

## **TREATMENT OF MECHANICAL SEPARATION ORGANIC RESIDUES IN A LANDFILL-BIOREACTOR**

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ABSTRACT: At Essent waste treatment company in Wijster a full-scale demonstration is in progress of bioreactor technology for treatment of the mechanically separated organic residue (MSOR) of a waste separation plant. A 49.000 tonne demonstration cell was built as planned and methanogenic conditions were rapidly established after closure of the cell. Besides lab-scale experiments and a desk-study was performed. The research made conceivable that MSOR can be treated in bioreactors in such a way that a stable product is obtained suited for reuse. Emissions to air, soil and groundwater can be minimised to negligible, energy production is comparable and its contribution to carbon dioxide emission reduction is superior to incineration of MSOR.

KEYWORDS: bioreactor; landfill bioreactor; flushing bioreactor; enhanced formation

## 1. INTRODUCTION

At Essent (previously known as VAM) waste treatment company in Wijster, waste is mechanically separated prior to treatment. One of the product streams is the mechanically separated organic residue (MSOR); a material characterized by its homogeneity and relative small particle size (< 45 mm). Dutch legislation does not allow landfilling of MSOR after 2000 and bioreactor technology is considered for future treatment.

A bioreactor is an anaerobic fermentation cell in which leachate or water is recirculated in order to enhance biodegradation of the waste. The bioreactor is depicted in figure 1 and its operation is summarized in table 1. It is expected that the material can be fully stabilized within about 30 years to a residue that has negligible rest-emissions.

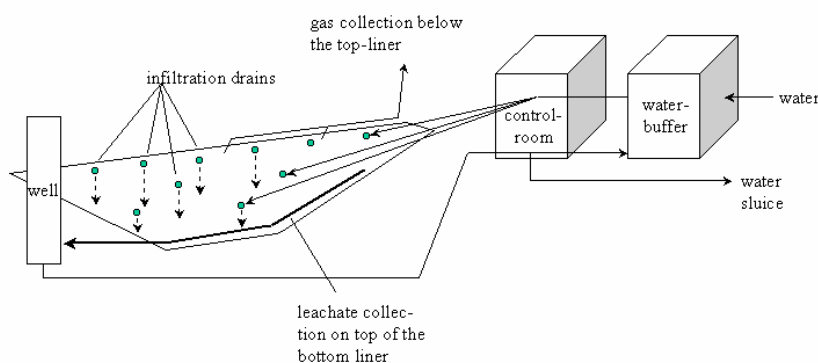


Figure 1 - The Essent bioreactor

Table 1 - phasing of the bioreactor construction and operation

1. construction	½ year	filling of the bioreactor and construction of the systems for leachate infiltration and collection and gas extraction. Lining of the bioreactor.
2. start-up	½ year	start infiltration, on-set of methanogenic conditions
3. methanogenic phase	5-8 year	complete anaerobic conversion of biodegradable organic components, immobilisation of heavy metals
4. post-methanogenic phase	15-25 year	flushing out of mobile pollutants as $Cl^-$ , $NH_4^+$ , possibly aerobic stabilisation of the waste

Treatment of wastes in bioreactors has been discussed throughout the last decade and the concept is described in literature under names as 'bioreactor', 'landfill bioreactor', 'flushing bioreactor' or 'enhanced fermentation cell'. Bioreactor technology is currently being demonstrated at several places throughout the world, e.g. at Yolo County in the US (Augenstein et al., 1998); at BFI-Lyndhurst in Australia (Yuen et al., 1997) and in the UK (Blakey et al., 1997).

Despite these efforts, the treatment of MSOR in bioreactors cannot be regarded as demonstrated technology. In order to be acceptable, MSOR has to be treated in such a way that:

- the organic material is fully stabilised and the product non-biodegradability under aerobic or anaerobic conditions;
- the energy production from MSOR is comparable to the energy production in case of MSOR-incineration;
- negligible emissions occur to air during construction and to soil and ground-water during operation;
- a product is obtained that can be re-used or which is, upon deposition in equilibrium with its surroundings

In order to make conceivable that these short and long-term criteria can be met, a research programme is performed, consisting of three parts:

- construction of a bioreactor at full-scale and demonstrating the technology for leachate infiltration and collection and gas extraction in the first few years of operation;
- simulating processes during the methanogenic and post-methanogenic phase at lab-scale and exploring the quality of treated MSOR;
- definition of prerequisites for reuse of the product and identification of options for reuse in a desk-study;

In this article the results of all parts are described and conclusions will be drawn, whether the above mentioned criteria are attainable.

## 2. THE DEMONSTRATION CELL

### *Construction*

In the period from June to November 1997 a 49.000 tonne demonstration cell was constructed as depicted in figure 1. The cell was based on a combined sand-bentonite and VLDPE bottom liner on top of which a system for leachate collection was placed. In and on top of the MSOR horizontal perforated pipes are dug in for leachate infiltration. On top of the upper infiltration system gas collection is realised in a bed of shredded wood. Moisture content and temperature of the MSOR are continuously registered using 36 combined sensors. The cell is covered gas- and watertight using VLPDE. The surface of the cell is 70 x 100 m, and its height is 8 m at maximum.

During construction emissions to air were measured. Methane emissions are measured to be 6,5 tonne, which is less than 0,5 % of the total methane potential. Carbon dioxide emissions are substantially higher, indicating that aerobic conversion of organic material does take place. The extent of aerobic conversion is limited to about 4,5% indicating that energy loss due to aerobic conversion is within predefined limits. Odour emissions however were not negligible, mainly because at several occasions MSOR was deposited after being stored for several days before deposition. Avoiding storage of MSOR, should suffice to minimise odour emissions in future bioreactors. Constructional details, analyses of the MSOR deposited and more information on measurements of emissions to air are described by Oonk and Woelders (1999).

### *Leachate-infiltration*

Starting February 1998, leachate was fed to the MSOR through the upper infiltration system. The design infiltration rate of 30 mm per week, however, could not be realised, partially as a result of technological problems related to irregular settlement of the waste (causing pipe ruptures and leaks in the connection of top- and bottom-liner) and scaling in the leachate extraction pipes. These technological problems however could all be solved.

A more serious problem was the low permeability of the MSOR, which made it impossible to achieve infiltration rates of 30 mm per week just using natural gravity. The low permeability was not expected during design, since previous experiments with MSOR indicated sufficient permeability of the waste (e.g. Woelders et al., 1993). Changes in waste composition and changes in the Essent-waste separation

plant resulted a MSOR with high specific weight of the waste (1,3 tonne per m<sup>3</sup>) a relative small size of MSOR, thus causing the low permeability.

In order to achieve higher infiltration rates, water was infiltrated under pressure through the intermediate infiltration pipes. Using this approach, the design leachate infiltration rate of 30 mm per week could be realised and maintained without any problems in the period of May to July 1999. In two years time 7730 m<sup>3</sup> of water is infiltrated, which is about 1/3<sup>rd</sup> bed volume.

#### Leachate recovery and quality

Leachate recovery did not cause many problems. Indicated in table 2, the leachate produced contains high amounts of bicarbonate; the heavy metals content however was initially rather low and is even more reduced upon elapsing methanogenesis to levels close to the objectives. Concentrations of BOD, N<sub>kj</sub> and Cl<sup>-</sup> however are very high and need a future reduction with a factor 30 to 100 in future. BOD and N<sub>kj</sub> are related to methanogenesis and such a drastic decrease is only expected after biological stabilisation; Cl<sup>-</sup> is already available for leaching out, so reduction of these levels requires sufficient flushing of the waste with relative clean water. This is confirmed by the lab-scale experiments (see below).

Table 2 - composition of leachate before and after treatment at full- and lab-scale

Component	initial concentrations	bioreactor		lab-scale experiment	
		after 22 months	after methanogenesis	after being flushed	objective after 30 years
BOD (mg l <sup>-1</sup> )	42 000	9 400	490	9	10
COD (mg l <sup>-1</sup> )	60 700	19 400	4 780	173	100
N <sub>kj</sub> (mg l <sup>-1</sup> )	4 700	4 200	1 900	120	2,2
P(mg l <sup>-1</sup> )			15	3,1	
Cl <sup>-</sup> (mg l <sup>-1</sup> )	4 700	6 500	5 700	7	200
Br <sup>-</sup> (mg l <sup>-1</sup> )				0,06	
CN <sup>-</sup> (mg l <sup>-1</sup> )				3	
As (µg l <sup>-1</sup> )	< 50	190	34	2,5	15
Cd (µg l <sup>-1</sup> )	< 0,5	<0,5	<0,2	<0,2	0,4
Cr (µg l <sup>-1</sup> )	450	1 300	120	24	50
Cu (µg l <sup>-1</sup> )	64	330	100	11	18
Fe(µg l <sup>-1</sup> )	650 000		3 400	800	
Hg (µg l <sup>-1</sup> )	0,63	0,58	0,2	< 0,1	0,1
Ni (µg l <sup>-1</sup> )	770	450	210	12	17
Pb (µg l <sup>-1</sup> )	180	56	46	< 10	42
Zn (µg l <sup>-1</sup> )	2500	560	1 000	55	70
HCO <sub>3</sub> <sup>-</sup> (mg l <sup>-1</sup> )	22 000	20 400	6 700	1 000	
PH	7,1	8,2	7,5	7,5	
EC (mS m <sup>-1</sup> )	40 000	40 000	20 800	1 500	
Eh (mV)			-57	350	

Comment:

#### Gas production and recovery

December 1997 passive gas extraction was started; in the second half of January 1998 the active recovery of biogas was initiated. Figure 2 shows the calculated gas generation, as a function of the half-time of biodegradation and the actual amount of gas generated in the bioreactor. Although water infiltration wasn't as effective as expected, the amount of gas generated is rather high and half time of biodegradation is about two years. In the period until Januari 1<sup>st</sup> 2000 in total about 2,77 million m<sup>3</sup> was produced, which is about half of the estimated gas potential of 5,7 million m<sup>3</sup>. The composition of the biogas is good with an average methane concentration of 56% and utilisation of the gas in a gas-engine an generator did not give any problems.

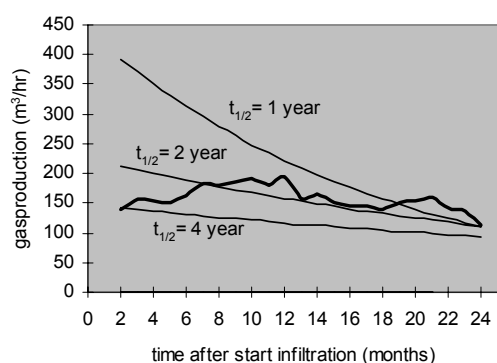


Figure 2 - Expected gas formation as a function of the half-time of biodegradation and actual gas production (thick line)

On basis of the initial composition of the waste and the results of the monitoring programme, the composition of the bioreactor in week 19 (2000) is calculated in table 3. The result shows that in 2 1/3 years time about 38% of the dry organic material has dissimilated.

Table 3 - material balances during construction and operation until week 19, 2000(in tonne)

	water	dry organic material	dry inorganic material
<i>during construction</i>			
deposition of ONF	(41,9 %) + 20 700	(22,7 %) + 11 200	(35,4 %) + 17 600
Precipitation	+ 1 960		
gas emissions	- 64	- 500	
<i>during operation</i>			
gas extraction	- 92	- 3 630	
leachate infiltration	+ 7 730		
leachate extraction	- 5 960	- 40	
total (wk 19, 2000)	(50 %) 24 300	(14 %) 7 000	(36 %) 17 600

#### *Other aspects*

The average temperature in the bioreactor immediately after completion was slightly over 50 °C (varying from 47 to 58 °C). In the top of the bioreactor, mean temperatures gradually declined to 37 °C (variation 35-42 °C); at lower levels the mean temperature drop was slightly less, though the variation in temperature is slightly greater (23-52 °C). The signal of the moisture sensors could not be interpreted in a quantitative way, and a more qualitative interpretation suggested an initial inhomogeneous distribution of moisture in the waste. Water supply resulted in increased wetting of parts of the waste that were already wet. Parts of the MSOR that were dry remained dry. Since the completion of the top-liner system settlements in the bioreactor are about 75 cm.

#### *Waste analyses after 2 1/3 year*

In week 19 (2000) samples were drilled close to the moisture sensors. In total of 36 samples were taken at different heights. The inhomogeneity in moisture content was obvious: about one third of the MSOR came out as a kind of wet slurry, while another third was completely dry, thus confirming the qualitative information of the moisture sensors. The samples were analysed on moisture content, ignition loss, grouped a larger dry and wet sample and subsequently subjected to a.o. a fermentation test.

Moisture content, dry organic material and dry inorganic material are calculated from moisture content, ignition loss and plastic content and are shown in table 4. The organic material in the samples

is substantially lower than expected on basis of the material balance in table 5 and this is most likely attributed to the drilled sample being not representative for the entire bioreactor (the drilled sample may have been contaminated by amounts of top-soil).

Table 4 – composition of the bioreactor on sampling in week 19, 2000

	moisture content	dry organic material	dry inorganic material
wet samples	73 %	7 %	21 %
wetted samples	41 %	5 %	54 %
dry samples	38 %	9 %	53 %
average bioreactor	49 %	8 %	42 %

An indication for the sample being not representative is the low biogas potential of the material in a fermentation test (see table 5), compared to actual gas formation in the bioreactor. Biogas recovery in the bioreactor and gas potential in the fermentation tests suggests a total gas formation of 85,3 m<sup>3</sup> per tonne MSOR or 4,2 million m<sup>3</sup> for the bioreactor. This potential is too low to explain the observed gas generation as depicted in figure 2.

Table 5 – remaining gas potential in week 19, 2000

	gas potential in fermentation test (m <sup>3</sup> per tonne MSOR /m <sup>3</sup> per tonne dry organic material)	gas formation in bioreactor until week 19, 2000 (m <sup>3</sup> per tonne MSOR /m <sup>3</sup> per tonne dry organic material)	% of potential formed
wet fraction	25,6/233		70 %
dry sample	22,9/118		73 %
total bioreactor	24,3/175	61/270	71 %

Dry organic material (as % of dry material) and biogas potential in the fermentation test do not differ so much for the wet and the dry sample. If there is any difference, the dried material is somewhat lower in dry organic material and gas potential, suggesting that conversion of drier organic material is somewhat enhanced. So if there is any effect of wetting on rate of biodegradation it seems to be an inhibition. This may be explained by reduced mobility of methanogens, nutrients and inhibitors under saturated conditions. This is in line with laboratory work Klink and Ham (1982), from which was concluded that moisture movement, rather than moisture content determines the rate of biodegradation.

### 3. LAB-SCALE RESEARCH

Processes in the bioreactor during the 30 years treatment period were studied using laboratory scale test columns (0,3 m diameter; 2,1 m height, waste density 1,200 kg m<sup>-3</sup>). Leachate from the methanogenic part of the Essent landfill in Wijster was infiltrated upwards through the columns in most columns, while one column was infiltrated downwards to enable comparison with the full-scale bioreactor. The first three columns were stabilised anaerobically and subjected to different treatment methods after methanogenesis. The treatment procedures are summarised in figure 3.

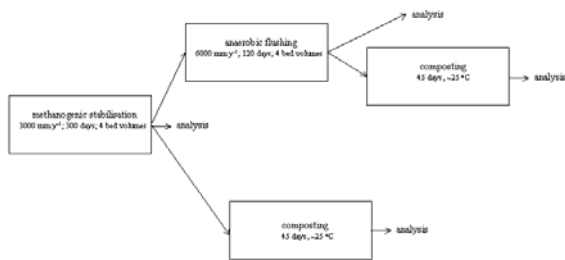


Figure 3: Overview of lab-scale treatment of MSOR

Monitoring focused on initial waste composition, biogas formation, biogas quality, leachate quality, and changes in waste composition during treatment. Samples of the leachate drained off were collected and analysed on common quality parameters. The cumulative gas production was measured continuously (by wet gas-meters), while the gas composition was analysed on a monthly basis (by a combined CH<sub>4</sub>/CO<sub>2</sub>-analyser). More details of this lab-scale research are presented by Vroon et al. (1999) and van der Sloot et al (1999).

Full methanogenic conversion of the organic material was achieved in about 300 days, after infiltration of about 4 bed-volumes of leachate. Taking into account the organic material that is flushed out as BOD in leachate, the maximum conversion of organic dry material is estimated to be about 70%. The observed gas production at maximum conversion is 140 to 150 Nm<sup>3</sup> of biogas per tonne MSOR (570 to 610 Nm<sup>3</sup> of biogas per tonne organic dry material). Leachate infiltration in the downwards-infiltrated reference column was limited to 460 mm y<sup>-1</sup> due to the low permeability of the MSOR. Biodegradation in this column was slow compared to the enhanced columns and about 130 Nm<sup>3</sup> biogas per tonne organic dry material was produced in the first year (which is comparable to the biogas production in the full-scale bioreactor).

When exposed to aerobic conditions in a mini-composting installation, the decrease in organic material in the anaerobically stabilised product was limited to negligible. Obviously anaerobic stabilisation consumes all rapidly degradable material, resulting in a stable residue.

As indicated in table 2, the heavy metal content of the leachate is significantly reduced during methanogenesis. Concentrations in BOD, Cl<sup>-</sup>, N<sub>kj</sub> and P are not affected in this period. Flushing with clean water significantly reduced concentrations of all contaminants, although N<sub>kj</sub> and BOD are reduced to a lesser extent than the other components. Obviously N<sub>kj</sub> and BOD are still being produced in significant amounts during the flushing phase.

The leaching behaviour of heavy metals is almost entirely governed by the organic material and for all heavy metals a clear correlation exists with the amount of organic material suspended and dissolved (TOC). Obviously complexation to TOC is the major mechanism for leaching of heavy metals. Non-volatile organic contaminants as PAH proved to have a similar leaching behaviour. Figure 4 indicates the leachability of TOC for untreated and various treated materials. As a result of the methanogenic conversion TOC-leachability is significantly reduced. Aerobic treatment doesn't affect leachability. Flushing of the material however gives significant improvement.

The acid-base neutralising ability of the material has increased much upon methanogenesis. This buffer capacity might be contributed to the formation of humic acids or precipitated CaCO<sub>3</sub>. The cation exchange capacity (CEC) of the MSOR doesn't change much upon treatment (a slight increase from 31 to 36 meq per 100 g dry material). For comparison: humus has a CEC of 400-800 meq per



100 g dm. Assuming that all CEC is due to the organic matrix, an increase is observed from 75 to 160 meq per 100 g dry organic material; still considerably lower than the CEC of humus.

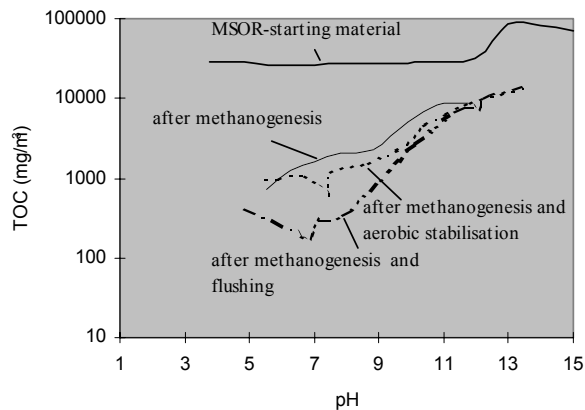


Figure 4 - Leaching behaviour of TOC. Heavy metal leaching follows identical patterns

#### 4. OPTIONS FOR RE-USE OF THE STABILISED MATERIAL

As described above, the product of bioreactor treatment has certain attractive qualities: biological stability, low leachability of heavy metals, low permeability and its capacity to immobilise heavy metals. Based on these qualities, some reuse possibilities are identified:

- using its high binding capacity for heavy metals and its low hydraulic permeability, the material might be used in bottom- or top-liner systems of landfills. This can be considered a moderate to high added value with moderate market potential/market size option
- filling material for landscape reconstruction: a low added value but high market potential/market size option

#### 5. ATTAINABILITY OF THE CRITERIA

##### *stabilisation of the material*

In the full-scale bioreactor stabilisation of the organic material progresses rather fast, even when moisture infiltration is not as effective as originally planned. Fermentation tests on drilling samples indicate that biodegradation in dry parts of the bioreactor proceeds just as rapidly as biodegradation in wet parts, so despite the inhomogeneous moisture infiltration, biodegradation seems to progress rather homogeneously. Half-time of biodegradation in the full-scale cell is estimated to be 2 years, so in about 8 years time full stabilisation might be almost achieved. In the lab, MSOR anaerobic stabilisation was enhanced through high rate leachate recirculation. This stabilised MSOR remains stable under aerobic conditions.

Moisture content does not seem to affect biodegradation that much (in the humidity range considered). This doesn't imply that leachate recirculation is ineffective in enhancing biodegradation. Promoting moisture movement most likely will enhance biodegradation, as observed in the lab-scale experiment. Both the full-scale and lab-scale and lab scale experiments make conceivable that the criterion on MSOR-stabilisation can be met.

##### *conversion of waste to energy/CO<sub>2</sub>-emission reduction*

Gas production in the first two years was 2,8 million m<sup>3</sup>. This biogas was of a good quality is converted to energy in a gas-engine and generator. The energy production is 18 PJ and upon utilisation

a carbon dioxide emission reduction is achieved of 2,8 tonne. The estimated gas potential is 5,7 million m<sup>3</sup>, which will produce 36 PJ on utilisation (0,8 GJ per tonne MSOR). When incinerated with energy production, the 49.500 tonne MSOR will produce an estimated 0,9 GJ per tonne, so the energy production from the bioreactor is almost comparable to energy production upon MSOR-incineration. When comparing CO<sub>2</sub>-emission reduction, the energy production is not the only aspect of interest. Upon incineration fossil carbon in plastics is incinerated and emitted as CO<sub>2</sub>. This emission has to be considered in the calculation, rendering incineration as a net emitter of CO<sub>2</sub>. On the other hand, in the biological process, part of the organic carbon is stored for longer times and this should be considered as a carbon dioxide emission reduction. In table 6 it is calculated that when all CO<sub>2</sub>-effects are taken into consideration, bioreactor technology is superior to incineration with regards to greenhouse gas emissions.

Conclusion is that the objective of comparable energy production is almost met. When CO<sub>2</sub>-emission reduction is considered, bioreactor technology is superior.

Table 6 - CO<sub>2</sub>-emissions upon treatment of MSOR in the bioreactor compared with MSOR-incineration (kg CO<sub>2</sub> per tonne MSOR)

	Bioreactor	incineration
emission reduction through energy utilisation	-121	-150
emission due to incineration plastics		180
emission reduction due to storage organic carbon	- 67	
total	-188	30

#### *emissions to air*

During construction the waste has been in contact with the atmosphere for over 100 days. The aerobic conversion of waste (loss of energy) and the methane emissions in this period were limited and met the demonstration objectives. For future bioreactors, a somewhat prolonged construction period seems to be acceptable. Emissions of odour during construction were not negligible, so this objective was not met. In future bioreactors odour emissions might be avoided by minimising storage of waste prior to deposition in the bioreactor.

The conclusion seems to be justified, that the criteria on emissions to air can be met in future bioreactors.

#### *emissions to soil- and ground water*

In the two years operation time, the quality of the leachate of the bioreactor cell has considerably improved. The lab-scale research gives more mechanistic information on development of leachate quality. Leachability of heavy metals is correlated to the amount of suspended and dissolved organic material (TOC). Upon elapsing methanogenesis TOC will be drastically reduced, so the objectives for heavy metal concentrations in the leachate will be met when anaerobic stabilisation is complete. Objectives for Cl<sup>-</sup>, O, BOD, N<sub>kj</sub> are not met after methanogenesis and need the flushing phase, where Cl<sup>-</sup>, BOD and P are more easily reduced than N<sub>kj</sub>. In order to reduce these concentrations, the possibility to flush the MSOR with large amounts of leachate becomes critical. For further reduction of N<sub>kj</sub>-emissions, application or storage under aerobic conditions might be considered. So the objective on negligible emissions to soil and groundwater can only be met when technological solutions are found to ensure the homogeneous flushing of large amounts of water.

#### *Reuse of the MSOR-product*

The product of lab-scale treatment met Dutch guidelines for building materials. In combination with its other properties (low permeability, capacity for immobilising trace materials) this enables reuse. Several options are identified and the perspective for reuse seems to be good. It is considered therefore conceivable that this criterion can be met.

## 6. CONCLUSIONS

At Essent in Wijster, the Netherlands a 49.500 tonne bioreactor is constructed and operated. Biodegradation was very fast with a half-time of about 2 years. Leachate infiltration was seriously hampered by the unexpected low hydraulic permeability, but a solution to this problem was found by infiltrating leachate under slight overpressure. After having injected 1/3<sup>rd</sup> bed volume of leachate, moisture distribution is still very inhomogeneous.

It is conceivable that the criteria for bioreactor application can be met:

- the organic material will most likely be stabilised, even when leachate infiltration is not as successful as planned. Anaerobically stabilised material seems to be stable, when exposed to aerobic conditions;
- the energy production from MSOR is almost equal to the energy production in case of MSOR-incineration. When compared for its contribution to carbon dioxide emission reduction, the bioreactor is superior;
- methane emissions to air during construction are negligible; measures for a further reduction of odour emissions are defined. Emissions of heavy metals to soil and groundwater seem to be low when the organic material is stabilised. For acceptable levels of N<sub>kl</sub>, Cl<sup>-</sup>, BOD and P a successful flushing phase is required;
- a product is obtained that can be re-used within existing legislation

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