guidelines, based on the 17th BImSchV, set process-internal requirements for minimum values of the oxygen concentration, temperature and residence time (6 vol.-% O_2, 850 °C, 2 s), with the objective of guaranteeing a sufficient burn-out. This requirement forces the operator to increase the temperature in the combustion chamber by e.g. reducing the primary excess air coefficient. This intensification of the combustion requirements in connection with the increased heating values of the waste in recent years has lead to higher thermal load, more corrosion and therefore to reduced availability of the plant [75].

The most influential parameters of oxygen concentration, temperature, residence time and reactor behavior (mixing) cannot be discussed individually, especially with respect to complete oxidation of CO and organic trace elements. This was illustrated in a practical plant (MHKW Mannheim) within the framework of a research project [71]. Five experiments were carried out in the waste reactor 2 of the MHKW Mannheim in which the parameter's combustion air and amount of waste were varied in order to influence the oxygen concentration, temperature and residence time. The experimental settings were accompanied by an extensive measurement, sampling and analysis program for the flue gas flow (gas and dust) and the grate ash. The residence time range for the flue gas during the experiments at temperatures above 850 °C was between $\tau_{850} = 0.7$ s and 2.27 s. An important result of the experiments (Fig. 3.25) was the discovery that there is no direct connection between the pollutant concentration in the flue gas and the residence time in the post-combustion chamber. The experimental settings V5 (total load) and V2 (partial load) result in almost identical requirements concerning heating value, fire position, combustion chamber temperature and flue gas composition. They differ, however, with respect to the flue gas flow rates and the residence times in the post-combustion process. A shorter residence time in experiment V5, with better mixing, yields concentrations of CO, $C_{organic}$, and PCDD/F almost identical to those of the V2 experiment. The results from the practical plant support those from investigations carried out in the pilot plant [14, 15, 72].

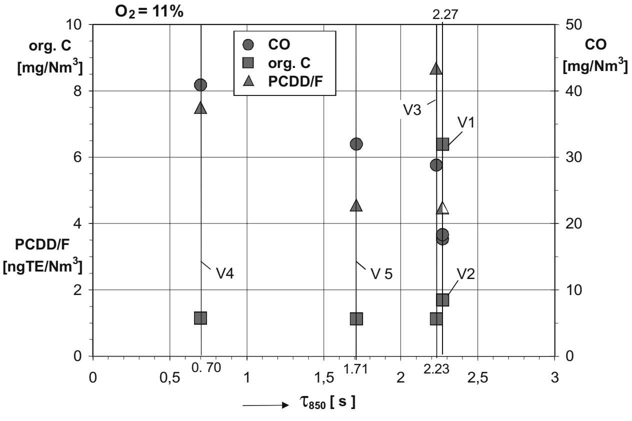


Fig. 3.25. PIC concentrations (CO, organic C, PCDD/F) of the flue gas as a function of the residence t ime of the flue gas τ_{850} above 850 °C (V1..V5: experiment number) [71].

In classical waste combustion, appropriate measures for the primary reduction of NO_X are still being investigated [90]. These measures however are far more related to reactions in the bed and directly over the bed than those applied for the oxidation of CO and organic trace elements. At the beginning of the grate, volatile nitrogen compounds (NH_i, $N_{org.}$), which can be converted to NO_X if sufficient oxygen is available, escape from the fuel bed. The conversion of NH_i radicals to HCN proceeds with increasing release of volatile organic components and the formation of CH_4 in particular. These reaction pathways are well known from batch grate and other experiments [95] and support the assumption that NO_X can be degraded to N_2 in the presence of NH_i. However, a temperature is required in the grate combustion chamber for this so-called internal "Exxon Process" which is higher than that for the classical SNCR process. In order to suppress the reaction of NH_i radicals with CH_4 leading to HCN, temperatures above 1000 °C are necessary. It can be concluded that the temperature of the gas in zone I is a highly influential parameter with respect to the release of volatile compounds and the degradation of CH_4 at the beginning of the grate. In addition, the oxygen supply or excess-air ratio λ in this zone has an increasing influence on the optimal NO_X /NH_i ratio in the first grate zone.

The effects of the most influential parameters, temperature and λ, described above were confirmed by tests in a pilot plant.

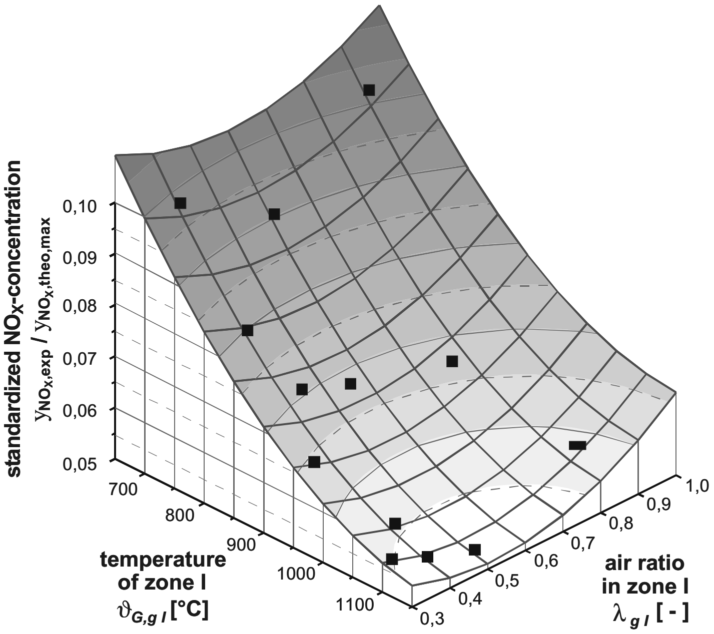


Fig. 3.26. Dependence of the NO_X concentration on the gas temperature in the ignition zone of the grate ($\vartheta_{G,gI}$) and the excess-air coefficient in this zone (λ_{gI}) during the combustion on the grate [16]

The results are shown in Figure 3.26. As expected, the NO_X values decrease with increasing temperature $\vartheta_{G,gI}$. In addition, local minima in the range of $0.4 < \lambda_{gI} < 0.6$ occur as a result of constant temperatures. Reference points supporting these results can be derived from investigations in connection with the NO_X reduction in a fixed bed gasifier with separate post-combustion [48].

As shown above, an independent optimization of the NO_X reduction, in addition to the optimization of the solid conversion, together with other advantages, is achieved when the process control of the post-combustion is clearly separated from that of the grate. Another degree of freedom for an independent post-combustion occurs as a result of the gasification on the grate.

Gasification - Post-Combustion Process

In the separated process control, as shown in Figure 3.12, the solid conversion on the grate (1st unit) can be operated under-stoichiometrically (e.g. $\lambda \approx 0.4$). Due to to the above-mentioned control options of grate systems, a complete burn-out of the grate residue (ash) can also be achieved in this mode of operation. The difference between this and the classical incineration process is the generation of a gas which can be combusted independently in the post-combustion process in the second unit. The second unit can therefore be designed as an independent gas-firing unit. This gasification-post-combustion concept, currently examined on a test-size scale, appears to be promising, as, in comparison to the conventional incineration processing in grate systems,

- the flue gas mass flows are significantly reduced (Fig. 3.27);
- combustible gases which enable an independent post-combustion process are generated;
- the post-combustion process itself can be optimized, regardless of the process on the grate, with the help of familiar primary measures for reducing the NO_X-emissions and at the same time achieving high burn-out results;
- emission loads can be reduced considerably.

These aspects are explained here in detail, with reference to first results at a pilot plant. It should be mentioned, that an industrial scale plant with a thermal power of 15 MW was also commissioned at the beginning of 2002 [8]. Initial considerations for the optimization of the process began over ten years ago [82] and the results achieved in a pilot plant in the mid 1990s [11, 17] have been confirmed by results of the recently commissioned industrial plants.

The diagram in Figure 3.27 shows that for a separated process control with a stoichiometric ratio of $\lambda \approx 0.4$ to $\lambda \approx 0.6$ for solid conversion on the grate and $\lambda \approx 1.2$ to $\lambda \approx 1.8$ for the post-combustion, total stoichiometic ratios of $\lambda \approx 1.1$ to $\lambda \approx 1.4$ are the result. The total stoichiometric conditions achieved during the separated gasification-post-combustion process are significantly lower than those for the classical gasification-post-combustion operation ($\lambda \approx 1.6$ to $\lambda \approx 2.0$) resulting in a slower flow velocity in the fuel bed (dust discharge) and a reduction in the flue gas mass flow in comparison with the classical combustion process.

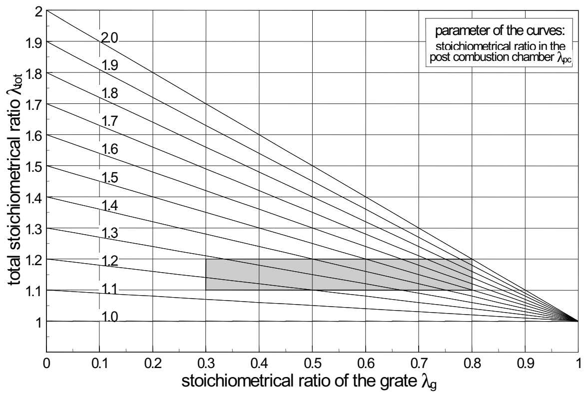


Fig. 3.27. Dependence of the total stoichiometrical ratio on stoichiometrical ratios of the grate and the post-combustion chamber [11]

The gas composition differs from calculated values [11]. The major combustible component is found to be carbon monoxide ($\psi_{CO} \approx 8..15$ vol.-%). The hydrogen content ($\psi_{H2} \approx 2..5$ vol.-%) is far below the calculated equilibrium concentration. This may be attributed to the fact that the water content in the combustible material evaporates at the beginning of the grate (Fig. 3.13).Thus, the heterogeneous water gas shift reaction between steam and the hot coke bed does not take place to the full expected extent. Furthermore, the equilibrium of the homogeneous shift reaction of CO and H_2O to form CO_2 and H_2 is not attained. Based on the assumption that the CO formation in the combustion bed of a grate essentially takes place via the heterogeneous gasification reaction of carbon with oxygen and, depending on the height of the bed, additionally via the so-called Boudouard reaction, a hot coke bed should result soon after the successful ignition of the combustible. Due to the decreasing carbon content along the length of the grate, less reaction air is required in the subsequent grate zones for gasification. This fact is confirmed by the results presented in Figure 3.29, obtained at a pilot reverse-acting grate (0.5 $MW_{thermal}$) [11, 17]. For evaluating the influence of air staging, three distinctly different air distribution settings (in each case with constant mass flows for both fuel and total air) have been tested. The main air supply is in zone 1 for the first setting and in zone 4 for the second. An even distribution over zones 1 to 4 is approached for the third setting. Figure 3.28 shows that the leveling off of hydrogen and methane concentrations ψ is more or less independent of the selected air staging settings. The wood used as a model fuel already ignites in the first stage of the grate. When shifting the main air supply from the beginning to the end of the grate, the CO concentration in the combustion gas is reduced. However, an increase in the grate bar velocity, which leads to a more intensive mixing and stoking of the combustion bed, causes an increase of the CO concentration in the example given (Fig. 3.28).

The distribution of air depends on the fuel or waste material gasified. Refuse-derived fuel (RDF) with a significant content of synthetic material requires careful degassing and ignition (Fig. 3.29). Supplying the main part majority of air at the beginning of the grate causes the degassing products to be burned immediately. This leads to high temperatures in the bed and consequently to a caking and fritting of the bed. An even flow through the bed is hindered. As with incineration, residual carbon contents of about 1% or less can be attained under gasification conditions. For example, results of combustion and gasification of wood from railway sleepers treated with coal tar are shown in Figure 3.30.

Marked differences between process conditions of the gasification and incineration mode with regard to the formation of flue dust are evident. The significantly lower mass flow of air resulting from the operation under gasification conditions causes the formation of less flue dust, as confirmed in Figure 3.30.

The gases generated by gasification in the grate process are fed to the postcombustion chamber. The net heating value is about $h_n \approx 1500$ kJ/kg to $h_n \approx 2500$ kJ/kg and temperatures reach levels of 750 °C to 1000 °C depending on the stoichiometric air ratio of the grate process. If the post-combustion chamber is well insulated, the post-combustion process runs independently, without additional fuel. Well-known primary measures for minimizing pollutants can then be applied (e.g. [49, 65, 109, 110, 111]). Consideration is given here to NO_X minimization with a simultaneous reduction of the CO concentration. First of all, the stoichiometric ratio of the gasification process affects the NO_X emission.

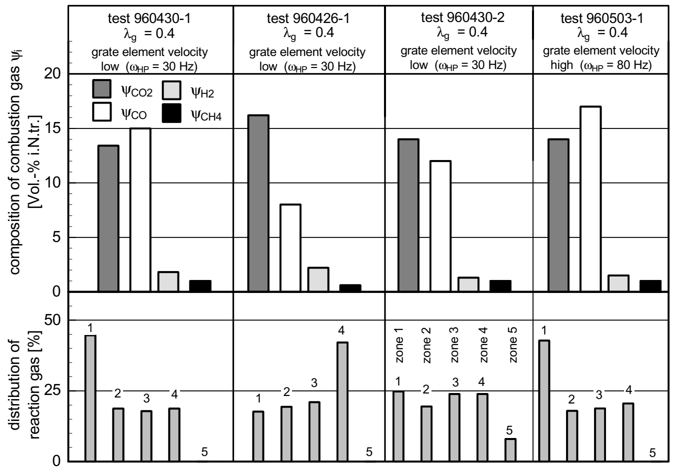


Fig. 3.28. Comparison of the composition of combustion gas with varying distribution of reaction gas along the grate path and grate element velocity (model fuel wood) [17]

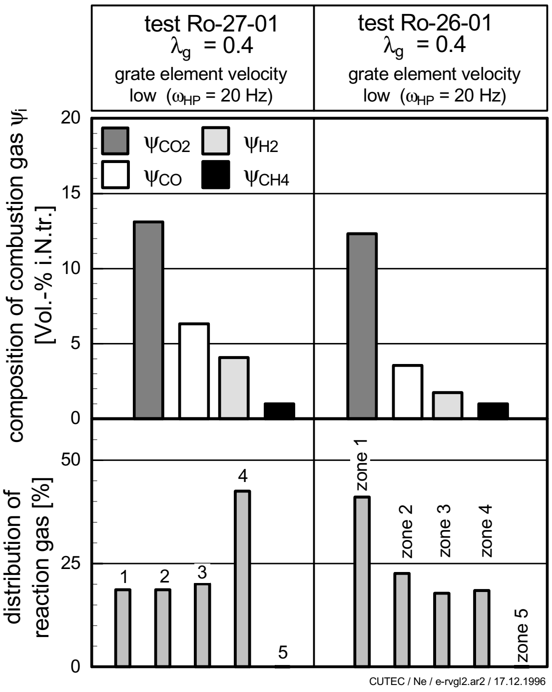


Fig. 3.29. Comparison of the composition of combustion gas with varying distribution of reaction gas along the grate path (refuse-derived fuel RDF, $\lambda_g = \lambda_{grate}$) [17].

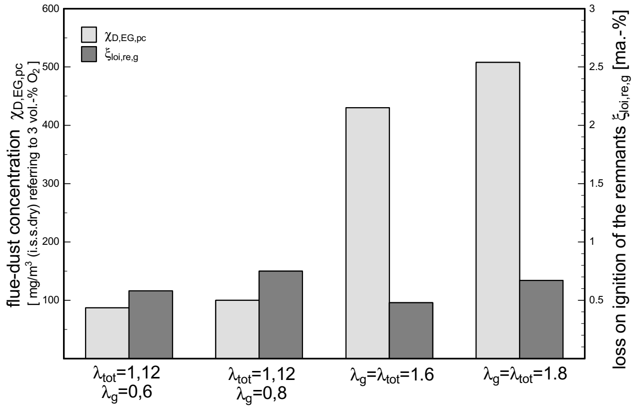


Fig. 3.30. Flue dust concentration before flue gas cleaning (χ) and loss of ignition (ξ) for different stoiciometric ratios in the stoker system ($\lambda_g = \lambda_{grate}$) [11]

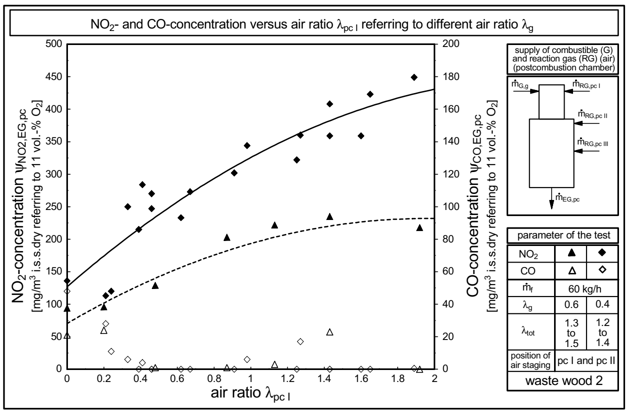


Fig. 3.31. NO_2 and CO concentration versus air ratio of the post combustion chamber $\lambda_{pc\ I}$ (different air ratio ($\lambda_g = \lambda_{grate}$) in the grate unit) [11]

Figure 3.31 shows the NO_2 and CO emissions of a staged combustion of the combustible gas generated at the grate for a primary air ratio of $\lambda_{grate} \approx 0.4$ and $\lambda_{grate} \approx 0.6$. For the higher primary air ratio, significantly lower NO_2 emissions are obtained. An increase in the primary air ratio is accompanied by a temperature increase from about 700 °C to about 1000 °C. Furthermore, there is an increase in the oxygen supply as a result. With these conditions, a better decomposition of volatile nitrogen components such as HCN and NH_i via NO, and a reduction of already formed NO via the "NO_X recycling" path is more probable. In addition to the influence of the primary air ratio, the NO_2 concentrations in Figure 3.31 show the typical course for the formation of NO_2 from the nitrogen contained in the fuel. The NO_2 concentrations decrease with a falling air ratio in the first stage of the combustion chamber whereby the total air ratio is kept constant at $\lambda_{tot} \approx 1.3$. For a primary air ratio of about $\lambda_{grate} \approx 0.4$, the NO_2 concentration drops from about 450 mg/m^3 for a single-staged post-combustion to 200 mg/m^3 for a double-staged post-combustion with $\lambda \approx 0.5$, whereby the CO concentration is far below 10 mg/m^3. In the same manner, the NO_X concentration can be reduced in the case of a primary air ratio of $\lambda_{grate} \approx 0.6$, from 200 mg/m^3 to about 120 mg/m^3. For a twofold-staged post-combustion, a further NO_X reduction below 100 mg/m^3 results when air is fed into the first and the third stage of the combustion chamber whereby the CO concentration remains below 10 mg/m^3 [12]. The further NO_X reduction here is due to the longer residence time in combination with higher temperatures and lower oxygen concentrations in the under-stoichiometric first stage. Furthermore, if air is fed to the third stage, plug-flow like conditions prevail in the under-stochiometric part after the enlargement of the post-combustion chamber, which is preferable for NO_X reduction steps [49].

3.4 Emissions from Incinerator Ash Landfills

Christian Ludwig and Jörg Wochele

3.4.1 Introduction

This section is a short introduction to the heavy metal problems associated with landfilling incineration residues. In the future, more ash residues from thermal MSW treatment will be produced. In Europe waste will be more extensively used for the production of heat and electricity (see section 5.1), and in many other countries incineration will replace common landfill practices because space is a limiting factor.

MSW incineration produces residues which contain toxic heavy metals. Landfills containing such residues are therefore potentially hazardous. However, compared to regular MSW landfills, these residues can be deposited in a much safer manner and under a higher level of control. The biological activities (see section 2.2) are much smaller due to the small amount of organic matter remaining in the residues after thermal treatment of MSW. The long-term behavior of such landfills is difficult to predict, although, relevant mechanisms determining leaching have been elucidated in the past.

The deposition of untreated filter ash is often not allowed; the upper concentration limits determined by legislation (this is generally a leaching test) can easily be exceeded. Therefore, filter ashes should be stabilized or stored in safe long-term deposits (or containments), which will never have contact with ground water (e.g. empty salt mines). Not all countries have such safe storage possibilities. Therefore, different stabilizing methods have been tested or put to practice which can substantially reduce the leachate concentrations for heavy metals, such as cementation of filter ash [23] or application of iron sulfate solutions [64]. Soluble phosphates were found to stabilize heavy metals in BA [28]. The goal of the treatment methods is to keep the concentrations below certain limits determined by the legislation. Taking the threshold value and the average discharge of a real site, the minimum durations can easily be estimated for the time it takes to totally wash out the heavy metals. Based on these calculations, it can be seen that such systems need to be under control for more than thousands of years. However, the concentrations will hopefully never exceed the limiting values.

3.4.2 Concentrations of Heavy Metals in Landfill Leachates

It must be emphasized that heavy metal concentrations in filter ashes are generally much higher than in bottom ashes (Table 2.5). It is therefore not surprising that the concentrations of heavy metals found in the leachates of filter ash landfills are higher than that of bottom ash landfills (Table 3.14).

Table 3.14. Comparison of concentrations found in the leachates of a filter ash and a bottom ash landfill. Filter ash data were obtained from a pilot landfill containing cemented filter ash, adapted from [63, 76]. Bottom ash values were adapted from [43, 45], experiments at landfill Lostorf, Switzerland. Please note that the values correspond to a given pH value/range. Threshold values of drinking water (Switzerland [5]) are given as a reference.

Heavy metal	Bottom ash [45]	Fresh filter Ash*1 [76]	Filter ash [a] after 5 a [76]	Drinking water Switzerland, limiting value
Cu [mg/l]	0.05	0.29	0.038	-
Pb [mg/l]	0.00031	5.39	0.083	0.01
Zn [mg/l]	0.002	7.85	0.98	-
Cr [mg/l]	-	4.68 [b]	0.52 [b]	0.05 [d]
Cd [mg/l]	0.0011	-	0.025 [c]	0.005
pH	9.7 - 11	ca. 12.5	ca 13.5.	-

[a] Cement-cubes of 0.5x 0.5 x 0.5 m

[b] Main fraction is Cr(VI)

[c] [60]

[d] Cr(VI)

Leachate concentrations in a landfill containing fresh ashes are higher than those found for old ones (Table 3.14). Still, leachate concentration can also change on a short term scale (days) due to rainfall (Fig. 3.32). Depending on the strength and amount of a rainfall, the concentrations in the leachate may be reduced by several factors [62, 63]. After a first washout period (a few years), concentrations approach threshold values for drinking water. Exceptions are possible, e.g. Zn (Table 3.15). However, the ashes pose a potential risk because pH may drop in the long run and the heavy metal concentration in the leachate will increase (Fig. 3.34).

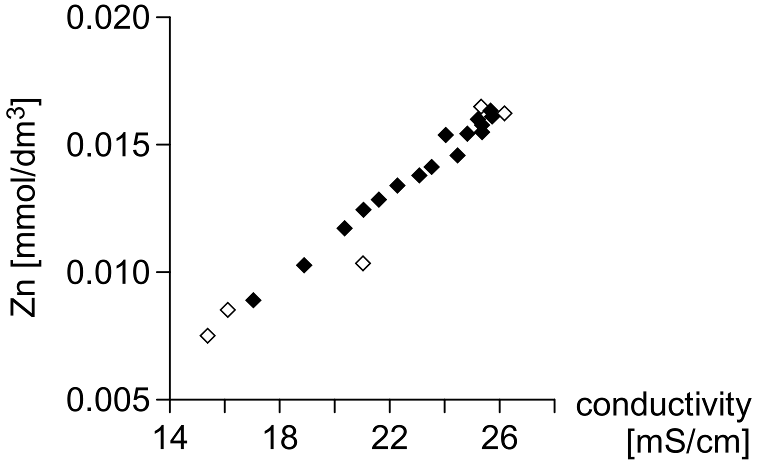


Fig. 3.32. Example of change in leachate concentration of a pilot landfill containing cemented filter ash due to a rain event. The symbols indicate the measurements before (◇) and after (◆) reaching the discharge maximum. The conductivity was used as a sum parameter which correlates well with the Zn, and with many other ion concentrations [63].

3.4.3 Long-Term Predictions

Solubility Controlled Leaching of Heavy Metals

According to well known sorption phenomena of heavy metals at mineral surfaces [97], changes in pH of less than one pH unit can sometimes lead to full desorption of a heavy metal. This example indicates the hazard potential if pH drops in the long run. The characteristic pH ranges for desorption varies from element to element. The main constituents, present mineral phases, and their physical properties will also change in the long run. Due to these changes, the leaching behavior of the heavy metals will also change. This suggests what difficulties one may encounter when making long-term predictions.

Huge R&D efforts have been made in recent decades to better understand the weathering and leaching processes. A review on the fundamental chemistry of dissolution and weathering can be found in [26]. A rough summary on the mechanisms relevant for leaching from landfills is given by [45, 47, 62, 63, 70]. Figure 3.33 gives an overview of the most relevant mechanisms.

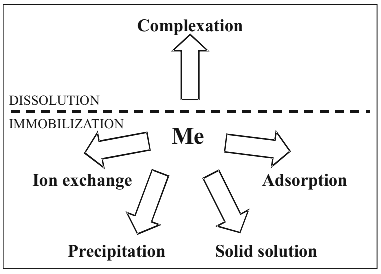


Fig. 3.33. Important effects and relevant mechanisms for the leaching of heavy metals from landfills containing ash residues from MSW incineration [adapted from 43].

Table 3.15. Saturation indices for heavy metal components. Metal hydroxides ($Me(OH)_2$, metal carbonates ($MeCO_3$), and calcium metal oxy-anions ($CaMeO_4$) are considered.

	log SI		
	CO_3	OH	Ca
Cu^{2+}	-4.31	1.91	
Pb^{2+}	-2.86	-3.94	
Cd^{2+}	0.33	-2.53	
Zn^{2+}	-5.19	-2.22	
Mn^{2+}	-3.34	-4.61	
MoO_4^{2-}			-0.18
WO_4^{2-}			-0.56
CrO_4^{2-}			-4.90

SI = $[Me]_{free}[\text{counter ion}]_{free} / K_{S0}$, where K_{S0} is the solubility constant. Experimental data cover a pH range of 9-11, bottom ash landfill Lostdorf, Switzerland [adapted from 63]

Based on [45] and [47], one can say that the mobility of heavy metals is primarily controlled by a combination of dissolution/precipitation, sorption and complexation reactions. The saturation index (SI) of a given metal with respect to a given solid phase can provide an indication of the potential role of the solid phase in controlling solubility [47] (Table 3.16). A strongly negative value signifies under-saturation and indicates that other solid phases or sorption reactions are important. Over-saturation, as found for Cu, is interpreted by the effect of organic ligands [47].

Leaching Tests

Generally, leaching tests cannot predict the leaching behavior of a landfill. Nevertheless, they can be useful for finding and assessing future leaching trends. The pH value is a highly influential factor which can change leaching concentrations by several orders of magnitudes. A decrease of pH values in a landfill is expected in the long run, and is related to its buffer capacity [43]. Cd concentrations found in leachate solutions containing different ash residues at various pH values are given in Figure 3.34 as an example.

Figures 3.34 and 3.35b show that Cd and Zn released from various ashes may increase drastically if pH in a landfill decreases in the long-term. This is especially pronounced for incineration fly ash and even more for ash residues from refuse derived fuel (RDF) utilization (Fig. 3.34). Vitrified products appear to be more resistant towards heavy metal leaching (see sections 5.3 and 5.4)

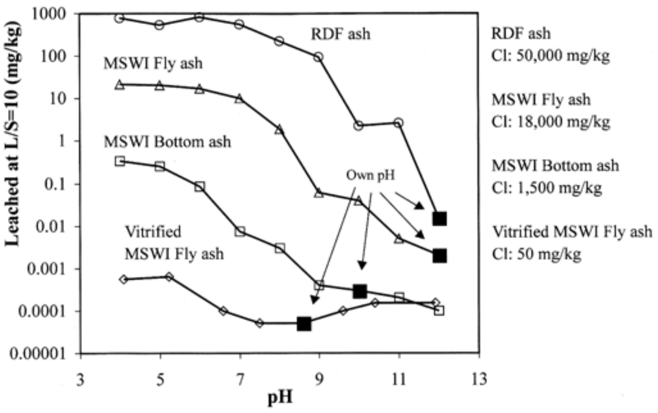


Fig. 3.34. Leaching behavior of Cd from MSW incineration residues in comparison with ash from refuse derived fuel (RDF) and vitrified MSW incineration fly ash. Cd leaching curves are largely related to the chloride content at pH>7. The amount released at pH<5 usually reflects the total content of Cd in the residue steam, as almost all Cd present is leachable. The "individual pH" of a material is the final pH of the leaching solution when the material is extracted with deionized water (marked as"own pH"). Reprinted from [102] with permission from Elsevier Science.

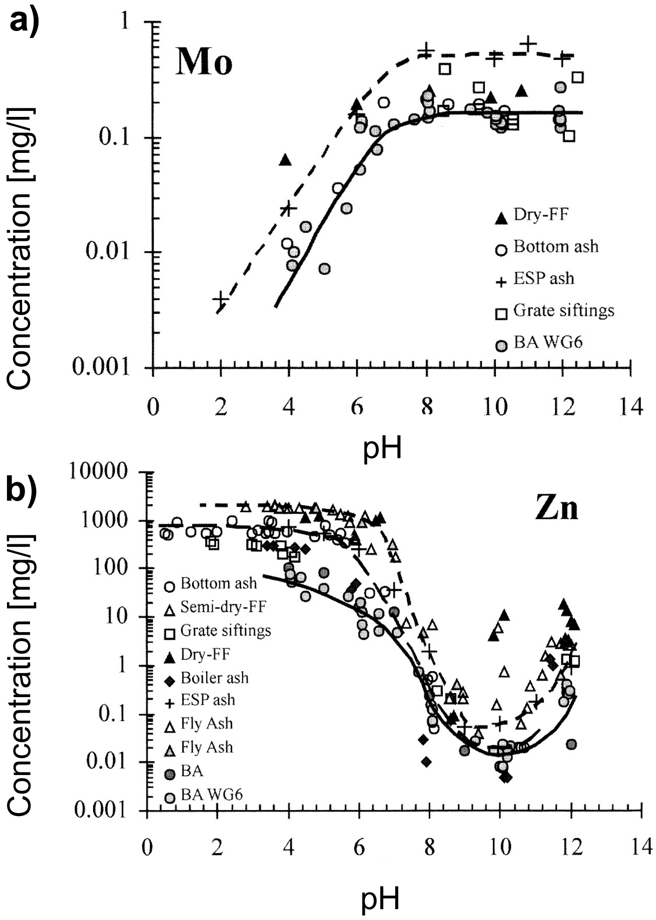


Fig. 3.35. Characteristic leaching behavior of a) Mo and b) Zn from MSW incineration residues. Reprinted from [102] with permission from Elsevier Science.

Heavy metals present as oxy-anions behave in a varied manner; whereas the solubility of cations (e.g. Zn^{2+}) increases with decreasing pH values, anions (e.g. MoO_4^{2-}) become less soluble. The pH value is a highly influential factor which can change leaching concentrations by several orders of magnitudes. A decrease of pH values in a landfill is expected in the long run, and is related to its buffer capacity [43]. Cd concentrations found in leachate solutions containing different ash residues at various pH values are given in Figure 3.34 as an example.

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In the long run, "nature" penetrates into the landfill system. Organics from the soil on top of a landfill contain chelating agents, which are known to be able to increase the solubility [47] and, additionally, the dissolution/desorption kinetics [61] of heavy metal compounds.

It is known that the changes between dry and wet periods in a landfill may also have an influence on the alteration and weathering processes. Carbonativation reactions seem to play an important role [43] in such wet-dry cycles [80]. Alteration has been simulated in the laboratory, but little is known about these effects in a landfill.

Even, if leaching processes are not fully understood and models cannot yet exactly predict and quantify the long-term behavior for incineration residues, such residues are, however, produced every day. Therefore, pragmatic solutions are needed to test, characterize and compare different residues.

Many leaching tests have been developed and standardized by the authorities of different countries. As the behavior of the materials is so manifold depending on the processes used to treat MSW, elemental composition, different mineral phases, pH value, chelating agents, ionic strength, availability of surfaces and active surface sites, pore sizes, residence times, and other factors, slightly different leaching tests can lead to totally different results. Therefore, harmonization of these tests is necessary and substantial efforts have already been undertaken [e.g.101].

Field Investigations and Hydrology

Laboratory leaching experiments cannot account for hydrological effects in a landfill. Therefore investigations in the field are important for the elucidation of the ongoing mechanisms. The hydrology of a landfill can be investigated best by studying the composition of leachates during rain events [47, 63]. In experiments of a pilot landfill containing cemented filter ash [63], it was shown that up to about one third of the rainwater appears to pass through the landfill within days with relatively little interaction with the cemented filter ash. The greater part of the drainage discharge (>60%) of a rain event is leachate of relatively constant composition that has a much slower response to a rainfall event. This leachate is in direct contact with the cemented filter ash. A quasi equilibrium condition between the solid phase and the leachate can also be assumed because of the relatively long residence time of the leachate. In Figure 3.32 it was shown that the heavy metal concentrations are much lower after a strong rainfall; however, due to the hydrogeochemical behavior, the absolute amounts leached increase because of the increase in drainage discharge. Very similar results have been observed in a MSWI bottom ash landfill [44, 46].

A comparison of field and laboratory data, using solid samples for leaching tests from the same pilot landfill, is given in [10]. The effect of different liquid/solid (L/S) ratios (50, 100, and 200 g/L) on the leachate concentrations was tested and it was found that the major components, such as Ca, Al, Si and sulfate, can be modeled assuming equilibrium with mineral phases known to be present in cement. However, for most heavy metals the concentrations were lower in the field than in the laboratory leachates. From spectroscopical data, there is evidence that Zn is incorporated into calcium-silicate-hydrates (CSH), which play a major role in the leaching mechanism [108]. Such a mechanism could also be important for other heavy metals.

3.4.4 Lessons to be Learned for Thermal Use and Treatment of MSW

The hazard potential of different ash residues increases in the following order: vitrified MSWI ash < MSWI bottom ash < MSWI filter ash < RDF ash. A comparison of different residues from various MSW thermal treatment methods is more extensively discussed in section 5.4.

The dissolution kinetics, even of simple mineral oxides, are still not fully understood after 30 years of extensive research (mostly performed for the nuclear industry). Long-term estimates for a complex system, such as a landfill, are even more uncertain. General trends can be interpreted and for certain cases it has been shown that heavy metals are solubility-controlled; however, in general the mechanisms are only roughly understood. In most cases, models can only support possible hypotheses, but quantifications for making long-term predictions are very difficult or even impossible.

Landfills can be sealed to avoid water contact, and leaching might thus be avoided. However, it is well known that today's sealing materials last no longer than 50-100 years. It is possible to delay water contact, but the problems are then left to coming generations. Such landfills need to be controlled for centuries or even longer. Bioactivity is an unknown factor if bacteria and organic chelating agents from biological active species penetrate the mainly inorganic body of a landfill containing incineration residues in the long-term.

Better technologies for the detoxification of MSW and/or MSW residues should be developed and introduced to the market. As a first priority, residues should be cleaned from the toxic substances such as the heavy metals. Otherwise, hazardous potential remains, even if incinerator ash landfills currently pose no risk for the ground water. Only when treatment methods cannot be exerted (e.g. for ecological reasons, if the impact on the environment is higher by treatment than without treatment) should the materials be inertized. The vitrification lowers the leaching rates drastically (section 5.4), but the long-term safety, nevertheless, cannot be guaranteed.

3.5 Secondary Raw Materials from Waste

Frank Jacobs

3.5.1 Introduction

In Switzerland – with a population of approximately 7 million - 2.58 million tons of waste was burned in municipal solid waste incinerators (MSWI) in 1999. Approximately 520’000 tons of bottom ash (slag) and 60’000 tons of fly ash were produced by incineration. Hence nearly 100 kg of MSWI residues were produced per inhabitant. These materials must be disposed of, because they can not be further used. If the same amount of burned waste would be produced in Europe per capita as in Switzerland, more than 20 million tons of slag and ash should be disposed of every year. Therefore attention has been given to whether or not the slag and/or ash might be of further use. Focus was placed on the building industry and, therein, on the cement and concrete industry, which produces nearly 4 million tons of cement, 50 million tons of aggregate and approximately 30 million tons of concrete in Switzerland on a yearly basis. The slag from traditional municipal waste incinerators (MSWI) was used in Switzerland years ago in the foundation of roads. Due to environmental concerns – e.g. release of heavy metals into the environment – this use is prohibited today in Switzerland. In other European countries the use of MSWI slag is still partly allowed. Fly ash from MSWI must be disposed of all over Europe. Technologies are being developed with the goal of treating MSWI slag and ash so that they are suitable for use instead of disposal. These technologies must reduce the amount of detrimental substances in the slag and ash.

If reference is made to cement production or cement, Portland cement, not high alumina cement, is always considered. Subsequently, the European cement standards (e.g. EN 197-1) are generally discussed rather than the ASTM standards (e.g. C 150-94). To make the distinction between different types of slag and fly ash easier- for example, those from the iron industry as opposed to those from coal power plants- subsequently slag and fly ash from new MSWI-technologies are classed together under the heading “further thermally treated MSWI-slag.” Mineral materials derived from further thermally treated MSWI-slag might be used as four different types of building materials:

1. Raw material: for thermal processes in, for example, brick or cement production; traditional raw materials in cement production are limestone, marl and clay;
2. Inert material: No significant reaction within the material (e.g. powdered limestone, quartz) takes place. In concrete inert materials are necessary either as aggregates (sand, gravel) having a grain size between approximately 0.1 and 32 mm or filler with a grain size of less than 0.1 mm.

3. Pozzolanic material: the material reacts chemically with the products (mainly $Ca(OH)_2$) from the reaction of cement with water (hydration). Traditional pozzolan materials are, e.g. fly ash from coal firing power plants or silica fume from the production of silicon metal and ferro-silicon alloys. Pozzolans and hydraulic material generally have a maximum grain size of less than 0.1 mm; silica fume is a very fine grained pozzolan with a maximum diameter of less than 0.001 mm.
4. Hydraulic material: the materials react in the presence of water and harden as a result. Normal cement (Portland cement CEM I according to the European cement standard EN 197-1; Portland cement is made from clinker, burned in a cement kiln, and interground additives like gypsum) is a typical hydraulic material. Materials are called latent hydraulic if the hydration reaction is slow and/or if $Ca(OH)_2$ from, e.g. the cement hydration acts as an activator in starting the reaction. If the reaction proceeds, then – in contrast to pozzolans - no further $Ca(OH)_2$ need be present.

The economic value of the materials generally increases from 1 to 4.

Figure 3.36. shows the main chemical composition of the different types of materials as mentioned before. This shows, for example, a certain similarity between Portland cement (CEM I) and granulated blast furnace slag from the iron industry.

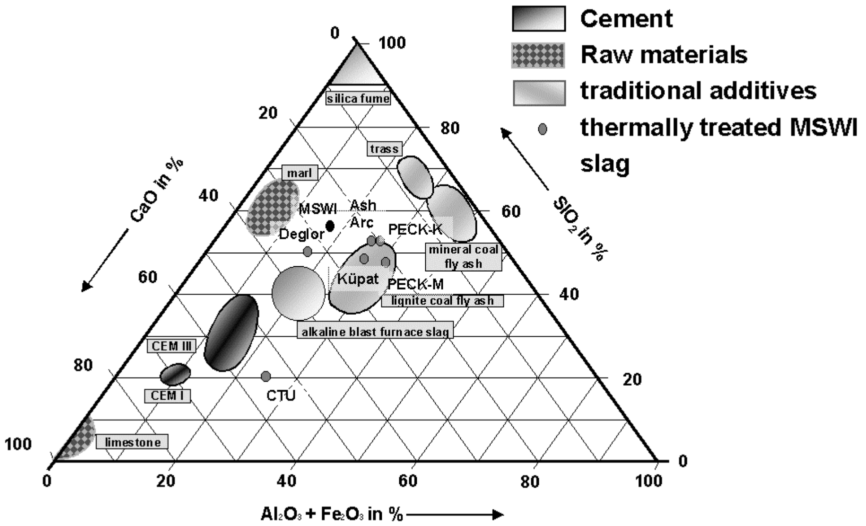

Fig. 3.36. Rankine-diagram for different types of materials: CEM I is Portland cement, CEM III a mixture of Portland cement with blast furnace slag, Trass is a natural mineral, coal fly ash and silica fume are industrial pozzolans, lignite coal fly ash is latent hydraulic, alkaline blast furnace slag is hydraulic.

Alkaline granulated blast furnace slag has an average composition of around 40 % SiO_2, 40 % CaO + MgO and 20 % Al_2O_3 + Fe_2O_3. Hydraulic materials like Portland cement have a CaO : SiO_2 ratio > 2, whereas pozzolan materials (e.g. lignite coal ash) generally have a CaO : SiO_2 ratio of less than 0.5. The composition of latent hydraulic materials (e.g. alkaline blast furnace slag) falls between these two.

3.5.2 Technical and Other Requirements for Construction Materials

Preliminary Remarks

Construction products are only allowed for public use according to Swiss or European legislation, if they fulfil several requirements for the following:

- Mechanical strength and stability
- Protection against fire
- Hygienic standards
- Health and protection of the environment
- Safety for use
- Sound protection
- Economical and rational use of energy

Subsequently, technical and environmental requirements of further thermally treated MSWI-slag are dealt with.

Technical Requirements

For commonly used building materials, two ways of specifying the technical requirements are possible:

1. In the set up of several physical and chemical requirements for each application field, the materials must be investigated intensively, to see if they fulfil the requirements or not.
2. Alternatively, one can set up a very limited set of chemical and physical requirements and define the process from which the material is derived. In this case, the process technologies of, e.g. a coal-fired power plant or of blast furnace define the basic material properties. The set up of further requirements only narrows the range of selected properties.

The second alternative is commonly used in many countries, particularly European countries. Examples can be found in European technical standards for fly ash from coal firing power plants (EN 450-1), silica fume from the production of silicon and ferro-silicon alloy (EN 13’263-1) and different types of cement according to EN 197-1. The standards are, for example, based on decades of experience in the case of cement, or for fly ash on a shorter period of experience but with very intense investigations. Around 45 million tons of this fly ash is produced in Europe in the coal power plants per year and around 2/3 of this is used.

Technical requirements comprise the fineness, influence on hardening, soundness, rheological properties, strength and durability. Decisive for durability are, for instance, the chloride and alkali content and the absence of corrosive substances for steel or concrete.

Environmental Requirements

Generally, only technical requirements are given in standards. The requirements are very strict because the field of application is generally not limited. This means that the materials in question can be used to make, for example, low quality concrete, elements to transport drinking water or high-rise buildings. The EU entrusted the incorporation of environmental properties of, for example, construction materials in the technical standards to the committee on normalisation (CEN). Up to now, this incorporation has not or has only seldom taken place. But within 5 to 10 years, the time for which the next revisions of the standards are scheduled, environmental aspects must be included. The environmental aspects to be considered will be, e.g. heavy metal content and the leaching behaviour of heavy metals. Organic substances in construction materials will probably also be included. Therefore it is necessary to know the environmental properties of further thermally treated MSWI-slag.

With the experience of several decades, for many widely used building materials (e.g. cement, aggregates, blast furnace slag) it has become evident that they cause no acute environmental risk (see e.g. [93]). The knowledge of the environmental properties of these materials can therefore serve as benchmarks for other, new materials.

In order to limit the content of toxic substances in clinker or Portland cement, standard values are listed in pertinent Swiss guidelines [24]. Among other things, the standard values relate to requirements regarding heavy metal concentrations in the secondary materials for cement production and cement clinker (Table 3.16). The levels are defined in such a way that they can be complied with through the fuels usually used, such as coal and heavy oil, as well as though natural raw materials such as limestone, marl and clay. Swiss standard values for heavy metal contents of excavated material are listed in the last two columns of Table 3.16 for comparison. Excavated material is from the rock strata lying below the root zone. This excavated material can be recycled for further use if uncontaminated, but also if below specific contamination levels (tolerable). It can be seen that the requirements for the materials used in cement production lie between the standard values for uncontaminated and tolerable excavated material. The heavy metal content of the cement can be either slightly lowered or increased through the use of secondary fuels. Overall, the standard values in Table 3.16 illustrate the high level of requirements stipulated by the Swiss authorities. Similar standard values exist in Switzerland for secondary raw materials for brickwork.

Table 3.16. [a] Standard values for heavy metals in ppm (g/t) according to [24] and further revisions for the production of CEM I cements, [b] provisional standard values for fly ash and granulated blast furnace slag and, for comparison, for uncontaminated (U) and tolerable (T) excavated material [93]

	Waste Fuels [a]	Raw meal substi tute [a]	Inter-ground addi-tives [a]	Clinker [a]	CEM I cement [a]	Fly ash, blast furnace slag [b]		Standard values for ecavated material	
						suitable	condi-tionally suitable	U	T
As	15	20	30	40		30	80	15	40
Be	5	3	3	5					
Cd	5	0.8	1	1.5	1.5	1	2	0.5	5
Co	20	30	100	50					
Cr	100	100	200	150		200	500	50	200
Cu	100	100	200	100		200	500	40	250
Hg	0.5	0.5	0.5		0.5	0.5	1	0.5	1
Ni	100	100	200	100		200	500	50	250
Pb	200	50	75	100		100	500	50	250
Sb	5	5	5	5		5	20		
Se	5	1	5	5					
Sn	10	50	30	25		30	80		
Tl	3	1	2	2		0.5	1		
Zn	400	400	400	500		400	1000	150	500

In other countries no standard values for the heavy metal content might have been published. But nevertheless, experience and data will be available which show the environmental properties of traditionally used materials. It can be assumed that the data do not deviate much from the Swiss standard values.

In addition to the heavy metal contents, levels of organic materials are also taken into consideration in examining environmental compatibility. Precise measurement of organic substances is usually very complex and in some cases still cannot provide unequivocal results. Data on the levels of organic carbon (TOC) for concrete constituents vary between 0 and approximately 5% [93].

Handling Requirements

Each type of material has it own storage and handling requirements. This depends on the condition (e.g. liquid, pasty, fine or coarse grained, soft or hard) of the materials. The condition determines the way of transporting the material to the plant and in the plant. The more difficult the transport is, e.g. for pasty materials, the more expensive is the equipment. Expensive equipment can only be amortised with large material flows and/or extra payment.

Additionally the constancy of the material properties is important in order to permit high quality production. Ideally, the material properties should also not be strongly influenced by the usual annual temperature variations.

3.5.3 Initial Experiences with Further Thermally Treated MSWI-Slags

Technical Properties

Samples from several new MSWI-processes were examined. The samples derived from small or laboratory processes and are mainly single spot samples (Table 3.17). In a first screening of the further thermally treated MSWI-slag, the investigations were based on the requirements given for the cement standard EN 197-1. In this standard, fundamental requirements are given. The following properties were determined:

- The effort required to grind the materials to a fineness similar to cement (determined property: hardness): A coarse grained cement has a fineness (Blaine-value) of approximately 2500 cm^2/g and a fine grained cement, one of about 4000 cm^2/g.
- The influence the materials have on the hardening behaviour (setting time).
- Whether the materials lead to internal damage of the concrete (soundness test).
- Whether the materials alter the rheological properties of concrete.
- Whether the materials are inert or reactive (strength development versus time).
- Whether the materials change the strength of concrete (compressive, bending strength).

Additionally the solidification of fly ash from traditional MSWI was tested by the use of further thermally treated MSWI-slag.

In Figure 3.37 results from further thermally treated MSWI-slag are shown. The cement used was always type CEM I 42.5 N (Blaine-value approx. 3000 cm^2/g), but delivered over a period of several years. Differences in the mortar strength were thereby achieved. This provides an idea of possible strength variations. The samples with further thermally treated MSWI-slag from Küpat or PECK-M showed the lowest strength. One reason for this is the gas generation in the samples. The gas pores which are generated lower the strength. A clear influence on the fineness of the further thermally treated MSWI-slag in terms of strength is visible. Increasing the Blaine-value from 2500 to 4000 cm^2/g increases the strength in general by approximately 10 to 20 %. Mortars with samples PECK-K, Deglor, AshArc and CTU-H showed a comparable strength. The contribution of further thermally treated MSWI-slag to the compressive strength of mortar was in the best case slightly better than inert quartz powder, having a Blaine-value of approx. 4000 cm^2/g (Fig. 3.37). By using 30 % of further thermally treated MSWI-slag, a reduction of the compressive strength of about 1/3 compared to cement mortar was found.

Table 3.17. Origin and nomenclature of the examined further thermally treated MSWI-slag

Process	Description of materials and process	Nomenclature*	Desity** [kg/m^3]	From
VS-Küpat	Mostly partially vitrified, sharp edged, soft, porous pieces of slag (1–10 cm) originating from thermal treatment of bottom ash (slag) from MSWI	Küpat 2550 Küpat 3000 Küpat 3800	2.77	Biollaz et al. [21]
ABB Deglor	dense glassy sharp edged pieces (1–10 cm) originating from the vitrification of fly ash and bottom ash (slag) in an oxidising atmosphere	Deglor 2530 Deglor 3100 Deglor 4050	2.81	Selinger et al. [91]
ABB AshArc	dense glassy sharp edged pieces (1–10 cm) originating from the vitrification of fly ash in a reducing atmosphere	AshArc 2460 AshArc 3030 AshArc 4060	2.77	
CTU	Dense spheres with a diameter < 1 mm originating from hydrolized vitrified fly ash	CTU-H 2500 CTU-H 4270	2.98	Jakob & Mörgeli [42]
	Dense spheres with a diameter < 1 mm originating from washed vitrified fly ash	CTU-W 2500 CTU-W 4830	3.08	
PECK	Vitrified bottom ash (slag) from traditional MSWI, molten and quenched sample	PECK-M 2500 PECK-M 4000	2.95	Biollaz et al. [21]
	Vitrified slag from VS-Küpat process, molten and quenched sample	PECK-K 2500 PECK-K 4000	2.78	

* Numbers indicate the fineness (Blaine-value in cm^2/g). The higher the number, the finer the material.

** Determined on milled material with a maximum grain size of ca. 0.1 mm

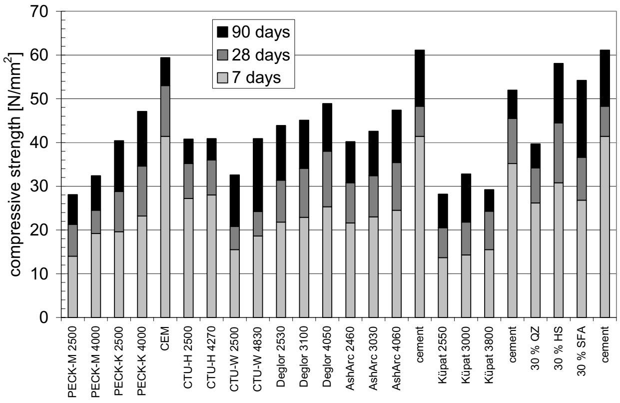

Fig. 3.37. The development of compressive strength of mortars with a binder consisting of mixtures of 70 wt.-% cement and 30 % further thermally treated MSWI-slag, quartz (QZ), fly ash (SFA), blast furnace slag (HS), and pure cement

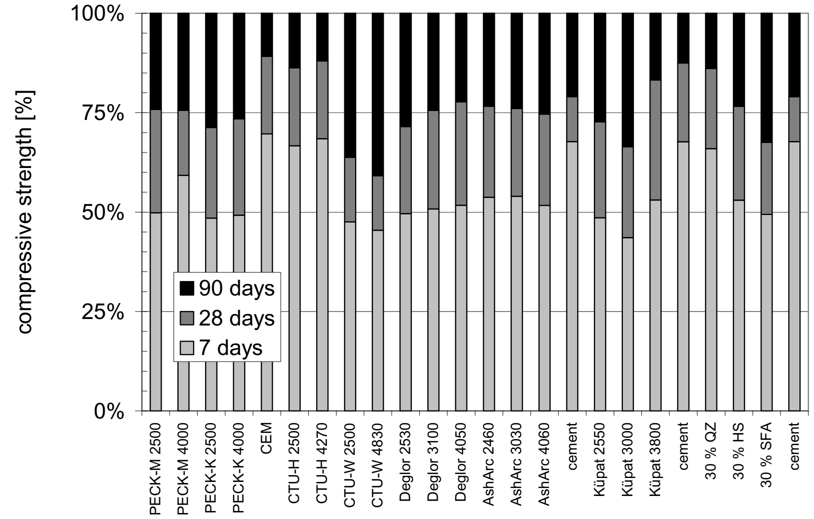

Fig. 3.38. Development of compressive strength (in percentage) for 90 day value of mortars with a binder consisting of mixtures of 70 wt.-% cement and 30 % further thermally treated MSWI-slag, quartz (QZ), fly ash (SFA), blast furnace slag (HS), and pure cement

In Figure 3.38 the strength development from the 90 day values is indicated in percentage. At 7 days, approximately 50 to 70 % of the total 90 day strength for the further thermally treated MSWI-slag samples is already reached. Between 28 and 90 days a further strength increase of about 20 to 40 % takes place. The relative strength development (over time) of the further thermally treated MSWI-slag is similar to that of fly ash from coal-fired power plants and blast furnace slag from iron industry; lower compared to quartz powder (Fig. 3.38). Samples with further thermally treated MSWI-slag CTU-H showed the lowest compressive strength and samples with further thermally treated MSWI-slag CTU-W showed the highest strength increase after 28 days. In general, for further thermally treated MSWI-slag, hardly pozzolan reactivity can be assumed.

Further experiments were carried out in order to study the use of further thermally treated MSWI-slag for stabilisation of MSWI ash. As binder for stabilisation purposes, cement and lime have been used and served as references. Further samples were made with mixtures consisting of cement, lime and further thermally treated MSWI-slag (PECK-M 2500, PECK-M 4000, PECK-K 2500, PECK-M 4000). In those mixtures, 15 % (by weight) of the cement was replaced by further thermally treated MSWI-slag. The compressive strengths of the stabilised MSWI fly ash are shown in Figure 3.39. The strengths of all samples are similar at 7 days. At 35 days the samples consisting only of cement as binder showed significantly higher strength. Nevertheless, the strength of the samples with further thermally treated MSWI-slag is sufficient.

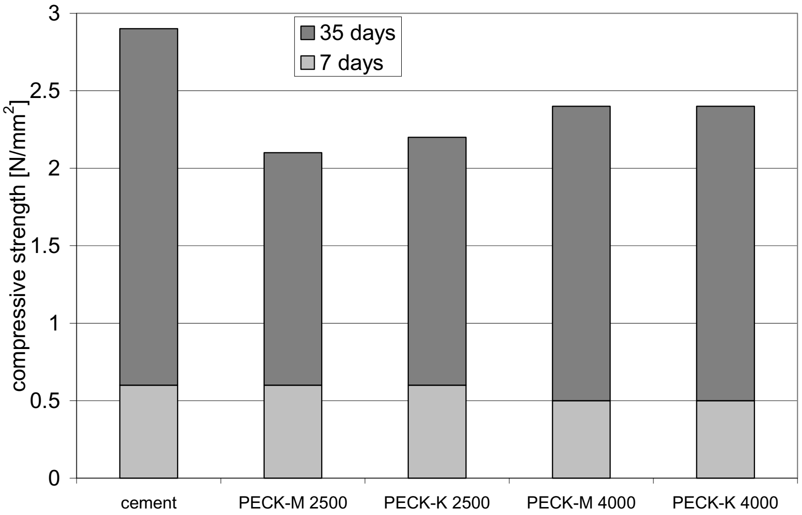

Fig. 3.39. Compressive strength at 7 and 35 days of the MSWI fly ash stabilised with cement and lime (denoted cement) or cement, lime and further thermally treated MSWI-slag replacing 15 % of cement per weight (denoted PECK)

In Table 3.18 a comparison is made between the examined further thermally treated MSWI-slag of different origin (e.g. type of input into process and process itself). It should be stated again that all samples derive from small scale processes and the properties of these single spot samples have not been confirmed by repetitions. The detailed results are given in the reports by Jacobs [39, 40].

Table 3.18 illustrates that nearly all examined materials (except Küpat slag) have both technical advantages and disadvantages. Many disadvantages might be reduced by a reduction of the quantity of material used as, for example, a cement replacement in the order of only 5 to 10 %.

Replacing cement by 30 wt-% of further thermally treated MSWI-slag significantly increased the initial and, particularly, the final setting times. Therefore for normal construction purposes, further thermally treated MSWI-slag PECK-M is generally not suitable. Further thermally treated MSWI-slag PECK-K might be suitable. The delayed setting could be caused by the heavy metal content of the further thermally treated MSWI-slag. The further thermally treated MSWI-slag PECK-K has high heavy metal contents of Zinc and Copper [33]. The further thermally treated MSWI-slag PECK-M has even higher contents (Fig. 3.40). These amounts of heavy metals, especially for the further thermally treated MSWI-slag PECK-M, are known to retard the hydration of cement [96] and hence the setting time.

The problem of swelling (soundness) might be solved by the following method: During a moist storage of several months, most of the reactions causing swelling can take place. Therefore, use after storage should cause no additional swelling.

This approach is also incorporated in the draft of [35]. This instruction leaflet regulates technical and environmental points in the use of fly ash from MSWI in road construction in Germany.

Some further thermally treated MSWI-slags cause a stiffening (increasing flow resistance: CTU), some a plasticizing (PECK) effect.

Table 3.18. Influence of cement replacement by approx. 30 % of further thermally treated MSWI-slag on mortar properties. +: positive effect, -: negative effect; 0: indifferent

Sample	Grind ability	Setting time	Soundness	Flow resistance	Remarks
PECK-M	-	-	o	+	minimal swelling of sample due to gas generation at higher ages
PECK-K	-	-	o	+	
CTU-H	+	o	o	-	
CTU-W	+	o	o	-	
Deglor	-	o	o	+	
AshArc	o	o	o	+	
Küpat	o	o	-	o	strong swelling of sample due to gas generation

Environmental Properties

The contents for selected heavy metals of further thermally treated MSWI-slag are displayed in Figure 3.40. For comparison, Swiss standard values for Portland cement clinker and for conditionally suitable fly ash from coal power plants (Table 3.16) are given. Additionally, data from a conventional MSWI slag are shown. The heavy metal contents of the further thermally treated MSWI-slag are up to approximately one order of magnitude higher than the Swiss standard values for Portland cement clinker and lay partly in the range of the Swiss standard values of conditionally suitable fly ash. Therefore, a further reduction of the heavy metal contents is desirable. If concrete is made with further thermally treated MSWI-slag as a partial replacement of cement, concrete will have higher heavy metal contents. The higher heavy metal content will usually lead, in the long term (over a period of decades or longer), to a higher heavy metal release from concrete. But the short term release due to leaching in, e.g. groundwater will not be significantly increased [93]. Aside from these environmental aspects, the reduction of heavy metal contents would help to avoid the strong retardation of the hydration reaction of cement as well.

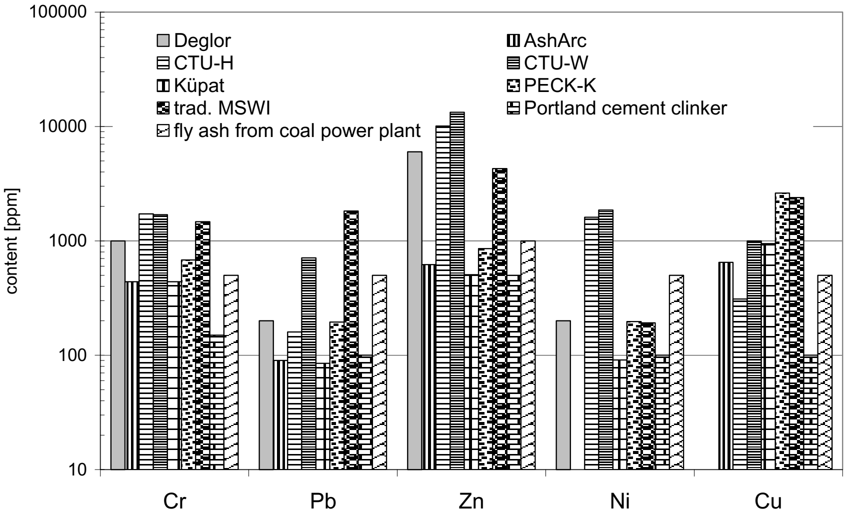

Fig. 3.40. Heavy metal contents of various types of further thermally treated and traditional MSWI slag [33, 39, 40, 99] and standard values for Portland cement clinker and fly ash (conditionally suitable) according to Table 3.16.

3.5.4 Applications of Further Thermally Treated MSWI-Slag

New materials, such as slag from MSWI, can not be used as generally accepted construction material, until very intensive investigations are carried out and bear positive results. Finally, the results must be approved by the national standardisation body. In [41] the general procedures with strict requirements for the introduction of a new product into the market are explained. Based on the preliminary results of further thermally treated MSWI-slag, Table 3.19 gives an overview of potential application areas in Switzerland and indicates relevant standards.

Thus far, it appears to be most promising to investigate the use of further thermally treated MSWI-slag in cement clinker production. [53] presented examinations for the use of MSWI-slag in cement plants and comes to the conclusion that this is a promising approach and should be further investigated. Less regulated application fields, where damages due to insufficient properties do not easily lead to severe accidents, should be pursued. Examples of these are floors or road stabilisation with no high requirements.

In different countries different standards may apply. For example, in USA the standards ASTM C 593-95 “Standard specification for fly ash and other pozzolans for use with lime” or ASTM C 595M-95a “Standard specification for blended hydraulic cements” define pozzolan as follows: “Pozzolan shall be a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but which will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.” Further thermally treated MSWI-slag possessing the required pozzolan properties falls within the scope of these ASTM standards. Swiss or CEN-standards do not allow the use of further thermally treated MSWI-slag for, e.g. the production of standard cement.

Table 3.19. Potential application fields in Switzerland for further thermally treated MSWI-slag, the requirements and judgement of the possible suitability for using further thermally treated MSWI-slag; based on [112]; Brackets indicate that further investigations are necessary; * Legal restrictions for the use of further thermally treated MSWI-slag

Application field	Standard	Requirements for	Possibly suitable for use
Raw material for cement clinker production	no BUWAL guideline	Defined by cement plant heavy metal content	yes
Cement compound	EN 197-1	Origin	no
Concrete structures	EN 206-1	Cement, aggregates	No
Precast concrete industry	EN 13’389, EN 12’839, SIA 320	Partly for cement and aggregates	(yes)
Concrete floors	SN 640’461	Cement, not for aggregates	(no)
Seamless industrial floors coverings and cement coatings	SIA 252	None	(no)
Floating support floors	SIA V 251/1+2	Cement	(no)
Brickwork	SIA V 177	None	(no)
Natural stone masonry work	SIA V 178	Binder	(no)
Stabilization	prENV 13’282	Binder	(no)
Injections	prEN 288’006	None	(no)
Stabilization of road constructions	SN 640’500a, SN 640’506a	Binder, partly on aggregates	(no)*
No regulated areas	no	Given by builder owner / constructor	yes

An important goal should be the improvement of the properties of further thermally treated MSWI-slag, in order to use further thermally treated MSWI-slag as, e.g. cement addition or pozzolan material. High quality further thermally treated MSWI-slag and high production rates would allow for the intensification of the investigations and would open a huge market. Globally, around 1.5 billion tons of cement and approximately 0.2 million tons of industrial pozzolan materials are used in the concrete field. High deposit fees would further stimulate the investigations and process optimisations.

To increase the properties, particularly the reactivity, of further thermally treated MSWI-slag, several methods exist (based on [54] with additions):

- Increased fineness (> 5000 cm^2/g), though this is rather expensive
- Increased amount of reactive (vitreous) components in the MSWI through e.g. appropriate quenching
- Further reduction of the heavy metal content
- Forced weathering of the mineral components through, e.g. longer storage under advantageous conditions
- Devitrification (zeolitisation) of glasses
- Altered composition of the input material in MSWI through the addition of appropriate materials or omission of waste fractions; in general the higher the ratio CaO : SiO_2, the higher the reactivity

3.5.5 Conclusions and Outlook

Large amounts of further thermally treated MSWI-slag are produced nowadays and the tendency, at least in Europe, is toward continual increase. In the building material industry, large amounts of materials are used (exploited from nature). Therefore, at first glance it seems most rational to investigate whether further thermally treated MSWI-slag can be used in the building material sector to reduce the use of natural resources. Based on investigations thus far, further thermally treated MSWI-slag is mainly inert in cementitious materials during the investigations over 90 days. In order to create a higher level of benefit from further thermally treated MSWI-slag, a pozzolan or latent hydraulic reactivity would be desirable. The optimisation of new processes at MSWI plants with respect to the quality of the further thermally treated MSWI-slag is strongly recommended.

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