I.FAST

Innovation Fostering in Accelerator Science and Technology

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DELIVERABLE REPORT

Basic engineering of e-beam sludge processing line

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ABSTRACT

In the era of circular economies, municipal wastewater treatment plants (WWTPs) are viewed as resource recovery facilities. At the very minimum, the targeted resources are water, biogas, and phosphorus. However, municipal wastewater streams (sludge and effluent) need to be adequately treated to eliminate the potential for the transmission of microbial pathogens including protozoa, bacteria, and viruses. In case of the use of ionizing radiation to hygienize sewage sludge, an electron accelerator seems to be a better solution in comparison to isotope gamma sources, however such a choice requires a low-cost electricity supply, which is very important for the profitability. This can be solved by biogas production and electricity generation on site. The concept of combining electron beam sludge treatment technology with biogas production in an industrial plant that is equipped to generate electricity to power the accelerator has been elaborated in the frame of the INCT project. Work performed concerned processing line concept, based on laboratory studies, and development of assumptions for industrial electron accelerator based sludge processing unit.

I.FAST Consortium, 2021

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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Delivery Slip

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TABLE OF CONTENTS

Executive summary

In the era of circular economies, municipal wastewater treatment plants (WWTPs) are viewed as resource recovery facilities. At the very minimum, the targeted resources are water, biogas, and phosphorus.

However, municipal wastewater streams (sludge and effluent) need to be adequately treated to eliminate the potential for the transmission of microbial pathogens including protozoa, bacteria, and viruses.

Proposed technology, providing organic fertilizer, biogas, and electricity fits well into the circular economy concept.

The work on pathogen deactivation and influence of radiation on the sludge physical parameters has been carried out.

The significance and novelty of the findings in demonstration of the influence of radiation on sludge disintegration and the resultant increase in the rate of anaerobic fermentation.

Studies were carried out with two different accelerators emitting beam of different energy.

After review of electron accessibility and their technical parameters selection of accelerator type feasible for the plant construction was proposed.

Additionally the study covered research on the geometry if under beam system providing low generation of X – ray.

Proof-of-concept technology is ready and the technology advanced to TRL 4 (Technology readiness level).

Design assumptions of advanced electron accelerator plant for biohazards treatment has been developed and basic engineering prepared by the company working in the field of biogas plant construction (presented in the other report covering Milestone IFAST-MS59.

1 Introduction

Increasing urbanization calls for effective management of human wastes. It is abundantly clear that for these urban areas to be sustainable, public health must be protected. The conventional view has been that to protect public health, there needs to be proper collection, treatment, and disposal of municipal solid and liquid wastes. Worth to understand that human waste streams are significant pools of water, energy substrates, and nutrients. In the era of circular economies, municipal wastewater treatment plants (WWTPs) are viewed as resource recovery facilities. At the very minimum, the targeted resources are water, biogas, and phosphorus. However, municipal wastewater streams (sludge and effluent) need to be adequately treated to eliminate the potential for the transmission of microbial pathogens including protozoa, bacteria, and viruses. In case of the use of ionizing radiation to hygienize sewage sludge, an electron accelerator seems to be a better solution in comparison to isotope gamma sources, however such a choice requires a low-cost electricity supply, which is very important for the profitability. This can be solved by biogas production and electricity generation on site. The concept of combining electron beam sludge treatment technology with biogas production in an industrial plant that is equipped to generate electricity to power the accelerator has been elaborated in the frame of the INCT project. Proposed technology, providing organic fertilizer, biogas, and electricity fits well into the circular economy concept. The work on pathogen deactivation and influence of radiation on the sludge physical parameters has been carried out. The significance and novelty of the findings in demonstration of the influence of radiation on sludge disintegration and the resultant increase in the rate of anaerobic fermentation. Both about mentioned studies were carried out with two different accelerators emitting beam of different energy. After review of electron accessibility and their technical parameters selection of accelerator type feasible for the plant construction was proposed. Additionally the study covered research on the geometry if under beam system providing low generation of X – ray, What is important for irradiation room construction. Design assumptions of advanced electron accelerator plant for biohazards treatment has been developed. Although the beam power of accelerators has improved over the past decade, and there have been changes in the electronic elements of the control systems, no dramatic changes have occurred in their operating principles and design since then. With regard to environmental applications, the high-power transformer-based accelerators with beam energy range of 1–2 MeV may be preferred because of their high beam power capabilities. Moreover, these units are of high-energy efficiency (plug to beam) and the capital expenses are relatively modest. On the other hand, the major drawback is the low penetration of the electrons from such accelerators, which requires that special consideration needs to be paid to designing the beam and product handling system to facilitate the low energy electrons

Work performed by INCT concerned processing line concept, based on laboratory studies, and development of assumptions for industrial electron accelerator based sludge processing unit construction. On this bases basic engineering of e-beam municipal sludge processing line based on industrial electron accelerator has been elaborated by Biopolinex.

2 Municipal WWTP Sewage Sludge and Current Regulations on their Agricultural Use

2.1 MUNICIPAL WASTE WATER TREATMENT PLANTS AND SLUDGE

Wastewater treatment plant (WWTP) is a facility which is purposed for mechanical and biological purifying of wastewater entering the system. WWTPs use natural biological aero-bio processes but in intensified form by providing appropriate conditions like temperature, pH, aeration or organic matter concentration. There are two main types of sewage sludge: preliminary sludge and secondary excess sludge. Both have different content and structure due to its origin however both have some similarities. Preliminary sludge obtained during present in raw wastewater organic matter particles sedimentation consist of human and animal faeces, organic and inorganic waste, etc. Secondary excess sludge is a suspension of flocks formed during settling of suspension from aerobic purification process. Bacteria taking part in process of aerobic treatment (mostly heterotrophic bacteria strains: *Pseudomonas*, *Bacillus*, *Micrococcus*, *Alcaligenes*, *Moraxella*, *Flavobacterium*) produce extracellular matrix consisting of polymeric substances. These flocks contain not only bacteria cells and EPS but also some other organic compounds: soluble high molecular weight substances and colloidal substances adsorbed on flocks surface, insoluble particles occluded inside flocks. Organic compound also occur in water phase. After treatment excess sludge is a perfect organic fertilizer.

2.2 PATHOGENS PRESENT IN SEWAGE SLUDGE

Occurrence of different pathogens in sewage sludge is a matter of concern, may contain helmiths eggs, protozoa, bacteria, fungi and viruses. Some of mentioned pathogens are persistent in environment thus they can survive in sewage system and enter WWTP getting more concentrated in primary sludge during primary settling process. Some of these are also able to survive treatment processes. In sewage sludge large amount of bacteria cells can be found. Next to sparophytes (organisms, particularly fungi, which obtain nutrients directly from dead organic matter or wastes) and faecal bacteria (*E. Coli*) also other pathogenic bacteria strains can be present: *Salmonella sp.*, *Shigella sp.*, *Clostridium Perfrigens*, *Clostridium Botulinum*, *Bacillus Anthracis*, *Vibrio cholerae*, *Mycobacteium Tuberculosis* etc. In sewage systems intestinal parasitic helmiths are present e.g.(Fig.1) as their living eggs as well. Sewage sludge are also abundant in viruses and fungi.

Fig. 1 Image captions.Fig. 1 Human parasitic helminths: A - human whipworm (Trichuris sp.), B – human hookworm (Ancylostoma duodenale)

Results pf the study to evaluate the contamination of sewage sludge produced by municipal waste treatment plants in by viable eggs of intestinal parasites of the genera *Ascaris*, *Toxocara* and *Trichuris* (ATT) was carried out recently and available at literature. Ninety-two municipal, mechanical-biological sewage treatment plants were selected. These plants belonged to types of agglomerations: group 0 (large), group 1 (medium), group 2 (smaller) and group 3 (small). Samples were collected at the final stage of sewage treatment after the addition of flocculent to sludge, followed by dehydration. The samples were examined by a method adjusted to examine sewage sludge dehydrated using polyelectrolytes. The viability of the isolated eggs was evaluated based on incubation in a moist chamber. Live eggs of intestinal nematodes were found in 99% of samples. Most samples were contaminated by the eggs of *Ascaris spp.* (95%) and *Toxocara spp.* (96%). However, *Trichuris spp.* eggs were detected in 60% of samples. The mean number of eggs in 1 kg of dry mass (eggs/kg d.m.) was 5600 for *Ascaris*, 3700 for *Toxocara* and 1100 for *Trichuris*. The highest number of ATT eggs was found in sewage sludge produced in large sewage treatment plants (agglomeration Groups 0 and 1), with mean values of 15,000 and 8900 eggs/kg d.m. The results of this study indicate that sludge produced in municipal sewage treatment plants is highly contaminated with parasite eggs. The presence of helminths eggs in sewage sludge obtained from municipal wastewater is still a current problem. The similar results were obtain at our work , all types of sludge tested in our work contained parasite eggs, even postflotation sludge though it was obtained from the liquid phase of municipal wastewater. Thus, any type of sludge obtained in WWTP can be infected with pathogens that are dangerous to humans, and the thought of farmers spreading sewage sludge on their fields without any previous processing is increasingly worrying. A hygienization process of any type of sewage sludge is strictly needed before agricultural utilization of such sludge.

2.3 CURRENT REGULATIONS ON AGRICULTURAL USE OF SEWAGE SLUDGE

Use of untreated sludge or wastewater in agriculture pose a serious risk of bacterial and parasitic infection among humans. European Union encourages to use sewage sludge in agriculture. EU Directive 91/271/EEC on urban waste water treatment however article 14 says: *„Sludge arising from waste water treatment shall be reused whenever appropriate. Disposal routes shall minimise the adverse effects on the environment*”. However due to Directive 86 / 278 / EEC article 2 : “*has undergone biological , chemical or heat treatment , long-term storage or any other appropriate process so as significantly to reduce its fermentability and the health hazards resulting”.* Following these Directives in Poland Regulation of the Minister of the Environment of February 6, 2015 impose strict limits concerning microbiological contamination : *fertilizers and agents supporting the cultivation of plants ….must not contain: live eggs of intestinal parasites Ascaris sp., Trichuris sp., Toxocara sp.; Salmonella bacteria. …… the number of bacteria of the Enterobacteriaceae family, determined on the basis of the number of aerobic bacteria, should be less than 1000 colony-forming units per gram of fertilizer,”* For use in agriculture and land reclamation for agricultural purposes - e total number of live eggs of the intestinal parasites *Ascaris sp.*, *Trichuris sp.*, *Toxocara sp*. in 1 kg of dry matter is 0. Similar regulations have been adopted in many countries all over the world.

2.4 EFFECTS OF IONIZING RADIATION ON LIVING MICROORGANISMS

Ionising radiation is lethal for living cells and one of the reasons of this fact is inducing damages of deoxyribonucleic acid (DNA) – a biopolymer responsible for genetic information storage. If the DNA strand is damaged so severely that it cannot be fixed by repair mechanisms cell dies. DNA strand damages can be caused by two separate mechanisms (Fig.2). First is indirect effect based on the chemical reaction of DNA with water radiolysis products. Second type of action is direct effect when radiation ionize DNA strand effecting in transforming bases into radical species undergoing further reactions and no longer able to perform its previous function or ionization of sugar-phosphate backbone leading to strand breaks.

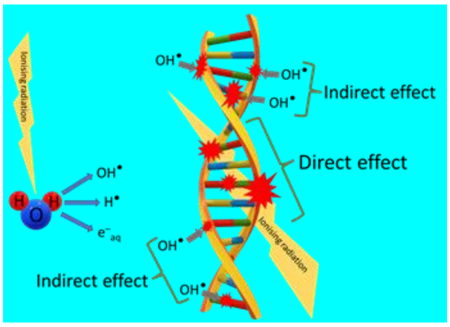

Fig.2 Schematic drawings presenting direct and indirect effect of ionizing radiation damaging DNA molecule.

These effects are basis for radiation sterilization which is a dominating in processing of single use healthcare products and tissue grafts. The other applications are food irradiation. There are two plants for sludge treatment using gamma isotope sources in India. However due to the risk connected with use of radioactive material the use of accelerators is becoming more feasible and it was the main objective of this task at which on the basis of laboratory research idea of advanced eb technology has been developed and lead to basic engineering preparation.

3 LABORATORY RESEARCH

3.1 EQUIPMENT USED

3.1.1 Electron accelerators

For the study of hygienization, electron beams from two types of accelerators, linear (Elektronika 10/10) and single cavity (ILU-6), were applied. For each type of accelerator, different irradiation methods were used: irradiation in sealed polyethylene bags using conveyor and flow irradiation installation. The first method was tested with the use of an ILU 6 electron accelerator (adjusted to the beam energy1.7 MeV) connected with a laboratory-scale flow irradiation setup (FIS) installation for the flow irradiation of suspension. Another system used for the tests was the Elektronika 10/10 10 MeV electron accelerator equipped with a conveyor, normally working in INCT’s commercial medical products sterilization plant. Around 1000 g sludge samples were sealed in polyethylene bags with diameters of 400 mm × 600 mm.

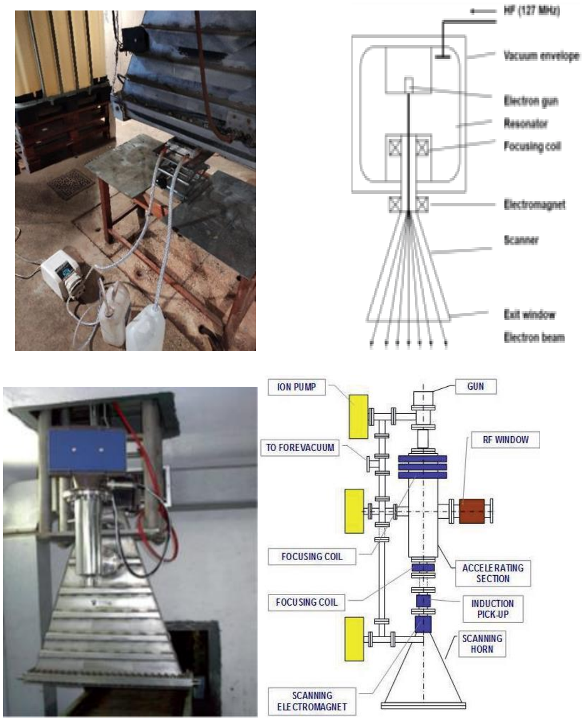

Fig.3 Electron accelerators applied in the research. single cavity radiofrequency accelerator (top); linear microwave accelerators (bottom).

An ILU 6 accelerator equipped pilot radiation installation was designed for the radiation processing of polymers, investigating the processes of removing impurities from the liquid sludge and gas phase and research covering a range of other radiation technologies. ILU 6 type accelerators (nominal electron: 2 MeV, nominal beam power: 20 kW) are manufactured mainly for the applications in industry. A simple method of electron energy adjustment is based on RF peak power regulation.

A microwave linear electron accelerator Elektronika 10/10 , with traveling wave and 10MeV electron energy, 10-15 kW average beam power was designed and built by the NPO Toriy, Moscow, Russia. High power microwave magnetron is used as a source of microwave energy. Beam exit system is equipped with scanning magnet.

The samples irradiated at different doses, were tested commercially for the presence of ATT intestinal parasite eggs, namely human roundworm (Ascaris spp.), animal roundworm (*Toxocara spp*.) and human whipworm (*Trichuris spp.),* and for the bacteria *Salmonella spp., E. coli and Clostridium* perfrigens by laboratory measurements according to the Polish norm: PN-Z-19000-04:2001 improved by the Institute of Rural Medicine (Lublin).

3.1.2 Biogas yield measurement equipment

Beside hygenization of the sludge , important for the process engineering is production of biogas depending on substrate and physicochemical conditions in the bioreactor. Moreover the electron beam leads to sludge flocks disintegration which increase yield of biogas in the shorter time period. The following equipment was used for investigations of biogas production rate for raw sludge and sludge irradiated with different doses.

Fig.4 DIN 38414/8 eudiometers used for small-scale (400 ml) experiments including water bath, A view of the AMPTS II device used in the experiments. A photo of the analytical set used for the SCOD measurements: Macherey–Nagel photometer, photometric tests—tubes filled with appropriate reagents (from left to the right).

The methane generation studies were carried out in 400-mL bioreactors (under mesophilic conditions) connected with eudiometer tubes compliant with DIN38414/8 standard (Fig. 2) (Behr Labor-Technik GmbH, Düsseldorf, Germany). The sludge samples used in these studies comprised of the non e-beam treated control samples and sludge samples exposed to 1 kGy, 2 kGy, and 3 kGy e-beam target doses. Aliquots of the biogas digester digestate from the WWTP were used as the inoculum. The chemical oxygen demand (COD) in the liquid phase (soluble chemical oxygen demand – SCOD) was measured before and after e-beam irradiation as well as before and after the methane fermentation process. To measure SCOD samples were centrifuged using MPW-54 (MPW Med. Instruments, Warsaw, Poland) centrifuge. The supernatant was filtered using filters (VWR, Pennsylvania, USA) and analysed using Macherey–Nagel photo- metric tests and Maherey–Nagel Nanocolr Vis II photometer (Macherey–Nagel, Düren, Germany). The total suspended solids (TS) content (d. m.) in bioreactor mixture was measured before and after the fermentation by initial drying (103°C, 48 h). The organic mass content in dried bioreactor mixture (VS) was measured by loss during combustion at 530°C using PSK-31 furnace (Elterma, Świebodzin, Poland).

3.1.3 Radiation shielding for sludge suspension irradiation

Another research concerned irradiation of the suspension of sludge in water. Water treatment requires low-energy, high-power accelerators. The lower the electron beam energy, the lower the penetration of the wastewater stream that sets the technological requirements regarding the low liquid thickness. Therefore, different geometry technological solutions and special injection nozzles are applied to ensure the appropriate thickness of the irradiated layer and the effective and homogeneous irradiation of the wastewater or liquid suspension stream.

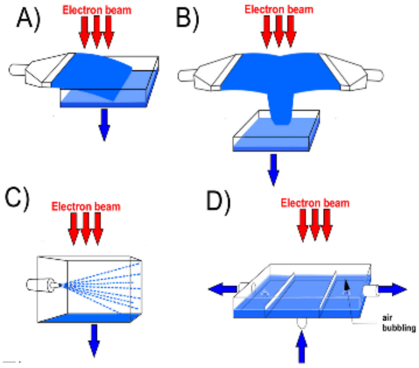

Fig.5. Different geometry of stream configuration for sludge suspension irradiation: (A) jet injection, (B) two opposite jets injection, (C) sprayer, (D) up-flow system with air bubbling.

The test measurements were performed on the pilot installation equipped with ILU 6 (INP, Russia) accelerator at INCT, Warsaw. The accelerator can emit beam of electrons of energy ranging from 0.2 to 2 MeV, average beam power up to 20 kW and can be used for polymers modification, liquids and sludge irradiation and gas treatment. The parameters of the beam in experiments were accelerating voltage—930 keV, beam current—1 mA, sweep width—50 cm. The parameters of experiments were selected taking into account the expected range of electrons in a commercial facility and absorption of electrons energy in an accelerator window, air in distance from accelerator widow to the irradiated surface as well or other used coverages. Penetration ability of electron beam was measured using stack of CTA dosimetric foil. To model irradiation conditions in the target installation, the range of generated electromagnetic radiation was estimated for two target materials. One was water, a medium which will be treated in the projected installation and the second one was steel, a constructing material considered as a main source of generated bremsstrahlung radiation. In the experiments, a 0.5 mm thick steel plate with an average density 7.5 g/cm^3 or 5 mm thick water layer were used. The properties of both materials provided complete absorption of the electron energy and the measured doses resulted from the bremsstrahlung effect. The measurements were performed using alanine dosimeters located under the target, in a distance of 20 cm and 1 m from accelerator window at floor, target and accelerator window levels.

3.2 RESULTS

3.2.1 Dose effect on sludge hygenization efficiency

Different samples from different WWTP were used for the tests. The obtained results showed that, for the preliminary sludge the dose required to remove all observed bacteria is 4 kGy. For the thickened preliminary sludge that dose is slightly higher at 5.5 kGy, while for the dose of 3.7 kGy (which is nearly 4 kGy) there are still some bacteria living. For the postflotation sludge), the dose required for hygienization is similar as for the preliminary sludge and 4 kGy. For the preliminary sludge the dose for complete elimination of examined bacteria is the highest. This may have been due to fact that sludge had the highest TS concentration. Moreover, this sludge was obtained after some purification processes partly removed microorganisms, so the numbers of measured bacteria were not as high as in the municipal wastewater sludge, and thus a lower dose to remove them was needed. After irradiation with a 3 kGy dose, the total number of bacteria in the postflotation sludge was four times lower in comparison to preliminary sludge irradiated with the same dose. Additionally, for thickened preliminary sludge, the number of bacteria was still 2.1 × 103 CFU at the 3.7 kGy dose. For two other samples, almost the same dose was enough to remove all bacteria, while the initial bacteria number was very close for preliminary sludge and thickened preliminary sludge. It is clear that E. coli reduction was slower for thickened preliminary sludge than for preliminary sludge, whilst the initial number of this strain is almost the same. Taking in account all the results the dose 5 kGy is the most appropriate to assure required microbiological decontamination effect.

The number of ATT in preliminary sludge and thickened preliminary sludge were very close, while TS concentration for thickened sludge was 2.5 times higher than TS concentration for preliminary sludge. The most numerous ones were *Ascaris spp.* , then *Trichuris spp*. and lastly *Toxocara spp*. As for the bacteria, the dose required for living helminths eggs removal from postflotation sludge and preliminary sludge and postflotation sludge from os 4 kGy. Additionally, in this case it can be observed again that TS concentration affects the dose required for complete hygienization, more so than the initial number of pathogens. Nevertheless, dangerous pathogens are present in all tested sludges, which is why all types of sludge taken from WWTPs should be hygienized before any form of utilization. These experiments have proven that the irradiation doses delivered using electron beams required to remove biological threat are 4 kGy for preliminary sludge with about 4% TS and for postflotation sludge with 2.5% TS, and 5.5 kGy for preliminary sludge thickened to about 12% TS. These data refer to the destruction of both pathogenic bacteria and helminth eggs. Obtained results also showed that the more thickened the sludge is, the higher the dose needed to remove all pathogens. However, the density of thickened sludge is still similar to the density of water, so increasing TS concentration should not affect the beam penetration depth when leaving the same thickness of the irradiated sludge layer. Therefore, two types of accelerators were tested, one with beam energy of 1.7 MeV and another providing electrons with energy of 10 MeV. These data gave us sufficient information needed for the construction of a plant using this kind electron beam.

3.2.2 Irradiation effect on sludge as a substrate for biogas production

The process of disintegration of excess sludge, being a feed to anaerobic digesters, results in the higher production of biogas, and a lower concentration of organic dry mass in digestate, improving its susceptibility to the dewatering processes, which is demonstrated by the higher SCOD values, and this means that the concentration of the nutrients is in both the hydrolysis and fermentation steps. Sludge irradiation can increase the biogas yield during downstream anaerobic fermentation (digester) process. The breakdown of the soluble and suspended organic matter possibly leads to SCOD increase and the availability of additional nutrients for digester performance. The yield of biogas production obtained in 11–14 days was comparable to the biogas obtained in 21 days in untreated samples at the same fermentation process conditions. This finding leads to ability to reduce digester residence times without reducing biogas production what is a major economic and process implication. This study has demonstrated that small WWTPs serving industrial or residential waste streams could be retrofitted with appropriately sized e-beam equipment to convert them into true resource recovery facilities.

3.2.3 X-ray shielding design for sludge suspension in water improvements

Considering the construction of an irradiation room for a water treatment facility, it is important to focus not only on a stream formation for irradiation to achieve the desired electron penetration, but also on the reduction in X-ray generation. The experiments demonstrated that both the target material and the configuration of the irradiation process (beam power, distance of the irradiated material from the accelerator window) are the factors that influenced the intensity of the X-ray field. The reduction in X-ray emission can be achieved by appropriate configuration of the irradiation process so that the electron beam has the least possible projection on the steel surfaces of the chamber and as much as possible on the wastewater stream, i.e., the shortest possible distance of the water jet from the accelerator window, adjusting the sweep width and the width of the wastewater jet, water tank under the irradiation zone so that the water absorbs most of the scattered radiation, both X-rays, and electrons. Because of low atomic numbers of atoms presents in sludge and water (considering concentration of components), the X-ray generation is low is geometry of irradiation is well planned.

4 Accelerators available for radiation processing

Direct current accelerators, single resonant cavity accelerators, and microwave source-powered linear accelerators have been found to be the most suitable for radiation processing technology (Fig.6.). Electron accelerators are of three types: DC type, where a constant beam is extracted; microwave pulsed type(GHz), where the output beam is repeated at a low frequency (repetition rate); and pulse or continuous wave type, where lower radiofrequency (RF 100-200 MHz) accelerates electrons with each amplitude. All of them - DC, RF and microwave accelerators - have become the workhorse of radiation processing and are extensively employed.

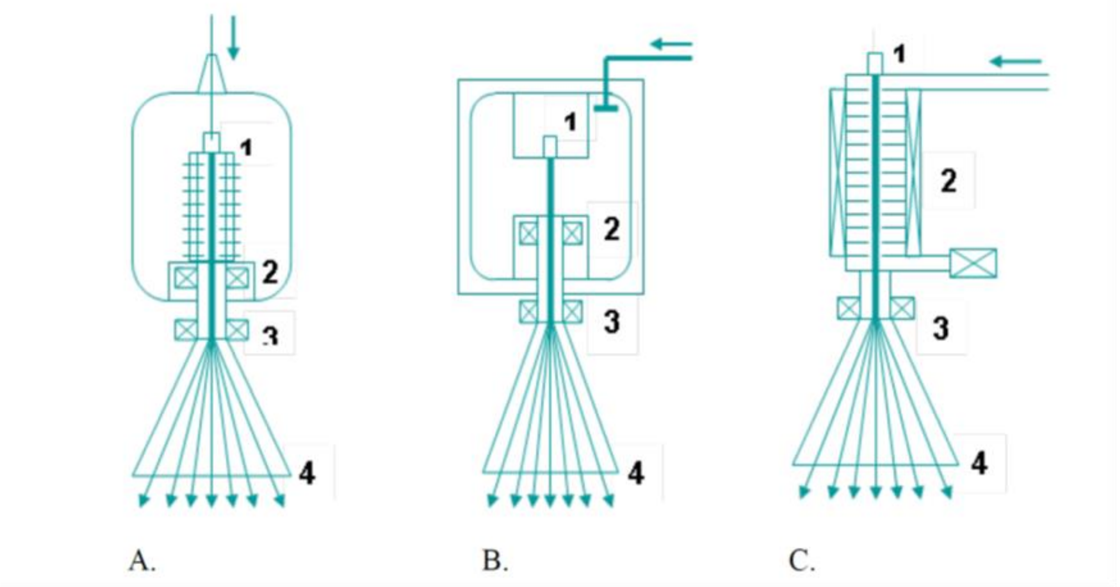

Fig.6. Electron accelerators applied in radiation processing: (A) direct high voltage accelerators; (B) single cavity radiofrequency accelerators; (C) linear microwave accelerators. 1 - electron gun, 2 -focusing coil, 3 - scanning electromagnet, 4 - foil window.

DC accelerators give high average beam power, whereas microwave accelerators, operated in the pulsed mode, give low average power. On the other hand, microwave accelerators have high energy gain per unit length, thus are more compact in construction, compared to DC accelerators. Continuous wave RF-type accelerators provide a DC-like beam current at higher energies. DC voltage is used to accelerate electrons in the direct acceleration method. The necessary DC voltage power supplies are usually based on high power, oil- or gas-filled high voltage (HV) transformers with a suitable rectifier circuit. They are simple and reliable accelerator components. An HV cable is usually used to connect an HV power supply to the accelerating head, for a voltage level not higher than 0.8 MV. The MV level in a conventional transformer is impractical because of technical problems with the insulation and dimensions of such a device. Different types of inductance or capacitance coupling make it possible to increase relatively low primary voltage up to 5 MV by multistage cascade systems. An

RF accelerator is based on a large, single cavity operating at a frequency between 100 MHz and 200 MHz. The high power vacuum tubes are applied to provide necessary electromagnetic energy that is used to accelerate electrons in a single pass or multi-pass system (e.g. Rhodotron). These inexpensive and reliable components require relatively simple and compact DC or pulse modulators to generate ultra-high frequency oscillations. Medium and high electron energy levels with beam power can be obtained. The main feature of a linear accelerator is related to the use of microwave energy in the electron accelerating process. Power supplies consist of pulsed microwave generators. A large number of small resonant cavities are used . The accelerating structure can provide an electric field over 10 MV/m as compared to 2 MV/m for DC accelerators, due to the magnetic isolation that is present in such systems. This makes linear accelerator (linac) construction very compact. However, the overall electrical efficiency of a microwave linac is only 10-20%, due to power loss in the microwave generator and accelerating tube. Electron accelerators nowadays can be considered as multipurpose machines that deliver beams with different energies and power levels. The most suitable type of electron accelerator for a certain application is defined at first by the required electron energy, which is directly related to the density and structure of objects to be irradiated, and beam power, which defines the total processing capacity of the installation. Performance limits for electron accelerators used in radiation processing is presented in Table 1.

Table 1. Performance limits for electron accelerators used in radiation processing.

Parameter	Direct DC	UHF 100 – 200 MHz	Liniac 1.3-9.3 GHz
Beam mean current	< 2A	<100mA	<30mA
Electrons energy	0.05-5MeV	0.3-10MeV	2-10MeV
Beam power	~500kW	700kW	150kW
Electrical efficiency	60-80%	20-50%	10-20%

5 Assumptions for basic engineering preparation

On the basis of above-described developments, a new concept of ‘zero energy’ sludge hygienization technology was elaborated. According to the invention, biomass originating from waste prior to its fermentation or digestate derived in the process of methane fermentation is irradiated with Ebs that use energies from 1 MeV to 10 MeV, preferably 1–3 MeV. For a digestate derived in the process of fermenting biomass originating from waste and having a liquid form with the content of dry matter less than 5%, the radiation dose is from 1 kGy to 5 kGy, whereas for a digestate from which the aqueous phase has been filtered out and which has a dry matter content up to 30%, the radiation dose is from 5 kGy to 20 kGy. An electron accelerator is favourably powered with energy provided by an electricity co-generator fuelled by biogas produced in the process of methane fermentation. The advantage of the method according to the invention consists of the fact that the energy is generated from renewable waste materials, which is widely available. The method according to the invention does not require energy from external sources (thanks to the fact that irradiated digestate is utilized as a fertilizer) and does not generate waste. The method allows pathogens to be eliminated from sludge and does not have a negative impact on the environment. The plant due to own electricity source may be installed in the remote site, providing electricity for accelerator, wastewater treatment plant and village. The heat from the co-generator may be used for fertilizer drying. Principle of such solution is presented in Fig.7.

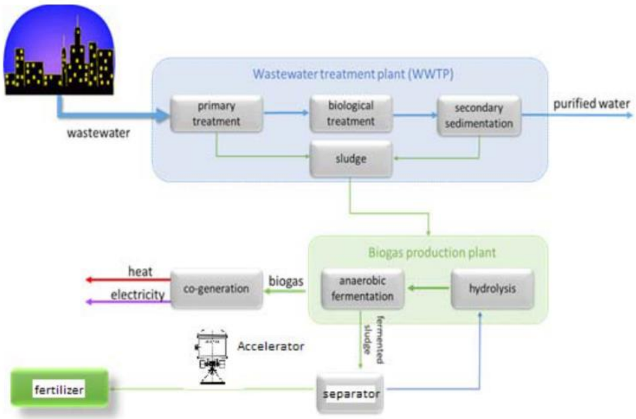

Fig.7. Principle of ‘zero energy’ sludge hygienization technology.

The results of experiments and data from biogas plants built on the basis of INCT patent, were used for preliminary comparison of economic effects of this technology application in comparison to WWTP in which sludge digestion is used only for biogas production.

Table 2.

Comparison of economic effects of “zero energy” technology application with conventional sludge sludge digestion.*

Wastewater treatment plant (Throughput: ~250 000 m^3 annually. Sludge output ~1500 tons dry mass annually)	
I. E-beam technology for sludge hygenization	II. E-beam technology for sludge hygenization and biogas cogeneration
Accelerator specification	
100 kW, 2 MeV	100 kW, 2 MeV + biogas generation
Cost savings	
Savings from avoiding sludge disposal costs	
1500 tons @ 100€ = 150,000 €	1500 tons @ 100 € = 150,000 €
Potential revenue from biosolid-based fertilizer sales	
1500 tons @ 94.5 € = 141,750 €	1277.5 tons @ 94.5€ = 120,723.75 € Biogas production (1,022,000 m^3 annually) Converted in co-generator in electricity and heat. Generator power 350 kW. Equivalent of electricity production: 350 kW × 8000 h × 0.13€/ kWh = 354 000 €
E-beam technology-associated operating costs	
Electricity consumption	
130 kW e-beam accelerator 70 kW wastewater plant equipment 10 kW heat generation	130 kW e-beam accelerator 70 kW wastewater plant equipment
Total cost	
210 kW × 8000 h × 0.13€ /kWh = 218 400 €	200 kW × 8000 h × 0.13 €/kWh = 208 000 € 1055 tons grass silage (annually) = 1,055 tons × 10 €/ton = 10 055€
Net income and savings	
73 350 € annually	271.668.75 € annually

*€ of 2020.

Concerning irradiation module following component have to be elaborated : (1)Determination of the geometry of the radiation treatment process, (2) Determining the optimal parameters of the accelerator (related to (1)), (3) Selection of accelerators that meet the requirements, (4) List of accelerator manufacturers to collect offers, (5) Determination of service requirements (frequency of replacements, cost of spare parts, service time), (6) Determining the requirements for the room where the accelerator will be installed, (7) Determining the requirements for the employment of personnel operating the accelerator, (8) Preliminary determination of operating, unit and investment costs of the radiation installation,

Following this study and requirements of eventual customer – the following input data should be considered: - Biomass flow 2.8 t/h – Average dry matter content 7.4% - Required dose of 6 kGy-Installation operation time up to 8000 h/year.

6 Annexes

Annexes are - the Milestone (IFAST-MS59) report and basic engineering approved by certified engineers prepared as the separated reports.

7 Technology readiness levels (TRL)

Once the proof-of-concept technology is ready, the technology advances to TRL 4. According to the definition if R&D works reach TRL 4. Technology is validated in lab. (EU) During TRL 4, multiple component pieces are tested with one another , therefore we may consider that this level has been achieved. Therefore basic engineering approved by licensed engineers is a key to move to next level TRL5 - Technology validated in relevant industrial environment TRL 5 is a continuation of TRL 4, however, a technology that is at 5 is identified as a breadboard technology and must undergo more rigorous testing than technology that is only at TRL 4. Simulations should be run in environments that are as close to realistic as possible in our case it should be a pilot plant built at WWTP on the basis of BE elaborated. Once the testing of TRL 5 is complete, a technology may advance to TRL 6. A TRL 6 technology has a fully functional prototype or representational model.

8 References

JOURNAL ARTICLES:

[1] Gryczka, U., Zimek, Z., Walo, M., Chmielewska - Smietanko, D., Bułka, S. (2021) Advanced Electron Beam (EB) Wastewater Treatment System with Low Background X-ray Intensity Generation". Appl. Sci. 11, 1119

CONFERENCE PAPERS

[1] Chmielewski, A. G., Sudlitz M. (2022) A Method for Hygienisation of Sewage Sludge Based on Electron Accelerator Application, Third Research Coordination Meeting for CRP "Radiation Inactivation of Bio-hazards Using High Powered Electron Beam Accelerators", Vienna, IAEA Headquarters, Jan 31 – Feb 4, 2022

[2] Andrzej G. Chmielewski, Zbigniew Zimek, Yongxia Sun, Andrzej Pawelec, Marcin Sudlitz, Urszula Gryczka , Dagmara Chmielewska – Śmietanko, Sylwester Bułka ,(2022) Radiation Chemistry and Technology for Environment Pollution Control, The Miller Online Workshop on Radiation Chemistry, 10-12 February 2022; PROGRAMME AND BOOK OF ABSTRACTS; Edited by: The Miller Trust Committee , February 2022, P7, page 66

[3] Chmielewski, A.G.,(2022) Electron accelerator based systems for air, water and soil pollution control, Plenary paper, International Conference on Accelerators for Research and Sustainable Development From Good Practices Towards Socioeconomic Impact 23-27 May 2022, IAEA Headquarters Vienna, Austria, pages 42-43, https://www.iaea.org/sites/default/files/23/01/cn-301-volume-2-book-of-abstracts.pdf; https://conferences.iaea.org/event/264/contributions/21505/attachments/11701/21800/S1_2_207_Chmielewski_Slides.pdf

[4] Chmielewski, A.G,(2022) Accelerators for the environment, Accelerators for the environment I.FAST's 2022 Challenge-Based Innovation programme, 13.07.2022, virtual

[5] Chmielewski A.G.(2021) Application of radiation technology based on eb for environment pollution control technologies World Nuclear University (WNU) School on Radiation Technologies (RT School), 11-22.10.2021 (online)

[6] Sudlitz M., Chmielewski A. G.(2021) Investigation of the methane fermentation process using ozonated and irradiated surplus sewage sludge. ChemSession'21. XVII Warszawskie Seminarium Doktorantów Chemików, Warszawa, Poland, 24.09.2021. Book of abstracts p. 88.

[7] Chmielewski A. G., Zimek Z., Sun Y., Pawelec A., Sudlitz M., Gryczka U., Chmielewska-Śmietanko D., Smoliński T., Rogowski M., Bułka S. (2021) Chemistry and radiation technology as a basis for environmental protection. 63. Zjazd Naukowy Polskiego Towarzystwa Chemicznego, Łódź, Poland, 13-17.09.2021.Book of abstracts, S12 WS01.

REPORTS

Gryczka,U., Zimek,Z., Walo, M., Chmielewska-Śmietanko,D., Bułka,S., Chmielewski,A.G.. (2021) X –RAY BACKGROUND INTENSITY MONITORING IN ELECTRON BEAM WASTEWATER TREATMENT SYSTEM, ANNUAL REPORT 2021, INSTITUTE OF NUCLEAR CHEMISTRY AND TECHNOLOGY, Warsaw, p.104-106

Annex: Glossary

Acronym	**Definition**
ATT	intestinal parasites of the genera *Ascaris*, *Toxocara* and *Trichuris*
BE	basic engineering
COD	chemical oxygen demand
d.m.	dry mass
DC	direct current
EB (eb)	electron beam
EPS	extracellular polymeric substances
FIS	flow irradiation setup
RF	radio frequency
SCOD	soluble chemical oxygen demand
TS	total suspended solids
WWTP	waste water treatment plant