Digestion and degradation, air for life

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Abstract Anaerobic degradation of dead biomass is a natural gasification process, an anaerobic crematorium producing a very useful end-product composed of methane and carbon dioxide, generally polluted with small amounts of some malodorous and quite toxic volatile S-compounds. It leads to the production of essential building elements for new life. This exciting field became my faith, vision, hope and expectation. This paper intends to present a reflection of more than three decades of research, teaching and advertisement in the field of sustainable environmental protection technologies, particularly of systems based on anaerobic digestion and the biological sulphur cycle. Considerable progress has been made during these decades worldwide, both in the basic understanding of the various processes and concepts, but also in the implementation of these systems, despite the fact that particularly the implementation frequently proceeded very laboriously. The difficulties certainly can no longer be attributed to technological limitations and/or insufficient understanding of the microbiology and chemistry only, but mainly to the frustrating social rigidity and short-term self-interest in all sectors of our society. By combining anaerobic processes with other microbiological degradation or transformation processes, like those based on the biological sulphur cycle, micro-aerobic and conventional aerobic and anoxic processes, ideal conditions can be created to valorise residues (wastes) from domestic, industrial and agricultural origin. It is simply not just “technology”, but also a route to achieve more sustainability and justice in society. It is a fight against conservative establishments. Decomposition, disintegration disb andment, it also stands for deliverance and liberation, space and air for continuation of life.

Keywords anaerobic digestion; anaerobic wastewater treatment; biological sulphur cycle; decentralised sanitation and reuse (DESAR); environmental protection and resource conservation (EP&RC); sustainability

Development of anaerobic wastewater treatment (AnWT) and biological S-cycle systems

Anaerobic digestion and wastewater treatment systems

The statement made by P.L. McCarty in the sixties, viz. “Anaerobic wastewater treatment doesn’t enjoy the popularity it truly deserves”, convinced many researchers that AnWT should be their main field of research (McCarty 1964). It was, and still is an extremely challenging field, the more so because it is not simply technology. Technologists are also faced with a lot of sociology regarding the big difficulties to implement AnWT-systems.

AnWT in South Africa in the fifties and sixties. Full scale experience with AnWT for concentrated industrial effluents using the reversed flow Dorr-Oliver Clarigester existed already in South Africa in the fifties (Stander, 1967). This system could be regarded as one of the precursors of sludge bed reactors, viz. the Upflow Anaerobic Sludge Bed process, (UASB) (Lettinga et al., 1980) and the Expanded Granular Sludge Bed process (EGSB) (Kato et al., 1999; Lettinga, 1995, 1996; Lettinga et al. 1980, 1984, 1999; Rebac et al., 1998). In South Africa in the sixties also interesting microbiological and biochemical research was conducted for characterising anaerobic sludge (Thiel, 1969; Siebert, 1967; Hattingh and Siebert, 1967; Thiel and Hattingh, 1967; Pretorius, 1972), and even promising AnWT-pilot plant feasibility studies were carried out dealing with the treatment of sewage (Simpson, 1971; Pretorius, 1971). During a round-trip in S-Africa in 1979, I had the opportunity to visit a full-scale reversed flow Dorr-Oliver clarigester treating wine...
distillery wastewater. Upon examining the sludge present in this reactor, to my big surprise, I observed that it was completely granular of character. Apparently nobody in S. Africa, despite all the microbial and biochemical work, ever noticed this or understood its importance. The engineers involved in reactor technology research were fixed on the idea that the retention of a maximum amount of sludge and mixing of the reactor contents comprised the main problems. Obviously the engineers involved lacked a sufficient understanding of the principles of the anaerobic digestion process, i.e. its microbiology and reactor technology. But presumably also quite a lot of preoccupation concerning the feasibility of AnWT prevailed, and possibly (already) some commercial disinterest from the side of the conventional (aerobic) wastewater engineering establishment. It was the end of the AnWT-story in S. Africa.

AnWT in the USA. Since the fifties important research in the field of AnWT has been conducted in the USA, viz. dealing with process technology, microbiology, (bio-)chemistry and some modelling as well. The most important work made during that époque undoubtedly was from the group of Perry McCarty (Young & McCarty, 1969). They made a tremendous contribution to the real understanding and further development of AnWT, particularly concerning the anaerobic filter (AF) systems. In the USA scientists and process engineers seriously attempted to get AnWT implemented for industrial wastewater treatment and even for sewage (Coulter et al., 1957), for which purpose they combined an upflow sludge bed tank + AF. Many of them were convinced of the huge potential of AnWT, and some of them (viz. Speece (1983), Switzenbaum, Jewell, Dague) continued working in the field, despite all the sepsis and obstruction from the side of the established sanitary engineering world. Contrary to the researchers in South Africa, they clearly recognised the crucial importance of bacterial immobilisation, i.e. their aggregation in flocs or biofilms, as we understood this for the granulation phenomenon (e.g. Hulshoff Pol et al., 1981, Visser et al., 1993, Alphenaar et al., 1993). In the eighties a quite promising immobilised sludge system, viz. the AAFEB- process (Anaerobic Attached Microbial Film Expanded Bed) was introduced by Jewell et al. (1981). However, despite all their efforts, a breakthrough with respect to the application didn’t come off in the USA. Due to that, hardly any funds came available for research, and therefore only very few people were able to continue research in the field. In the USA the reluctant attitude against AnWT still persists, presumably mainly due to prejudice, scientific and commercial disinterest, particularly from the “established groups” working in conventional aerobic wastewater treatment (AeWT). This “establishment” is unwilling to understand the enormous potential of AnWT for sustainable environmental protection. The experiences with the development and implementation of AnWT in South Africa and USA clearly illustrated that established groups (business, university, and politics) constitute a major barrier for achieving more sustainability in this world.

AnWT in Europe. Prior to 1970 the interest in AnWT in Europe was negligible, in fact, like elsewhere, even negative. But for some researchers, after having read the papers of McCarty, it presented a big challenge to start working in this field. Our first research in 1970 concerned a study aiming to assess the applicability of the AF-system for potato starch wastewater, because this effluent represented an enormous environmental problem in the North-East of the Netherlands for many decades. We obtained very promising results, and – in fact like Young and McCarty – we noticed that for retaining the anaerobic sludge no packing material was required. This resulted in the development of the UASB system, like the AF system an extremely simple reactor concept. In the early seventies it has been tried out at small and big pilot plant scale for sugar beet wastewater and potato-starch wastewater, later
for various other types of agro-industrial effluents. We succeeded to scale up the UASB system from laboratory scale to full scale within only 4–5 years as a result of:

- the excellent co-operation with the CSM-sugar beet company,
- the financial support of the Dutch government,
- the fact that polluting industries were forced since 1970 to treat their wastewater, or to get it treated,
- the excellent co-operation for many years with scientists from the microbiological field, in our case with the group of Zehnder and Stams at Wageningen Agricultural University.

As a consequence, industries became interested in the development of cost effective new treatment methods, in order for example to become self-sufficient.

Already in 1976 the first 200 m$^3$ demonstration reactor was put into operation at the CSM-factory in Halfweg, The Netherlands, and the next year the first full scale UASB reactor (1,000 m$^3$) was put into operation (de Vletter 1977), followed by many others in the eighties and nineties. Since the mid-nineties EGSB reactors have become increasingly popular, mainly because of their very high loading potentials compared to conventional UASB reactors. EGSB reactors are very feasible for treatment of very low strength soluble acidified wastewaters (COD < 150 mg/l), even at very low ambient temperatures of 4–10°C.

In view of the above, the implementation of AnWT proceeded rather smoothly in The Netherlands, despite the sepsis and prejudice also prevailing here in the world of the established conventional urban wastewater treatment. Since wastewater treatment in The Netherlands in the seventies still was in the preliminary stage of implementation, a lot of work was waiting in the public sanitation sector. The resistance against the development and implementation of AnWT for application in the industry remained relatively small. And gradually more polluting industries became interested in AnWT. New polluting control industries, viz. the companies Paques B.V. and Biothane Int. B.V. and some consultants succeeded to develop world-wide the new AnWT pollution control market segment.

Modern AnWT systems offer a number of very important benefits over conventional AeWT systems (Table 1). This was particularly recognised by polluting industries. However, apparently so far not world-wide, because in a country like the USA and in Latin America the implementation still proceeds laboriously.

When properly designed and operated the application of AnWT and AnDi (anaerobic digestion) systems as primary/secondary treatment methods for liquid, slurries and solid wastes will also lead to a reduction of the release of greenhouse gases (Lexmond and Zeeman, 1994). The knife cuts from two sides. Taking for granted that AnWT merely is a pre-treatment method, because it is only effective in removing biodegradable organic pollutants, it virtually doesn’t suffer from serious drawbacks. So, any malodour nuisance, frequently brought up as a drawback, can be easily prevented in the modern systems. And with respect to process stability, presumed to be small in textbooks, it can be stated that they are as good as any other biological system, likely even better. It is just a matter of proper design and operation, consequently

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<th>Table 1</th>
<th>Benefits of modern AnWT-systems over conventional aerobic systems</th>
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<tr>
<td>• Relatively very simple technology, like reactor systems such as UASB, AF, EGSB, or hybrid reactor types,</td>
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<td>• Applicable everywhere and at any scale, because little if any energy demands, therefore high self-sufficiency,</td>
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<td>• Very compact systems in view of the very high applicable organic and hydraulic loading rates,</td>
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<td>• No consumption of resources, but rather the production of energy carriers in the form of biogas, and fertilisers like ammonia and phosphates, and non-biodegradable residues as soil conditioners.</td>
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<td>• Feasible for a wide range of waste and wastewaters, i.e. complex in composition, very low and very high strength, low and high temperatures,</td>
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<td>• Very well applicable for campaign industries, because adapted anaerobic sludge can be preserved under unfed conditions for a long period of time.</td>
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of sufficient understanding of the basic principles by designers and operators. This was never
the case in the past with the involved civil engineers, who monopolise the sanitation field.

AnWT elsewhere in the world. Elsewhere in the world little if any use was made of any
modern AnWT system until recently, and therefore this also was true of the research in this
field. However in countries like China and India anaerobic digestion processes have been
extensively implemented for digestion of farm and domestic residues, i.e. for the produc-
tion of energy (biogas) and fertiliser and soil conditioners. In the meantime the interest
increased quite significantly.

Treatment systems based on the biological S-cycle
In the early eighties we started research on the application of methods based on the
biological-sulphur cycle ($S_{bio}$ C) in close co-operation with the group of Kuenen of
the Technical University Delft (e.g. Keunen and Robertson, 1992). These methods in many
aspects are complementary to AnWT and AnDi methods.

The $S_{bio}$ C consists of:

• **a reductive part**, i.e. the microbial processes involving the reduction of oxidised forms
  of sulphur, viz. sulphate, sulphite, elementary sulphur. Generally these processes
  already proceed in anaerobic reactors, where they lead to the production of $H_2S$, which
  partially will appear in the biogas and in dissolved form in the effluent or accumulate as
  insoluble sulphides in the sludge. Under unbalanced anaerobic conditions quite mal-
  odorous and toxic volatile organic compounds will be formed, like mercaptans, disul-
  phides, etc.

• **oxidative part**, where reduced S-compounds are converted into more oxidised sulphur
  compounds, depending on the conditions prevailing in the systems. So, under well con-
  trolled conditions of redox-potential (Jansen et al., 1998) and the supply of oxygen they
  will be converted into elemental sulphur. This process offers enormous perspectives for
  eliminating $H_2S$ and likely also various other volatile S-compounds from polluted
  liquids and gases.

The reductive and oxidative part of the $S_{bio}$ C therefore can be applied in an integrated
sequential set-up. So for instance in case of the presence of oxidised S-compounds first the
reductive part is applied in order to produce $H_2S$, and next the oxidative part to convert $H_2S$
into elementary sulphur. When combining $S_{bio}$ C processes with AnWT and various types
of physical-chemical processes, we’ll have available really sustainable Environmental
Protection and Resource Conservation (EP&RC) concepts. Recently evidence has been
obtained that the $S_{bio}$-C offers interesting possibilities to be combined with the $N_{bio}$ C for
the removal of ammonia-N by sulphate reduction (Fdz. Polanco et al., 2001).

The impact of the implementation of methods based on environmental protec-
tion and resource conservation (EP&RC)
The concept “sustainability” stands for the idea that the present and coming generations
should preserve resources, energy and a balanced healthy life environment for the future
generations. It clearly represents a long-term objective! However, considering what is
going on in our present world, we observe an ever growing number of very poor, while at
the same time the few very rich are becoming richer, like in fact also the prosperous indus-
trialised world. Since most discussions about “sustainable development” are taking place
in the prosperous world, some serious doubts arise concerning the real intentions of the
industrialised world e.g.

• Do we really want to leave something of the resources for those we never will know?
• Can sustainability be achieved when politicians (Brundlandt Commission) at the same
time postulate that “we” need a continuing “economical growth”? Even although they also state there should be a guarantee that the poor will share in this growth? But who can or is willing to guarantee that?

In theory sustainability may be achievable, but in real everyday life it is quite doubtful, regarding the daily concerns and priorities of people, i.e.:

- their own survival, e.g. a long good life, employment, business etc.
- retaining, even improving, the privileged conditions.

The industrialised world “wants, or even needs”, an ever continuing economical growth, and due to that, an ever on-going technological innovation of any kind, just for the sake of business, money making and employment. As a consequence almost all discussions concerning sustainability in daily life are extremely tunnelled, e.g. sustainable enterprising, sustainable money investment, achieving or maintaining a super high quality of “our” surface water, air or soil, regardless of the resources needed for that. In the light of the Brundtland definition given, this is far away from the meaning of the sustainability concept, which is an ongoing process of maintaining good life conditions for those who are coming. In the light of this some Sustainability Commandments (criteria) for the field of environmental technology are listed (Table 2).

As a matter of fact various methods are already available, or at least can be made available at relatively short notice, which comply with these criteria, viz. integrated methods consisting of AnWT and S_{bio} C systems, combined with proper AeWT and physical-chemical processes. Regarding this, the question arises: “Why have these methods not been already implemented world wide?”

The explanation is relatively simple. There are not merely technological, but particularly also social and economical bottlenecks which prevent their rapid wide scale implementation. The majority of the politicians, and likely all free enterprises in the industrialised world need continuous economic growth, and consequently continuous technological innovation. Something new hardly has been implemented and an innovative development is already there, making the “old” system or technology in many cases “inferior”. This process of innovation for the sake of innovation frequently leads to unacceptable destruction of capital, resources and energy to an endless transport of goods and animals and also to an alarming ever-continuing specialisation in all fields, etc. In fact it has not been different for previous centuries. However, most of the innovations in the past led to a significant improvement of the quality of life. But things proceed at an ever-increasing speed; it is becoming a goal in itself, just for the sake of a short-term economic growth. As a result “man” increasingly is alienated from the basis of his existence. There obviously doesn’t exist a real interest to obey commandments like those listed in Table 2, because they don’t lead to economic growth. But an ever continuing economic growth forces things in a direction just opposite from that leading to more sustainability, and consequently irrevocably to some kind of social disaster. Many thinking citizens are seriously concerned about what is happening to us. Some adequate social-economical control instrument is urgently needed, so that society would be capable to cope with even a negative economic growth, which likely would move society in the direction of more sustainability, more robustness and more

Table 2  Relevant long term sustainability commandments to be met for environmental technologies

- Little if any use of mineral resources and energy,
- Enabling production of resources/energy from wastes,
- Pairing high efficiency with long term of life,
- Applicable at any place and at any scale,
- Plain in construction, operation and maintenance

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stability. The good things need to be more equitably distributed, i.e. all kinds of available resources, available employment etc.

Considering the field of environmental protection, it certainly is not true that all concepts and methods applied elsewhere in the world (e.g. in developing countries) or in the past, are so inferior. Moreover, old methods or concepts frequently can be improved relatively easily on the basis of present insights and with modern technologies. In many cases this can be accomplished in a simple way. But doing things simply does not belong to the habits of the modern industrialised world.

Fortunately there exists evidence that plain, robust and sustainable technologies like AnWT and S\textsubscript{bio}C systems are going to make it! Particularly when combined with adequate AeWT and physical-chemical post-treatment systems all sustainability criteria can be met.

For the above-mentioned reasons we believe that the impact of the implementation of methods like AnWT will become very significant in at least two aspects, viz.:

1. achieving a healthy and ecologically balanced environment, because these methods will become increasingly applied for:
   a. waste and wastewater treatment, resource recovery and also pollution prevention,
   b. energy production as a conversion technology for various types of biomass

2. achieving a more balanced society:
   a. with more public awareness
   b. more self-sufficiency.

In the following this will be illustrated on the basis of the present application of AnWT, AnDi and \textit{S}\textsubscript{bio}C methods in industry, public sanitation, for energy generation and in the agricultural sector.

\textbf{Present application and applicability of AnWT, AnDi and S\textsubscript{bio}C processes}

\textbf{The industrial sector}

\textit{The field of AnWT & AnDi}. The interest in almost all industrial branches for applying AnWT and AnDi methods is sharply increasing. In many countries, particularly in Europe and Japan, AnWT is considered as “grown-up” technology. Modern AnWT systems are very flexible systems, i.e. feasible for treating low, medium and high strength industrial effluents, applicable at low temperatures in the range 1–20°C (Koster \textit{et al.}, 1985, Rebac \textit{et al.}, 1998,) and high temperatures viz. between 50–70°C (Van Lier, 1996, Wiegant \textit{et al.}, 1985), and for simple and quite complex wastewaters. They also have been found to be capable of accommodating quite high salt concentrations, even of ammonium salts (Van Velsen, 1979, Koster \textit{et al.}, 1988. Zeeman \textit{et al.}, 1985).

Very significant progress has been made since 1975 in treating effluents of most agro-industries, except for those from slaughterhouses and the dairy industry. Although they are well applicable for these effluents, the implementation proceeds much more laboriously (Rinzema \textit{et al.}, 1993, Petruy \textit{et al.}, 1997, Sayed., 1988). AnWT has been shown to offer very interesting potential for treating the effluents of forestry and paper industry (Field \textit{et al.}, 1990 a,b; 1991; Sierra-Alvarez \textit{et al.}, 1990; Kortekaas \textit{et al.}, 1998), for highly saline wastewaters such as from the sea food industry (Omil \textit{et al.}, 1996) while the potential for treatment of wastewaters from chemical and petro-chemical industries are quite good, despite the fact they frequently contain quite complex, sometimes toxic compounds. This progress can be attributed to the rapidly improving knowledge and understanding of the microbiology, (bio)chemistry and process technology. New “staged” AnWT systems will soon become available, i.e. reactor systems composed of modules consisting of UASB, upflow and downflow AF systems, and EGSB reactors or hybrid AF-UASB reactor systems (Elmitwally \textit{et al.}, 1999). Also specific types of fluidised bed reactors might become definitely feasible, like the system introduced by Iza (1991).
Quite promising new developments concern the integrated anaerobic- (micro-) aerobic treatment systems, processes applying chemical compounds (natural as well as synthesised) as mediator for the transfer of electrons, and AnWT systems integrated with physical-chemical methods. The perspectives of integrated AnWT treatment systems therefore are enormous, enabling the degradation of all kinds of “very difficult compounds, like higher fatty acids, azo-dyes, aromatic compounds, viz. toluene, terephthalic acid, nitro- and chloro aromatics etc. More information can be found in the literature, e.g. publications of staff members and PhD-students of our group (Field et al., 1990, 1991; Hwu et al., 1998; Kleerebezem et al., 1999; Razo-Flores et al., 1997, 1999; Sierra-Alvarez et al., 1990, Sierra et al., 1994, Tan et al., 1999, Van Eckert et al., 1999).

A very promising and exciting field of research undoubtedly represents the investigations dealing with the effect of trace elements (Florenic et al., 1994, Gonzalez-Gil et al., 1999). Various trace elements exert an extraordinarily strong effect on anaerobic conversion reactions, but so far very little quantitative information is available. Regarding the complexity of this matter, it requires an integrated multi-disciplinary attack. We feel fortunate having been enabled to co-operate in this new field with researchers of the departments of Microbiology and Physical-colloid chemistry on the basis of financial grants of the Dutch research foundation STW.

AnWT comprises pre-treatment, but by combining it with complementary biological systems like micro-aerobic methods, specific types of AeWT systems (conventional or newly developed) and/or physical-chemical treatment systems, a very complete treatment can be accomplished. Moreover excellent options are then created for recovery of useful by-products.

Regarding the present situation in the field of AnWT in The Netherlands, undoubtedly by far the most progress has been made in the industrial sector. This increasingly leads to the implementation of more advanced – but still technologically relatively simple – concepts, enabling industries to close their water and materials/matter cycles in future. This represents the ideal situation, zero discharge, as a result of reuse of very well treated water and recovered by-products. In many cases a very profitable use can be made of chemical precipitation processes, i.e. insoluble salts carbonates, phosphates, sulphides, of which many frequently already proceed in AnWT treatment systems (Van Langerak et al., 1999). Precipitation of sulphides is particularly interesting under conditions of sulphate reduction.

Regarding the very distinct economical advantages this development irrevocably will continue. It will make industries increasingly more self-sufficient with respect to environmental protection measures they need to take. Despite this, in food industries the closing of water and matter cycles tentatively proceeds rather laboriously. This can be due to a kind of “image” problem, i.e. the doubt the customer might have with the quality of the foods produced. But this is likely to be just a temporary problem.

Since AnWT and AnDi systems create very proper conditions for the production and recovery of useful products, they constitute the core method in water and material recycle treatment concepts, as illustrated in Figure 1.

S\textsubscript{bio}C processes. The presently available S\textsubscript{bio}C based treatment systems are relatively new, but regarding their large potential in EP&RC (Environmental Protection and Resource Conservation) concepts, they undoubtedly will find wide scale and world-wide implementation in future. There potentially exist many options for application for the treatment of wastewater(s), polluted gases (e.g. natural gas, biogas and exhaust gases), polluted soils and for the recovery of metals from polluted effluents, solids etc.

A very recent development of an oxidative S\textsubscript{bio}C process comprises the conversion (almost stoichiometric) of sulphide and/or H\textsubscript{2}S into elementary sulphur. This process
already found full-scale application for the removal of H$_2$S from biogas and natural gas, and of sulphides from aqueous solutions (e.g. Buisman et al., 1990a, b, Janssen et al., 1998). The potentials of the method are enormous.

The S$_{\text{bio}}$C processes also offer big potential for the removal of sulphate from wastewaters and of SO$_2$ from off-gases. In this case first the reductive part of the S$_{\text{bio}}$C needs to be applied (Lens et al., 1998), followed by the above mentioned micro-aerobic oxidation process for the conversion of sulphide into elementary sulphur. The system also offers interesting potential for the degradation of various other, malodorous and hazardous, volatile S compounds like mercaptans and methylsulphides.

Processes based on the S$_{\text{bio}}$C already found full-scale application for the extraction and recovery of Zn from polluted soil. There exist numerous other applications for removal and recovery of heavy metals, e.g. from acid mine drain water, or from industrial wastewaters.

Since the systems based on the S$_{\text{bio}}$C are of very recent date, their breakthrough in practice will need some more time. This particularly is true for those applications where there already exist established technologies, even although these might be (much) less economical or sustainable. Regarding their newness undoubtedly attractive innovations can be expected and in the meantime the required scientific and commercial infrastructure can develop further.

**Implementation aspects.** Despite the very significant benefits of AnWT, AnDi and also S$_{\text{bio}}$CT systems, it appears to be difficult to get these systems implemented in countries like the USA, despite almost 2 decades of very satisfactory full-scale experience with industrial wastewater treatment. Apart from factors like prejudice and commercial interest from the side of establishment(s) in conventional treatment methods, other reasons for the low popularity can be found in the following:

- Poor experiences of companies with implemented AnWT systems, i.e. malfunctioning of their systems. Although the latter mainly can be due to lack of knowledge and experience in the field, they frequently stop the further marketing in favour of conventional treatment systems, and they start making bad advertisements about AnWT in general.
- Lack of reliable information about the potential of the technologies,
- Complete absence of academic, bureaucratic and commercial infrastructure in the region/country.
• Unwillingness of authorities to take any risk to implement something “completely” new in the public sector.
• Absence of interest in “plain” treatment systems, e.g. for reasons of scientific prestige of expected unemployment problems.

**Agricultural sector**

AnWT and AnDi processes inherently are ideally suited for the agricultural sector, for on-site production of energy, fertilisers, soil-conditioners from agricultural residues and for environmental protection purposes as well. Virtually every agricultural waste/residue, like any other natural type of “biomass” are well amenable for anaerobic digestion. Presently a variety of digestion technologies are available.

• **Conventional AnWT systems** as applied for wastewater treatment such as UASB reactors, AF systems.
• **Conventional sludge digesters** of the type applied in municipal sewage treatment installations. Based on present insights in the digestion process, more cost-effective reactor and process technology and optimal designs can be made for on farm application.
• **Accumulation type digested systems**, which are attractive for the digestion of e.g. manure in case the digested residues only can be applied periodically in the fields for fertilisation and soil conditioning.
• **Batch or continuous solid state digesters for ‘dry’ types of biomass** (Baeten and Verstraete, 1993). Solid state systems like the batch type “Biocel” (Ten Brummeler, 1999) are simple in design and in operation and therefore potentially very attractive.

All these installations are relatively low in investment, operational and maintenance cost. Despite that, so far in The Netherlands only very few digesters have been installed at farms while so far only one of the Biocel type has been installed for the stabilisation of refuse.

This is quite different in countries like China and India where AnDi has been widely implemented in rural areas. One of the reasons for poor popularity in The Netherlands undoubtedly can be found in the still low energy prices. However, this is only one of the reasons, because AnDi is much more widely applied on farms in countries like Germany, Denmark and Switzerland, which all enjoy similar low energy prices. Another reason for poor popularity in The Netherlands likely can be found in the fact that the highly industrialised agricultural here is not interested, since it hardly contributes to solutions of prevailing environmental problems of this “agricultural industry”. A type of agriculture, which is unable to utilise a technology like AnDi, lacks sustainability itself. Indeed several serious objections can be brought in against these agricultural practices, viz.:
• stimulation of mono-cultures, which lead to less diversity and to deterioration of soils,
• animal, plant, environment unfriendly practices merely to increase the productivity to the maximum possible level,
• inefficient use of natural renewable resources, like manure, due to big manure surpluses as a result of excessive animal breeding practices,
• deterioration of landscapes and viability of rural areas,
• high vulnerability of our food supply, i.e. dependence of transport sector,
• overproduction of food in Europe, but regional food shortages, like in densely populated regions/countries,
• “needs” large scale transport of fodder, manure, products and animals,
• alienation of men from nature (its nature),
• elimination of “real farmers”, viz. the “workers” with heart for animals, vegetation, natural conservation, characteristic landscapes,
• manipulation of food, viz. functional foods that – according to the advertisement of the
scientist working in the field with their industrial financiers – are meant to improve the quality and life expectancy, but in fact primarily are just big business.

This is a sad – and for society likely – a disastrous development. Agricultural engineers (scientists), agricultural research institutes, universities, agro-industries, together with transport and trade companies and most politicians want, or at least, support this development. Useful residues like manure are considered as wastes instead of as a resource, because no land is available to utilise them, apparently not even for energy production. Although these actors are responsible, they attempt to get the farmers prosecuted for the bad image of their industrialised type agriculture, even including the few “real” farmers left. Since World War II the politicians, the industries, fodder suppliers, the banks, the “consultants” continuously pushed the farmers to more scaling-up and mechanisation, consequently to high and on-going investments, always using the argument that it would make the enterprise economical. But this never was the case, except for a very few very big farms. It was false information, unfortunately still on-going.

Real farmers deserve big respect, and not merely respect, society needs them like we need sustainable EP&RC systems, the more the better . . . much more than all the highly specialised, but frequently morally blind, engineers and scientists. They, these real farmers, took care of our beautiful and characteristic rural environment and landscapes, for the high natural diversity. Real farmers are also a crucial factor in achieving regional food self-sufficiency, which is less and less the case here. They undoubtedly would be interested in the application of AnDi-systems, because it fits in with their ecological concept. But they need to become properly informed about these methods, which is unfortunately still not the case.

What sense does it make if present farmers are capable to produce 9,000 kg grain/ha in 9–15 hr labour time, while it was 1,500 kg/ha in 370 hr labour time before 1940 (Van Kasteren, 2000)? His income does not improve. Why could it not be somewhere between these extreme figures, e.g. by using less fertilisers, insecticides and pesticides? This would result in more diversity, a better life for the animal husbandry, in a more viable rural area with more trade and more work for the good stewards for nature and the environment, utilisation of all resources, less vulnerability, much less international transport, etc.

Public sanitation sector

The modern concepts of public sanitation of the prosperous industrialised world seriously lack sustainability, robustness and are not pollution prevention directed. Although the citizens presently undoubtedly enjoy excellent hygienic conditions and a high life comfort at their residential sites, they are going to pay an increasing bill for it. These concepts are based on the “aged paradigm” that waste and wastewater should be conveyed far from our residential sites to some off-site location, where it will be treated in some highly sophisticated, expensive and energy-demanding central sewage treatment plant. Costly sewerage with a life span of 40–50 years needs to be installed, and excessive amounts of costly clean tap water will be wasted as transport medium. Moreover sewerage systems suffer from serious nuisance problems (mal-odour, periodic excavations in cities and villages), whereas they imply risks for uncontrolled discharges of hazardous pollutants into the sewer and uncontrolled discharges of untreated sewage in surface waters due to storm weather conditions. This centralised sanitation concept (CENSA) is inherently a vulnerable system with its high dependence on an undisturbed power supply. They also are not pollution prevention directed, but instead they lead to spreading out of pathogens (present in human excreta) over the environment with huge amounts of transport water and they lead to destruction rather than to recovery and reuse of resources that can be produced from wastes and wastewaters. As a matter of fact CENSA is “a problem creation concept”, giving business and employment for the public sanitation branch. Well considered, this also is the net result of
strengthening the effluent discharge standards. In order to be capable to comply with these strengthened standards, technological innovations are needed, which lead to capital destruction and to an assault on the already very scarce free space in our country, i.e. for the construction of new huge sewage treatment plants and sewerage. Because of the effect of these innovations on the improvement of the surface water quality, some doubts arise about the real objectives of the involved ministry? The more so, because in The Netherlands it is the Ministry of Public Works that pushes the strengthening of the standards! It is the contrary of sustainable development!

But are there realistic possibilities to develop and to implement a real sustainable, robust and pollution prevention directed solution in the public sanitation sector, and if so, on what terms? In imitation of what already is common practice in the industrial sector. Our answer is clear, it technically is quite well possible and the implementation can be commenced at short notice. Use can be made of already available systems/concepts, even although they might be considered as “aged”, but concepts based on a correct paradigm, viz. “Minimisation of transport of waste and wastewater, separation of concentrated wastewaters, and on-site treatment of wastewater and resource recovery.”

However, the established public sanitation sector including their well developed networks, does all that is possible to prevent this, by letting the public believe, including also the innocent policymakers and politicians, that it is wishful thinking to expect any better alternative for the modern CENSA-systems. So Harremoës (1997), a prestigious authority from the CENSA world, comes off with statements like:

“Local wastewater treatment is not a viable solution in cities, because the approach is either ‘low tech’, which does not live up to established hygienic requirements and risk assessment, or it is ‘high tech’, which suffers from energy consumption.”,

“The present De-centralised Urban Sanitation systems lack on adaptability into the urban environment, manageability & control (maintenance of standards)”.

“There is no miracle ‘low tech’ solution in sight, because it (environmental pollution) is a social rather than technical problem”.

This is a deceiving representation of the actual situation; it indicates that Harremoës either is poorly informed about the potential of methods like AnWT for sewage treatment and modern concepts of Decentralised Sanitation & Reuse (DESAR), or simply not interested. The situation in many respects is exactly the contrary of what he insinuates. Various DESAR concepts/systems are quite well feasible and in fact already available now (Van Lier et al., 1999; Van Buuren et al., 1999), even although in various respects considerable improvements are possible. But exactly the same is happening with conventional CENSA treatment systems. For house on-site application, conventional septic tanks or improved septic tanks can be installed. In countries like China and India well performing big community on-site anaerobic-aerobic treatment facilities are available. Although these systems may not be acceptable for the industrialised world, use can be made of the experiences obtained there. Wilderer (2001) compared the centralised and decentralised wastewater management concepts and formulated some very interesting questions in order to come to workable systems for various situations.

The development of real very optimal DESAR-designs for application in the industrialised world needs some time to eliminate the present practices of the drastic dilution of the – from nature – highly concentrated human excreta. This is an issue of crucial importance in DESAR, because excreta represent perhaps the most hazardous domestic waste for public health. Therefore low cost and well functioning waste(water) collection systems based on separation of black water and grey water need to become available. This can be accom-
plished only step by step, presumably starting with new residential areas and large build-

ings. Obviously we need to get rid as soon as possible of combined sewers in order to avoid
any further dilution of pollutants with rainwater. It fortunately is an issue presently well
acknowledged in The Netherlands, although presumably mainly for reasons to prevent a
further lowering of the groundwater table in urban regions. Regarding the huge investments
already made here for 80,000 km sewerage, sewerage only gradually should be abandoned.
However, in countries still behind (?) in the field of environmental protection, i.e. develop-
ing countries, such huge mal-investments for installing CENSA-systems should be
prevented.

The treatment systems to be applied in DESAR comprise the following:

- **AnDi or AnWT systems** for black water, because they comprise a compact, cheap and
  quite effective means for removing biodegradable soluble and insoluble organic matter.
  Moreover these anaerobic reactors also suit the treating of slurries/solid wastes, like
  food residues and vegetable and garden wastes. The impact of that is very significant,
  because it leads to big savings in the transport of refuse, particularly for a country like
  The Netherlands with its very centralised approaches. For diluted black water, or com-
  bined black + grey water, an UASB or AF can be applied, or even better, a hybrid reactor
  system (Elmitwally et al., 1999).

- **Physical-chemical treatment processes**, e.g. membrane processes, for the removal and
  (if possible) the recovery of fertilisers from the effluent of the anaerobic reactors.

- **Compact (high rate) or extensive (micro-)aerobic processes** for the treatment of grey
  water and/or anaerobic effluent, viz. for the conversion of (remaining) biodegradable
  organic matter, and for nitrification and pathogen removal.

- **Anoxic treatment systems** for the removal of nitrate.

Undoubtedly the DESAR-concept would highly benefit from specific innovations, such
as particularly for “slurry transport”. The more houses that can be connected to a reactor,
the more economical will the total system be. In tall buildings slurry transport is relatively
simple and a relatively large number of apartments can be connected easily. The reactor,
together with auxiliary equipment, can be installed in the basement.

The issue of recovery and reuse of valuable by-products tentatively will be difficult to
realise. It needs a lot of logistics and the involvement of a number of quite diverse disci-
plines. The schematic diagram in Figure 2 illustrates a possible DESAR system.

One of the biggest challenges undoubtedly was, and in fact still is, the implementation of
AnWT for domestic sewage. The first thing was to prove the feasibility of AnWT for
domestic sewage treatment. Based on financial support from the Dutch government, we
have been enabled to conduct a 64 m³ UASB-pilot plant research in Cali, Colombia, during
the period 1983–1989. The project was a joint effort with Haskoning B.V, a Dutch consult-
ant, the municipality of Cali and the Universidad of Cali. The results of these investigations
clearly demonstrated the excellent feasibility of AnWT for sewage treatment under tropical
conditions, even for very low strength sewage. The impact of these investigations is gradu-
ally becoming significant. So the UASB system is already quite popular in countries like
India (Kalker et al., 1999), Brazil (Florence et al., 2000; Sousa et al., 1996; Torres et al.,
2000) and Mexico. The group of Verstraete in Belgium also demonstrated that direct anaer-
obic sewage treatment is possible provided special attention is given to the particulates (De
Baere et al., 1984). Major barriers for the rapid implementation of AnWT in practice com-
prise the lack of knowledge and experience with AnWT and the frequently complete
absence of an adequate infrastructure. Moreover in most countries the CENSA-approach is
well established, which makes it difficult to motivate engineers to switch to a quite differ-
ent and not well established, perhaps (for them) less prestigious, concept. Nevertheless, the
big benefits suggest, particularly for developing countries, that they select AnWT and suc-
ceed with its implementation, even although it still represents a treatment solution in the CENSA concept. Although there exists a lot of opposition from all kinds of established groups, and still extremely expensive and non-sustainable treatment systems are installed in developing countries, we are convinced that the extensive implementation of AnWT-pre-treatment will come off in tropical countries. They ultimately will replace the presently so popular, and so much advertised (e.g. the involved scientists in their textbooks) oxidation ponds and lagoons as primary treatment method. The latter systems in fact merely are suitable for post-treatment, sometimes even for resource recovery like duckweed ponds (Gijzen et al., in press) and high-rate conventional aerobic systems. AnWT of sewage undoubtedly also will find application in sub-tropical countries, replacing conventional extensive systems like oxidation ponds. In many cases these systems perform very poorly. A typical example is the lagooning system at Alsamra, installed for treating the wastewater of the city of Amman, viz 160,000 m$^3$ per day of rather concentrated sewage. Preliminary results of a 100 m$^3$ two-stage UASB pilot feasibility study conducted at the Alsamra location with the Amman sewage clearly demonstrates the excellent feasibility of AnWT as a pre-treatment step for sub-tropical conditions. And even in moderate climates AnWT might become applicable for pre-treatment of raw sewage, although it then becomes more complex and will require longer hydraulic retention times. An overview of the research carried out over the last 20 years has been presented by Seghezzo et al. (1998).

Energy production from biomass

AnWT and AnDi-systems are attractive energy conversion systems for various types of biomass, e.g. energy crops like sugar cane. As a matter of fact they are far more sustainable than the ethanol production processes, which have been very popular for a number of decades in Brazil. The net energy production using AnDi exceeds that of the ethanol fermentation significantly as illustrated by the figures shown in Table 3 (Lettinga and Van Haandel, 1993). Moreover the AnWT technology is far simpler compared to the production of pure alcohol, and the system is applicable at any location and at any scale. The later could result in a considerable reduction of the transport of the sugar cane. Furthermore the solids remaining after the digestion process represent an excellent soil conditioner and the nutrients are preserved for fertilisation. On the other hand the alcohol is produced at almost 100% purity, whereas the methane is produced in the form of biogas, i.e. a mixture of about 20% CO$_2$ and 80% methane. And transport of a liquid likely is cheaper than of a gas.

Regarding the advantages of the methane over ethanol production, the question arises
Why alcohol fermentation and not methane production? For a country like Brazil the main reasons are:

- liquid fuels are needed for cars and planes,
- transport by car or plane is very popular,
- there seems to be no extra demand for electricity (for its generation biogas is well suited), or these can be met in other ways,
- the commercial interests of landlords, the car industry and oil companies so far is focused on alcohol production.

The prosperous industrialised countries in this respect certainly also will have their specific (self-)interests. The devotion of the rich and the prosperous world to contribute to the improvement of the life conditions of the very poor or for attaining more sustainability in our world, is very small. Illustrative in this connection is the commotion about the threat of a disastrous climate change due to the release of greenhouse gases. But at the same time there hardly exists any concern about the enormous amounts of mineral resources they waste at the expense of coming generations and of the poor who presently attempt to survive. Considering this hypocrisy it looks doubtful if we ever can achieve substantially more sustainability. On the other hand, there still exist people, common citizens, scientists and some politicians, and even powerful multinationals like Shell and BP, who apparently really want to give meaning to the conception “sustainability”. Soon it will become clear what these oil companies really can achieve, or want to achieve.

And there exists also an increasing group of people who believe, many even are convinced that the continuing implementation of sustainable methods like AnWT offers prospects for making substantial progress on the way of sustainability.

### The social impact of the implementation of sustainable environmental protection methods like AnWT

A dangerous discrepancy is developing between the enormous technological achievements of our society and its social and moral impacts. In order to prevent the untimely collapse of our industrialised, robotised and commercialised society, adequate actions urgently need to be taken. We need impulses for smooth but drastic social changes. Aged established structures should resolve to make “space” for new challenging developments and structures. Rigid structures, as I illustrated for the public sanitation world, constitute the major bottleneck for forcing the development in a sustainable direction. These aged structures merely serve the interests of the privileged group they represent. As a result the majority of the citizens have no confidence in their society for achieving substantial progress in sustainability and more social justice.

However, there are some reasons to be not too pessimistic. Sustainable treatment methods like AnWT, once implemented somewhere, will become a crowbar to get rid of out-dated established structures and groups in the field of environmental protection. Because once successfully implemented somewhere – which already increasingly is the case – it irrevocably will find its way elsewhere. No doubt about that! It is in accordance
with the philosophy of the French philosopher and palaeontologist De Chardin (1955): “A truth seen once, even only one mind, ultimately always coercively will impose itself to the totality of human conscience.” Regarding the good experiences with full-scale application of AnWT so far, a rapidly increasing group of highly motivated and experienced people will push the developments forward. As a result even very sceptical and conservative groups and institutions gradually will accept and support these systems.

The implementation of AnWT represents perhaps a very small step in the direction of more sustainability, but it is an essential step. It also will push other developments in society to more sustainability, viz. it will contribute to achieve more self-sufficiency in society such as in food production, to more problem directed policies and to more public awareness. And with that it will contribute to the development of a less “stressed” society, a society in which more priority will be put on essential things for mankind, such as the development of the talents of all individuals. This will lead to what man ultimately hankers for, real happiness.

But in the short term it will contribute to improve the public awareness, a process that already takes place. So citizens gradually become aware that there exist quite a lot of environmental protection hysteria (Rozendaal, 1989) and sometimes misrepresentation by governmental administrations. Awareness is growing that the ever increasing severity of all kinds of standards sometimes are meant more as a stimulant for business (employment and economical growth) and academic research, than for improving the quality of our life environment. A lot of the ongoing commotion concerning issues like “natural soil or surface water quality” looks a kind of manipulation. These issues are repeatedly publicly advertised by the ministries, which at the same time stimulate the deterioration of beautiful characteristic landscapes, free space and nature for the sake of construction of hideous industrial sites, highways and airports. These attainments of the past apparently are abandoned at breakneck speed for the sake of economic growth. But a sustainable development in many respects exactly needs the opposite actions, like for instance in the field of public sanitation development and implementation of proper DESAR-concepts. Therefore society needs to find a tool to get rid of established pressure groups in all facets of society, governmental institutions, universities etc. In this respect society could learn something from the way anaerobic granular sludge, immobilised consortia of organisms, grow in amount. In EGSB reactors, which rely completely on the maintenance of granular sludge, an excessive growth in size of the granules should not occur. This would deteriorate the performance of these systems, e.g. due to the occurrence of flotation of the granules and substrate transport limitation problems within the aggregate. For this reason the granules occasionally need to fall apart in small fragments, in order to increase the amount of granules with the proper size. But the fragments should not be too small, because these might be rinsed out from the system. A balanced process of breaking up and renewed growth needs to proceed. But sometimes we also need a much more complete disintegration of the mother granules, though without destroying the micro-ecosystems already present. We need new organisms, required for the degradation of some new pollutant, to be incorporated in the micro-ecosystems. Disintegration for the sake of renovation! So, as with augmentation of granular sludge, we should be able to manage our society in such a way, that aged established structures are timely disrupted.

Mankind has to go a long and difficult way, but according to the fascinating philosophy (not really accepted by the Roman Catholic Church at that time) of the Jesuit Teilhard de Chardin (1955) “For a fundamental part we, mankind, have the evolution in own hands, through its past we are compelled to its future!” Man in fact more or less discovers that he is nothing else than the evolution itself that he is becoming aware about it. This holds for mankind in its totality, but likely also for each individual life. The essence is to proceed in...
the correct direction; each small step on this route is one, it is not necessarily to get to the final destination.

Life can become more worthwhile for a lot more people, “simply” if no problems would be created (e.g. for business and employment), as frequently is the case nowadays. A lot of the work carried out under high stress nowadays in the industrialised world better could be remain undone, or at least performed in a much more relaxed way, when it really makes sense. It will result in more sustainability, and undoubtedly also in less materialistic prosperity, but we’ll gain time and energy for developing our talents. And this represents a new and motivating challenge for “new style” universities. Not (mainly) business directed universities, but science devoted universities, schools for all people working on the totality of the human conscience, on the creation of real valuable things, music, a clean balanced environment, etc.”. Or in the light of the ideas of Teilhard de Chardin (1955) “The ‘good’ never will get lost, once created or developed and implemented, it will irrevocably find its way.”

Conclusions
Recently developed sustainable and robust environmental protection systems and concepts, like those based on anaerobic digestion, the biological sulphur cycle, irrevocably will become accepted world-wide. They can be considered as core elements in Environmental Protection and Resource Conservation (EP&RC) concepts. Such EP&RC concepts consist of a well integrated set of biological and physical-chemical treatment systems, all of them directed to pollution prevention and valorisation of residues (wastes). In addition they also will contribute to the accomplishment of significantly more self-sufficiency in environmental protection, as already is increasingly the case for the industrial sector but likely also will become the case for common citizens. Furthermore their wide-scale implementation will lead to a better conservation of characteristic landscapes and to a higher natural diversity, to an ecological type of agriculture with a maximum of real farmers. Considering how sadly frequently many things presently are managed in the field of environmental protection and in society in general, this may look a kind of utopia. However, in order to achieve more real long-term sustainability, the developments in society should move in the correct direction. Regarding the successful implementation of technologically simple and sustainable waste and wastewater treatment methods like AnWT and the increasing interest for DESAR concepts, this obviously sometimes already is happening. Consequently there are some reasons to be not too pessimistic, the more so, because the well performing (which generally is the case) AnWT systems implemented so far, will act as a crowbar for accomplishing more sustainability. And there are reasons to expect that this will not remain restricted to the protection of our life environment, but also will have a positive impact elsewhere in society. It will contribute to improving public awareness, which then gradually may result in a more “intelligent” management of society in order to achieve more social justice and human dignity, leading to a future society in which all humans will benefit from the technological and cultural achievements. In this way not just an elite, but many people are enabled to develop their personal talents, which then again will contribute to more real progress. We need digestion and degradation in order to get air and space for new life.

Note
The author would like to stress that this paper is not intended as an extensive review on anaerobic digestion and degradation processes. Most references listed are rather close to the author’s colleagues.
Abbreviations
AnWT Anaerobic Wastewater Treatment
UASB Upflow Anaerobic Sludge Bed
EGSB Expanded Granular Sludge Bed
AF Anaerobic Filter
AAFEB Anaerobic Attached Microbial Film Expanded Bed
AeWT Aerobic Wastewater Treatment
AnDi Anaerobic Digestion
S\textsubscript{bio}C Biological Sulfur Cycle
N\textsubscript{bio}C Biological Nitrogen Cycle
EP&RC Environmental Protection and Resource Conservation
AnDi Anaerobic Digestion
S\textsubscript{bio}CT Biological Sulfur Cycle Treatment
CENSA Centralised Sanitation Concept
DESAR Decentralised Sanitation and Reuse

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