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„Final Sinks“ as a Necessary Element of Sustainable Waste Management

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EXECUTIVE SUMMARY

Anthropogenic flows and stocks of materials are large and growing. All materials taken from the earth crust must either be recycled or disposed of in the environment. Waste management has the following key function within this “anthropogenic metabolism”: 1. Facilitate clean material cycles, with emphasis on “clean”, 2. Supply safe final sinks, 3. Send out signals for the design of products in view of recycling and final sinks. The paper focuses on the sink issue: Many materials cannot be recycled “forever”, and - for thermodynamic reasons – cycles cannot be completely closed. Thus sinks are required to accommodate both non-recyclables and losses from cycles. There are natural (air, water and soil) as well as anthropogenic sinks (landfills and transformation processes). Sustainable waste management mineralizes organic non-recyclables and immobilizes inorganic residues for very long time periods, not requiring after-care treatment. While for organic materials, perfect sinks are modern waste incinerators with sophisticated air pollution control, for inorganic materials the search for the ultimate sink is still under way. Sanitary landfills require long-term after-care for centuries, and thus new treatment and management technologies are needed to fulfill sustainability criteria. It is recommended that while focusing on the cycling society and urban mining, the waste management community should not neglect the need for and the research into landfills and final sinks.

INTRODUCTION

During the last ten thousand years, the world has seen an unprecedented change in its metabolism (Brunner & Rechberger, 2001). The overall per capita turnover of goods has increased by 1-2 orders of magnitude. For individual substances such as lead, the increase was even more dramatic and amounted to 4-5 orders of magnitude (factor 10.000 - 100.000). In parallel with a population increase of 10^{2-3}, the man-made lead flows increased by more than 10^6. More recently, the production of synthetic organic substances has risen sharply in the last one hundred years. Today, more than a million synthetic organic substances are being produced, and annually several hundred thousand new substances are looking for a market. Thus, not only the mass flow of substances increases highly, but also complexity of

product composition (number of different substances in one product) is escalating. As a consequence, waste management is faced by a growing amount of wastes with ever increasing complexity.

Wastes can be divided into two categories: Those resulting from low residence time consumer goods, and those arising from long living products in infrastructure, buildings and constructions. Although much of present attention focuses on packaging and consumer products, most of the goods produced – and thus also of the wastes arising - are long living products that are used in infrastructure and constructions (networks for energy, people, goods and information; production and service facilities; buildings for housing, service industry and production, etc.). These goods have a long residence time of several decades up to 100 years. They make up the anthropogenic stock of materials that is usually growing. This is particularly the case in young and fast growing economies such as in China, India and Brazil that are in the process of building up their infrastructure.

Waste management of today receives the amount of materials that have been built into the stocks of infrastructure and buildings around 50 years ago. The consequence is as follows: If a region is experiencing a long growth period, such as Europe after World War II, the amount of materials built into the infrastructure has risen at a steady growth rate. Due to growth, today´s input flow of solid materials is much larger than 50 years ago. In construction waste management, Europe today gets the wastes that arose from the low input in the 1950ies. It is obvious that these wastes, even when 100 % recycled, cannot supply a large share of a growing resource market, because they result from a time when the input was considerably smaller than today. In 50 years, when today´s high input mass flow will become obsolete, the resulting mass of wastes will be much higher than today. Thus, for systemic reasons, future waste management in regions of high growth rates has to cope with increasing amounts of wastes of highly changing composition. Analogously, shrinking regions with decreasing material input will experience waste outputs that are quite substantial when compared to today´s input product flows.

The large and growing flow of materials has consequences: While in the 1970ies, and again recently, the issue of scarcity and availability of resources has been put forward, another issue arose at the back end of the life cycle, namely the scarcity of sinks. The large man-made flows increasingly interfere with geogenic flows, and start to influence natural systems on a regional and global level. The question arises if nature has plenty of capacities to take up all CO_2 /CH_4 resulting from the anthropogenic use of fossil fuels and from methane producing agriculture? What is needed to prevent the halogenated hydrocarbons CFCs from destroying the stratospheric ozone layer? What will be nature's carrying capacity for brominated flame retardants and other endocrine substances? Inputs and outputs of the anthroposphere must be assessed together. It appears that there are - in parallel to the challenges at the front end of the material system - serious questions at the back end of the life cycle of substances. When large amounts of substances are extracted from the earth`s crust and synthesized by chemical processes, environmentally sound means must be developed to either transform these substances into harmless materials or to store them safely in geological formations for long time periods.

The goal of this paper is to draw the attention of the waste management community to the challenges arising from the need for sinks: What is the function of waste management within the anthropogenic metabolism regarding the sink issue? It is shown, that sinks and final sinks are necessary elements of every metabolism, and that proper thermal processes and sophisticated landfilling of pretreated wastes can contribute substantially to directing non-recyclable substances to appropriate final sinks.

DEFINITION OF SINKS

That sinks are a prerequisite for a healthy metabolism has long been recognized: Abel Wolman noted in his famous study on “The Metabolism of Cities” the need for sinks for materials such as sewage and wastes in order to leave the metabolic cycle with minimum nuisance and hazards (Wolman, 1968). Joel Tarr, describing the history of urban pollution and environmental protection in his outstanding book “The Search for the Ultimate Sink”, was likewise worried that without appropriate sinks, the output of the anthroposphere might overload the environment (Tarr, 1996). Similar concerns were raised in the Brundtland Report (United Nations, 1987) and by (Alberti, 1996).

What is a “sink”, and what are “final sinks”? There are neither official nor conclusive definitions yet. First attempts have been made in (Döberl & Brunner, 2004; Brunner, 2004). Based on Material Flow Analysis methodology, a “sink” is the opposite of a source: It is a place where the output of a system can be accommodated. Thus, each process outside of a given system boundary can be labeled a sink. From an urban metabolism point of view, a “sink” is a manmade or natural process at the end of the material life cycle that receives material flows and stores these materials for a certain time period. Sinks can include transport as well as transformation and storage processes. Residence times of materials in sinks are limited to time periods of minutes to centuries. Thus, sinks can become sources of material flows, too. Examples of sinks are waste water treatment plants, waste treatment processes, or air, water (e.g. a river) and soil as receiving bodies.

A „final sink” is either i) a transformation process that destroys materials by mineralization or other process, or ii) a storage process that receives and stores immobile material flows for geological time periods. Ad i) Destruction (or transformation) ends the existence of a substance: E.g. cellulose is transformed by thermal or biochemical oxidation into CO_2 and H_2O. Such a process thus is a “final sink” for cellulose. Ad ii) A “final sink” storage process receives only materials that are of very little mobility in the final sink environment even for geological time periods. Thus the very little amount of a substance leaving the final sink is not likely to have a negative impact on the environment. However, due to accumulation, the concentration of a substance in a “final sink” might become large and thus exert a hazardous effect on the final sink. Hence, it must be distinguished between “environmentally sound final sinks” and “final sinks”. To give two examples: The ocean is an appropriate and environmentally sound final sink for chloride, because even if all chloride that is used by men finally reaches the ocean and stays there for thousands of years, this will not significantly increase the concentration of chloride in the ocean. On the other hand, the stratosphere is not an environmentally sound final sink for anthropogenic halogenated hydrocarbons CFCs. They accumulate in the stratosphere, and the resulting concentration in this final sink becomes so high that the ozone layer is being destroyed with harmful consequences for men and environment.

The difference between a final sink and a sink is determined by the mobility of materials: If not transformed, substances will stay “forever” in a final sink, while the residence time in a sink is limited. Thus, substances in a sink are mobile and might migrate to some other place where they may exercise a negative impact on the environment. In a final sink they pose no hazard for the environment anymore, because they are of extremely little mobility. However, substances may accumulate in final sinks, thus changing the chemical composition of the final sink and posing a threat for the final sink and its constituents (e.g. organisms). In certain cases, the accumulation of substances in final sinks can be beneficial, too. For instance, it can be anticipated that by accumulating filter ash from municipal incineration over very long time periods in underground salt mines, these anthropogenic repositories might become large enough for economic recovery of heavy metals such as zinc, cadmium, tin and others (Kellner, Kral & Brunner, 2011).

Since the distinction between sinks and final sinks is due to the mobility of substances, it is essential to examine potential changes in chemical speciation of substances during the residence time in these sinks, too. If long time periods are taken into account, speciation of substances in the environment may change considerably. Over millennia, environmental compartments such as soils, surface waters, or even landfills are not stable. Natural as well as anthropogenic impacts such as eutrophication, acidification, or change in redox conditions may result in mobilization or immobilization of substances. In addition to biogeochemical reactions, geological processes such as erosion, weathering, seismic activities, and landslides may displace substances from one sink to another. Therefore, a sink such as a landfill may not be a final sink in a long-term perspective!

CONTRIBUTION OF WASTE MANAGEMENT TO SINKS

As mentioned above, in the long run, each substance taken from the ground or industrially synthesized will find a final sink, either by natural or by anthropogenic processes and mechanisms. Environmental legislation ensures that substance flows from the anthroposphere to the environment are within certain limits. Thus today, for many substances, emission flows are highly controlled, and comprise only small amounts of total flows e.g. of heavy metals and persistent organic compounds (exceptions concern carbon, nitrogen and other non-metals). The bulk of these substances is not contained in emissions but in waste materials, and is controlled by waste collection, recycling, treatment and final disposal. Hence, waste management is by far the most important “conveyor belt” of many substances at the back end of the consumption system, and plays a crucial role in directing materials to appropriate treatments, sinks and final sinks.

The goals of waste management as stated in the legislation of several countries are: 1) Protection of men and the environment, 2) conservation of resources, and 3) after-care-free waste treatment (landfills without long-term emissions; “clean” recycling without carrying hazardous substances into future material cycles). These goals are generic goals applicable to all economies, emerging as well as affluent. The first two goals should be viewed as a hierarchy: Protection of men and environment comes first, and conservation of resources second. The third goal arises from sustainability as defined in the Brundtland report (United Nations, 1987): “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Landfilling as practiced today, and cycling hazardous materials shift burdens from today`s consumers to future generations; they will have to pay for treatment, monitoring, and management of landfills closed more than a century ago, and they will have to take care of the hazards arising from cycling toxic substances such as heavy metal additives in plastic wastes.

If above waste management goals are to be really followed, only three products may arise: 1) “Clean” recycling products, 2) emissions from waste management that are compatible with environmental standards and that do not overload the capacities of final sinks, and 3) residues tailor made for final storage quality that are not mobilized for long time periods when disposed of in final sinks. “Final storage quality” has been defined before (Baccini, 1989). The term fits into the final sink concept. A waste with final storage quality is not mobile anymore if exposed to a landfill environment, even if such environments change over time. Final storage quality applies to stone-like materials: They are not completely insoluble, but their rate of dissolution is so very low that the resulting substance flows are neither a challenge for men nor the environment. A material with final storage quality is well suited to be disposed of in a landfill because it fulfills final sink criteria: It will stay in the landfill for many thousand years.

While in most cases, waste management is capable of achieving the three objectives stated above, for certain substances this may require a very costly and excessive waste treatment. Thus, waste management must send out signals to manufacturing, too. The design of prod-

ucts needs to take the issues of “clean cycles” and “final sinks” into account. Products should be recyclable, or should at least be suited for safe disposal in final sinks. In ultima ratio, if no appropriate final sink can be assigned to a substance, it should be phased out and replaced, as happened to DDT, PCB, certain CFCs, heavy metals, and others. It should be remembered, that in contrast to nuclear waste with decay rates and corresponding half-life times of up to hundreds of thousands of years, the risks from landfilled “normal” wastes stays “forever” and do not decay.

Waste management fulfills a key role in directing hazardous (and other) substances to final sinks. First, incineration (waste-to-energy) is capable of transforming persistent organic compounds completely (>99,99%) into harmless mineralization products such as water and carbon dioxide. Thus, state of the art thermal treatment serves as a perfect final sink for organic substances. There is no other process available that is capable to fulfill the same purpose at similar economic and environmental boundary conditions.

Second, wastes composed of hazardous inorganic substances that can neither be recycled nor mineralized have to be transformed into residues with final storage quality, and disposed of in final sinks. It is a fact that present day MSW landfills do not comply yet with the requirements of final sinks: They require after-care, such as treatment of leachate and off-gas, and monitoring for long time periods (centuries) (Baccini & Belevi, 1989). For landfills containing mainly inorganic wastes (e.g. construction wastes or bottom ash), time scales for the completion of the after-care period may be somewhat shorter (Laner, 2011), but most of them do not comply yet with sustainability criteria as discussed above. In order to assess if a substance will stay “forever” in a landfill, the following information has to be considered: Reactions between waste constituents, landfill leachates and landfill gases taking place within the landfill body, transport across the man-made envelopes of the landfill (penetration and diffusion of gas and leachate), and migration through and attenuation by the landfill environment beyond the manmade barriers. At present, landfills are only in part final sinks for inorganic substances, and may leak considerable amounts of metals and non-metals for long time periods.

Taking into account production and consumption of materials with a large material turnover in the order of close to 10 tons of solid materials per capita and year, waste management must supply large capacities of final sinks to accommodate these substances at the end of the life cycle. Even if 90 % are recycled, there will still be the need to dispose of about 1 ton of waste per capita and year. Finding appropriate sinks for these wastes requires a tailor made approach, because substances vary widely in their properties and thus behave differently in the various waste treatment processes and landfills. For each substance, an appropriate final sink must be designated by waste management. If such sinks cannot be found for a specific substance, the substance should – as mentioned above - be phased out.

In the future, the sink issue must be addressed by a more systematic approach: 1) It has to be investigated if “sink-limitation”, such as in the case of CO_2, CFCs, DDT, or Hg will become rather the rule than an exception. 2) The role of waste management in directing substances to appropriate final sinks must be elucidated in detail (mass flows of selected indicator substances from consumption and infrastructure via waste management to sinks and final sinks). 3) In case of a “zero emission” or “zero landfill” policy, ways have to be explored for creating the perpetuum mobile of indefinite recycling without losses from material cycles. 4) A new definition of landfills as final sinks is required. As a starting point serves the final storage concept developed by (Baccini, 1989). 5) If landfills have to fulfill the function of a final sink, new pretreatment technologies and analysis methods for wastes and residues suited for final storage need to be developed. 6) Case studies are needed to exemplify the feasibility of a coherent “final sink” approach in waste management. Such case studies could focus on selected heavy metals such as mercury and cadmium, and on persistent and toxic organic waste constituents such as brominated flame retardants or halogenated hydrocarbons. 7)

The implementation of a “final sink” strategy will require additional financial resources for waste management. Since such resources are scarce, and so far even affluent societies are reluctant to spend more than 0.5 % of their GDP for waste management, the question of how to finance a final sink strategy is crucial.

CONCLUSIONS

A life cycle perspective of the anthropogenic metabolism comprises sources, flows and stocks, as well as sinks of materials. While production and consumption control material flows at the front of the material system, waste management bears responsibilities at the back end. Based on the goals of protection of men and environment, resource conservation, and long-term after care free waste management, two challenges arise: First, to establish clean cycles for wastes that represent a market value; and second to find appropriate sinks for those materials that cannot be recycled for economic or ecologic reasons. Waste treatment processes such as incineration and landfilling fulfill an important role in directing and storing specific substances in appropriate sinks. In the future, the sink issue is to be addressed in a holistic way, linking production and waste management: For all substances exploited from the earth crust or synthesized in man-made processes, waste management must supply corresponding sinks for final disposal. Organic substances can be readily mineralized by thermal processes to carbon dioxide, water and other harmless materials, and hence do not pose a long-term problem if managed properly. On the other hand, inorganic substances must be pretreated and transformed into stable species that under landfill conditions can only be mobilized in trace amounts complying with environmental standards even for very long time periods. It is necessary to understand the fate of landfilled substances along the path landfill body – landfill containment – landfill environment in order to assess if the requirements of an appropriate final sink – no detrimental outflows of hazardous substances - are fulfilled.

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