E-BEAM TECHNICAL CONFERENCE FOCUSED ON SCIENCE, APPLICATIONS, AND DESIGN CONSIDERATIONS

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Florida Atlantic University

College of Engineering and Computer Science

Note that all photographs not **c**ited were taken by Dr. Bloetscher.

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CHAPTER 1

INTRODUCTION

1.1 Overview

In 2015, the US Department of Energy (DOE) started a major initiative to develop the science needed to produce high power accelerators, which would be needed for large scale application of electron beams in the environmental sector. As part of this initiative, the DOE sponsored a workshop held in 2015 at Argonne National Laboratory in Illinois. That workshop explored research and development opportunities for high-impact applications of accelerator technology to address energy and environmental challenges in a broad sense.

Parallel with this initiative is the need to introduce this technology to the civil and environmental engineering community, which is largely unaware of its existence and potential use as a viable treatment option. Preliminary indications are that electron beam technology may provide attractive solutions to problematic issues associated with biosolids, leachate, potable reuse and contaminated groundwater (such as on a military base).

The purpose of this National Science Foundation (NSF)-sponsored workshop entitled, "*Workshop on Application of Electron Beam Technology on Wastewater and Biosolids Treatment*" was to promote use of e-beam technology for wastewater treatment and biosolids management, inform wastewater treatment professionals about e-beam technology and opportunities, and provide feedback to NSF that opens future funding opportunities. The format of the two-day workshop held on May 10-11, 2018 at the Illinois Accelerator Research Center at Fermi National Accelerator Lab (Fermilab) in Batavia, IL included expert speakers on the current state of wastewater treatment, a summary of the science of using e-beam technology for treatment of waste, the current state of electron beam accelerator technology, a tour of Fermi National Accelerator Lab, panel discussions with wastewater treatment experts, breakout discussions and a summary close-out session.

Invitations to participate in the workshop were sent to nearly 150 selected industry representatives, research faculty, regulatory agencies, engineering organizations and key contributors conducting e-beam research or involved in their operations. A series of specific solicitations for presentations was pursued in the Fall of 2017. An initial announcement (Figure 1) for attendees and invitees from targeted stakeholder groups, including, but not limited to, industrial users, manufacturers, industry representatives, sales engineers, design consultants, regulators, academics involved in research, and organizations that might be targets for the technology was distributed in February 2018. Specific invitations were made to non-profit groups

that might have interest in the application, including the Water Reuse Association, Water Environment Federation, American Water Works Association, and Association of State Drinking Water Administrators. Federal agency personnel (e.g. USEPA, USDoD, USDOE) were also notified and invited to attend. Federal travel restrictions were a major barrier to federal employee attendance. A second and third notice were sent in early April and late April 2018.

Figure 1. Workshop flier announcement

The participants listed in Table 1 included wastewater treatment professionals, e-beam researchers, industrial accelerator experts, industry and utilities partners, academicians, regulatory personnel, and government officials.

Table 1. List of Participants

Name	Affiliation
Amhaus, Dean	The Water Council
Bloetscher, Frederick	Florida Atlantic University
Boulware, Chase	Niowave, Inc.
Brown, David	Mevex Corporation
Burkhart, Craig	SLAC National Accelerator Lab
Buttles, John	DMS South/Bailey Tool LLC
Cardiff, Patrick	Grande Cheese Company
Ciovati, Gianluigi	Jefferson Lab
Cooley, Lance	Fermilab
Cooper, Charlie	FNAL
Coriton, Bruno	General Atomics
Cox, Albert	Metropolitan Water Reclamation District of Greater Chicago
Curry, Randy	University of Missouri
Dhuley, Ram	Fermilab
Fergen, Robert	Miami Dade Water and Sewer Department
Ferreyra Tello, Everaldo	*Xylem*
Folcik, Alexandra	Texas A&M University
Frenkel, Steven	Current
Frost, Karen	The Water Council
Geelhoed, Mike	Fermilab DI/IARC
Giuliani, Joan	MillerCoors
Godinez, Itzel	NAVFAC EXWC
Grdanovska, Slavica	Fermilab
Holland, Leo	General Atomics
Kroc, Thomas	FNAL
Kutsaev, Sergey	Radiabeam Technologies, LLC
Lewellen, John	Los Alamos National Lab
Liner, Barry,	Water Env. Federation
Lin, Yupo	*Argonne National Lab*
Magruder, Matthew	Milwaukee Metro Sewerage District
Malatesta, Mike	n/a
Martinez-Guerra, Edith	ACOE Research and Development Center
Meeroff, Daniel	Florida Atlantic University
Moeller, Jeff	Water Research Foundation
Nagaitsev, Sergei	*FNAL*
Pillai, Suresh	Texas A&M University
Rajagopalan, Nandakishore	*Illinois Technology Center*
Rimmer, Rober	Jefferson Lab
Schideman, Lance	Illinois Sustainability Center
Schmidt, Cherri	FNAL
Shaha, Bishow	Florida Atlantic University
Solyak, Nikolay	FNAL
Waite, Thomas	Florida Institute of Technology
Walden, Steven	Steven Walden Consulting
Yoon, Seong	Nalco Water

Names in italics did not attend in person but contributed

1.2 Background

Techniques for accelerating electrons under a field of high-voltage have been known for over 100 years, but the technology has been sparsely applied in industrial processes except in a limited number of applications that take advantage of the ability of accelerated electrons to increase the rate of polymer cross-linking (Lugão et al. 2007; Jamal et al. 2011). Figure 2 shows some of the industrial areas where electron beams are used (Grdanovska and Cooper 2018). Roughly 87% of these processes involve crosslinking, occurring in applications represented by the blue segments in the pie-chart.

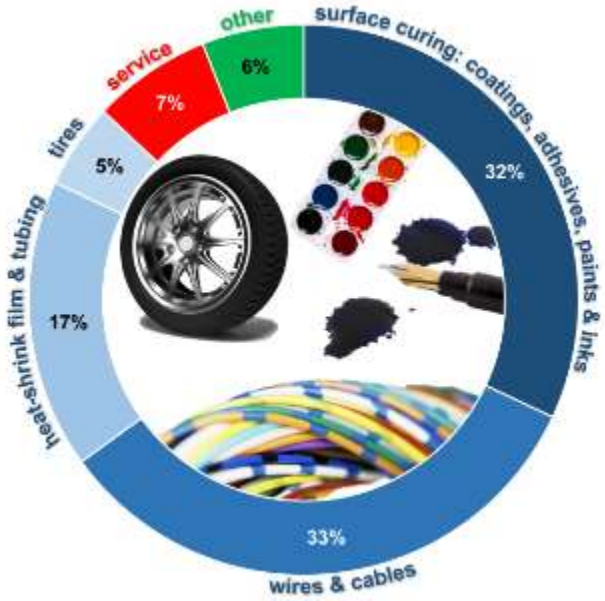


Figure 2: Current end-use market distribution of electron beam industrial applications

However, there are many other applications for excited electrons beyond cross-linking. From an intellectual merit perspective, electron beam technology has the potential to address a number of water quality and treatment concerns related to biosolids and wastewater treatment based on work done in the 1980s (Kurucz et al. 1995; Cooper et al. 1992). There is an extensive literature base associated with laboratory and pilot scale studies of electron beam treatment of aqueous systems over the past 25 years (Kurucz et al. 1995; Cooper et al. 1992; Frank 1993; Borrely et al. 1998; Wang and Wang 2007; and references therein). This research indicates that free radicals formed upon exposure to high-energy electron beams are capable of treating a broad spectrum of contaminants; both chemical and biological in aqueous systems.

While two full-scale electron beam installations in a wastewater treatment plant have been tested (Deer Island, MA and Miami, FL – Cleland et al. 1984, Waite et al. 1998), no other

meaningful implementation of this technology for environmental applications has been undertaken in the United States to date. Even though past electron beam/accelerator studies have been supported by NSF, seemingly insurmountable barriers to commercial accelerator technology adoption (e.g. cost, wall plug efficiency, reliability, regulatory approval, and end user resistance to new technology) have been encountered, which have prevented this technology from being widely adopted. As a result, only about 1,550 industrial irradiators are currently operating world-wide (Berejka and Cleland 2011; Berejka et al. 2014), and to our knowledge, none of these are being utilized for water or wastewater treatment applications. However, recent improvements in accelerator design have lowered the cost, enhanced performance, and increased reliability (USDOE 2015). Currently available accelerators now cost less than $5 per kilowatt of beam power, which is significantly less that just five years ago (Shiltsev 2016). Also, newer commercial accelerators have achieved beam power in the 400 kW range. Therefore, the opportunity now exists for electron beam technology to quickly become disruptive in the marketplace.

The principal motivation for the "*2018 Workshop on Application of Electron Beam Technology on Wastewater and Biosolids Treatment*" is because the US Department of Energy (USDOE) "*Workshop on Energy and Environmental Applications of Accelerators*" held on June 24-26, 2015 at the Argonne National Laboratory explored research and development opportunities for high-impact applications of accelerator technology to address energy and environmental challenges. That workshop restarted a major initiative to develop the science needed to produce high power accelerators (>1 MW), which would be needed for large scale application of electron beams for environmental use. Parallel with this initiative is the need to introduce this technology to the environmental engineering community, so that it can become a competitive tool in water and wastewater management.

1.3 Brief Recent History

In October 2009, USDOE's Office of High Energy Physics sponsored a symposium and workshop entitled, "*Accelerators for America's Future*." The purpose of that workshop, chaired by Walter Henning and Charles Shank, was to solicit the views of a wide range of accelerator users on the challenges and opportunities for developing and deploying accelerators to meet national needs. The report published in June 2010, has drawn Congressional interest in enhancing stewardship of accelerator science, research, and development. In 2011, DOE's Office of High Energy Physics sought input from the community via the "*Accelerator R&D Task Force*" on the preferred strategy for an accelerator stewardship program, which was authorized by Congress in 2014. To assess the potential for interest in accelerator applications in energy and the environment, a request for information was issued in 2014, which yielded responses from practitioners in industry, national laboratories, and universities.

On June 24-26, 2015, the DOE hosted the "*Workshop on Energy and Environmental Applications of Accelerators"* at Argonne National Laboratory in an effort to determine the research needs for bringing electron beam technology into the environmental sector. The meeting was co-chaired

by Stuart Henderson of Argonne National Laboratory and Dr. T.D. Waite of Florida Tech who conducted e-beam research at the Miami-Dade Central District Wastewater Treatment Facility in the 1990s with Dr. Daniel E. Meeroff, who is currently at Florida Atlantic University (FAU).

The 2015 workshop participants identified the principal constraints to adoption of accelerator technology for environmental applications to be cost and familiarity with the technology. It was suggested that new equipment designs were required to make an inexpensive and robust electron beam system. The proposed long-term strategy was for technology scientists to develop complete electron beam systems that demonstrate higher beam power with reduced capital costs, increased reliability, and improved efficiency. Armed with these newer capabilities, engineers must demonstrate the efficacy of this technology at large scale in real environmental applications in conjunction with major potential users and professional societies. Concurrently, designers and academicians must develop training formats, design guidance, and educational programs for engineering professionals to properly specify electron beam units for environmental applications.

A listing of recent meetings related to this topic including dates and locations is found in Table 2.

Table 2. Summary of Related Historical Electron Beam Meetings

Title	Dates	Locations
Workshop on Energy and Environmental Applications of Accelerators	June 24-26, 2015	Argonne National Laboratory, Lemont, IL
Accelerator R&D Task Force	November 29, 2011	Advanced Photon Source, Argonne, IL
Accelerators for America's Future	October 26, 2009	Marriot Wardman Park Hotel, Washington DC
Enhancement of Wastewater and Sludge Treatment by Ionizing Radiation: A Workshop on the Potential for Engineering Scale Processing of Waste Treatment Systems by Electron-Beam Irradiation	January 13-15, 1997	Holiday Inn La Concha, Key West, FL

1.4 Workshop Structure

The 2018 Workshop chair was Dr. Frederick Bloetscher, P.E., of Florida Atlantic University (FAU), supported by an organizing committee consisting of Dr. T.D. Waite (Florida Institute of Technology, who co-chaired a session at the recent workshop on e-beam technology at the Argonne National Laboratory in 2015; Dr. Daniel E. Meeroff (FAU), who was an invited participant at the Argonne National Laboratory and current e-beam researcher in the field of environmental applications; and Dr. Charles Cooper, representing the host institution of Fermilab, who was also

an invited participant of the 2015 Workshop and organized the 2015 Accelerator Stewardship Test Facility Pilot Program at Fermilab. A listing of the names and members of the organizing committee is summarized in Table 3.

Table 3. Organizing Committee.

Name	Role	Affiliation
Frederick Bloetscher, Ph.D., P.E.	Conference Chair	Florida Atlantic University
T.D. Waite, Ph.D.	Co-Chair	Florida Tech
Daniel E. Meeroff, Ph.D.	Co-Chair	Florida Atlantic University
Charles Cooper, Ph.D.	Host	Fermilab – Batavia/IARC

The Conference Chair, Dr. Frederick Bloetscher, P.E., and both co-chairs, Dr. T.D. Waite and Dr. Daniel E. Meeroff are well known and respected in the environmental engineering sector, each having over 15 years of experience and active participation in professional organizations. Dr. Cooper is well known in the field of accelerator construction and applications, having been at the Fermilab in Batavia, IL for over 14 years with prior experience in treating industrial wastewater gained at the USEPA.

The initial proposal suggested holding the workshop in the Fall of 2017 in the Washington, DC area. However, the workshop was eventually scheduled for May 10-11, 2018 at the Fermilab in Batavia, IL. The scope of the workshop involved 2 days of discussion and presentations concerned with: 1) electron beam science, 2) environmental applications, and 3) design considerations. An interactive breakout near the end was conducted with the goal of soliciting discussion. Sub-topics included: technology application gaps, equipment innovations, high energy electron chemistry, process economics, proof of concept testing, training for engineers, design concepts, and resources and support needed. Breakout groups were created for the second day, although initial discussions were solicited on Thursday evening. A concluding session to summarize the findings was captured. All workshop information was agreed to be published on-line as open access. This document, plus on-line publication of the powerpoint presentations and special topics papers were made available to the public (https://indico.fnal.gov/event/16325/overview). A chapter for the next edition (6^{th}) of the Metcalf & Eddy Wastewater Engineering Treatment and Resource Recovery textbook (Tchobanoglous et al. 2014) and 2 peer review submittals were also suggested.

The agenda for the workshop was as follows:

Event	Time
May 10, 2018 (Thursday)	
Registration, meet and greet	08:00 – 08:30
Opening session welcome **Joe Lykken** – Deputy Director and CRO of Fermilab	09:00 – 09:10
Welcome and logistics **Charlie Cooper** – General Manager of IARC at Fermilab	0910 – 09:40
Session 1 – Presentation: Municipal Wastewater Treatment Technologies: Present and Future Tom Kunetz, Assistant Director of M&R, MWRD	09:40 – 10:25
Networking Break	10:25 – 10:45
Session 2 – Presentation: Electron Beam Treatment of Wastewater and Biosolids: Current State of the Science Terri Slifko, MWD of Southern California Suresh Pillai, Texas A&M University	10:45 – 11:30
Working Lunch **Industrial Wastewater Application Opportunities** Dean Amhaus, President and CEO of the Water Council	11:30 – 12:45
Session 3 – Moderated Panel: Industrial Wastewater Issues **Moderator:** Dean Amhaus, President and CEO of the Water Council Karen Bleach, Covanta Environmental Solutions Matt Magruder, Milwaukee Metropolitan Sewerage District Edith Martinez-Guerra, US Army Corps of Engineers Water Treatment Pat Cardiff, Grande Cheese	12:45 – 13:45
Session 4 – Moderated Panel: What are the Barriers to E-Beam Implementation? **Moderator:** Tom Waite, Florida Institute of Technology Gigi Ciovati, Scientist Jefferson Lab, USDOE Sekou Sidime, ComEd Sandip Chattophadyay, NHS Research Center, USEPA **Barry Liner**, Director, Water Science and Engineering Center for the Water Environment Federation	13:45 – 14:30
Networking Break	14:30 – 14:50
Tour of IARC/Fermilab Accelerator Technology Illinois Accelerator Research Center, Cryomodule Test Facility, Wilson Hall, Technical Division Industrial Center Building	15:00 – 17:00
No host networking reception at Two Brothers Round House	18:00 – 19:00
May 11, 2018 (Friday)	
Session 5 – Presentation: Miami-Dade County Experience with E-Beam Robert Fergen, Chief of Operations and Maintenance, Miami-Dade County	08:30 – 09:00

Session 6 – Presentation: Economics of Wastewater/Biosolids Treatment by E-Beam Daniel E. Meeroff, Florida Atlantic University	09:00 – 09:30
Networking Break	09:30 – 09:45
Session 7 – Presentation: State of EB Accelerator Technologies & Future Opportunities Charles Thangaraj, Fermilab Gigi Ciovati, Jefferson Lab Chase Boulware, Niowave	09:45 – 10:15
Session 8 – Breakout into Moderated Groups	10:15 – 11:15
Networking Break	11:15 – 11:30
Session 9 - Summary and Wrap-Up with Working Lunch Moderator: Frederick Bloetscher, Florida Atlantic University	11:30 – 13:15

1.5 Fermi National Accelerator Laboratory (FNAL)

The 2018 Workshop was hosted in Batavia, IL at the Fermi National Accelerator Lab (FNAL), which is a national lab funded by the US Department of Energy Office of Science at a level of $400 million per year. FNAL has approximately 1,900 employees and is considered one of the United States' fundamental tools for science. It is the largest accelerator facility in the western hemisphere and was the highest energy accelerator in the world until CERN's Large Hadron Collider was built. Its base mission is scientific discovery through high-energy physics research. The principle instrument for discovery at FNAL is the 150 GeV proton accelerator complex. FNAL has one of the largest concentrations of accelerator experts in the world, with expertise in design, simulation, fabrication, integration and testing of systems of accelerators and components. This provides the capability to conduct science and develop new technologies from concept to prototype to full-scale industrial applications. Examples of successful efforts include the collider using the largest superconducting magnets, which gave rise to magnetic resonance imaging (MRI) and a quantum computer lab that uses RF (Microwave) technology.

Within the FNAL campus is the Illinois Accelerator Research Center or (IARC), which is focused on developing accelerator-based technologies to the point where they are attractive to industry. IARC leverages its human capital, facilities and technologies to enable new fields and demonstrate Fermi's impact, beyond basic discovery science, on the nation's health, security and wealth (http://iarc.fnal.gov/). The 2018 Workshop was held in the Office, Technical and Education Building (OTE), which was designed to better facilitate collaborations between IARC users and Fermilab technical experts. The OTE building holds office space for 140 people, has 4 breakout meeting rooms, a lecture hall for 170 people, a 4000 ft^2 technical area, a networking lobby, and an eating area for 80 people.

1.6 Benefits to the Community

As the need for cost-effective treatment technologies increases, the e-beam has been largely ignored by the environmental engineering community. Yet the technology holds promise for dealing with microorganisms, micro-constituents, biosolids, medical waste management, flue gas treatment, and industrial/hazardous waste management. However, consulting engineers and industry operators are not familiar with the technology nor are they trained in the application of accelerated electrons for environmental applications. Therefore, the engineering community is ill-equipped to properly design such unit processes, which means that this technology is rarely ever considered as a viable option, even in cases where it clearly should be.

To bring this technology into practice, it is necessary to address the synergistic application side needs by sponsoring research to develop science-based predictive models (for design purposes) to support future use of electron beam technology in applications of interest to environmental engineers. This has the potential to completely transform the industry. Therefore, to galvanize the environmental engineering sector, a focused workshop was conducted to create the research roadmap that will begin to demystify the technology to the engineering community and create the groundwork necessary to begin to develop predictive design approaches for specific applications.

1.7 Workshop Charge/Goals

The stated goals for the 2018 Workshop include:

1. Outline the treatment goals for wastewater treatment plants with respect to key issues such as nutrients, microbiologicals and emerging contaminants like pharmaceuticals, endocrine disruptors and personal care products
2. Outline current measures for treatment to meet treatment goals and the degree to which these treatment methods achieve the above goals
3. Outline the electron beam technology as it currently exists and how it is applied in the wastewater treatment field (current and past studies)
4. Outline the potential barriers to adoption of electron beam technology
5. Outline the current cost for implementation of accelerator technology at wastewater treatment plants
6. Define current innovation needs and provide research direction and potential demonstration projects

CHAPTER 2

UNDERSTANDING THE SCIENCE OF ELECTRON BEAM TECHNOLOGY

2.1 Electron Beam Technology Description

Since the mid-20th century, electron beam technology has provided the basis for a variety of novel and specialized applications. The basic concept of the technology is to accelerate electrons in a vacuum and focus those electrons using a magnetic field to create a concentrated, high-energy beam that can be directed at a target.

In 1913, William Coolidge developed a high vacuum, thermionic cathode that he used to produce an electron beam at the General Electric Company, which he later applied for patents (Coolidge 1916; Coolidge 1917). This was the prototype of the modern electron beam accelerator. In 1925, Coolidge placed a thin foil window at one end of a high vacuum tube and studied the effects of the electron beam on a variety of materials using a 200 keV tube (Coolidge 1926; Coolidge and Moore 1926; Coolidge 1933). Berejka and Cleland (2011) note that in the early 1930s, John Cockcroft and Ernest Walton, two of Rutherford's students, developed circuitry for increasing the voltage for particle discharge, which was the basis for many high-current, mid-energy electron accelerators. This design was improved by Willem Westendorp, who developed one of the first industrial electron beam accelerators, the GE resonant transformer, which was patented in 1940 (Westendorp 1940) and used in some of the very first industrial electron beam processing.

Gustaf Ising proposed using a radiofrequency linear accelerator (linac), and in 1937, William Hansen and Sigurd Varian developed the klystron amplifier, which increases the amount of available power levels of microwave linear accelerators. Today, linacs with one or two milliamps of average beam current at 10 MeV are widely used for medical device sterilization and food treatment, accounting for most of the current industrial applications (Berejka and Cleland 2011). By 1941, technological innovations brought forth the commercialization of the industrial computerized tomography accelerator (Berejka and Cleland 2011). At this time, several companies involved in accelerator technology were established including: High Voltage Engineering Company, Vivirad-High Voltage, Cryovac division of the Sealed Air Corporation, Nissin-High Voltage (NHV) and Wasik Associates.

Arno Brasch and Wolfgang Huber developed a pulsed accelerator, based on capacitor banks being charged in parallel and discharged in series, made commercially available through the Electronized Chemicals Corporation (Berejka and Cleland 2011). With their pulsed accelerator, they showed that short pulses of high voltage, high current electron beams could effectively sterilize and preserve food with minimum damage.

Marshall Cleland and Kennard Morganstern founded Radiation Dynamics, Inc. (RDI) in 1958 to sell their Dynamitron (Berejka and Cleland 2011), many of which remain in operation. The Dynamitron could attain the combination of higher electron energy and higher beam currents (Berejka and Cleland 2011). The Dynamitron can operate at up to 5.0 MeV with total beam power up to 300 kW. The technology forms the basis for the electron transformer-rectifier (ELV) electron beam accelerators produced by the Budker Institute of Nuclear Physics in Novosibirsk, Russia (Berejka and Cleland 2011). Berejka and Cleland (2011) and Nayak et al. (2016) report that the Budker Institute has accelerators that operate between 400 keV and 2.5 MeV with a maximum beam power of 400 kW at 1.0 MeV. In addition, high current pulsed beams, radiofrequency accelerators which operate between 700 keV and 5.0 MeV with a high current version have been developed, and researchers are working on a 10 MeV at 100 kW accelerator.

The Efremov Research Institute of Electrophysical Apparatus in Saint Petersburg also produces a variety of industrial electron accelerators ranging between 0.5 and 2.5 MeV with electron beam power ratings up to 100 kW (Berejka and Cleland 2011). Low energy electron beams (400 keV or less) have been used to cure coatings. Initially a Ford Motor Company idea, it has sprouted competition from Radiation Polymer Company (now Broadbeam Equipment part of PCT Engineered Systems), Energy Sciences Incorporated (ESI), Applied Advanced Technologies (now known as Advanced Electron Beams - AEB), and Ion Beam Applications SA (IBA), among others. The IBA design has become better known as the Rhodotron™. Today there are eight to nine times more commercial electron beam units in world-wide operation than commercial gamma-ray irradiators (Berejka and Cleland 2011).

All electron beam accelerators have some common features (Berejka and Cleland 2011): 1) electrons are emitted from heated cathodes; 2) electrons are focused into a beam with an extraction electrode; 3) electrons are accelerated within an evacuated space with a strong electric field; and 4) electrons pass into the air through a thin titanium-foil window. How they attain this energy differs. The basic components of a typical electron beam device are a sealed device kept under high vacuum, a heated emitter (cathode) that releases electrons to be accelerated using a high-voltage power supply or radiofrequency. Typically, magnetic fields are used to focus and direct the beam toward the exit window. The accelerated electrons emerge with an energy proportional to the voltage applied to the anode and in quantity depending on the cathodic current. By controlling these parameters, it is possible to adjust beam penetration in proportion to beam energy and the dose-rate in proportion to beam current.

Environmental applications of electron beam accelerators have been proposed for several decades (Calvo et al. 2012; Duarte et al. 2004; Gehringer 2004; Gehringer and Fiedler 1998; Han et al. 2009, 2005, 2012; Kim et al. 2006; Kurucz et al. 2002; Pikaev 2000; Pikaev et al. 2001; Rela et al. 2000; Skowron et al. 2014). These include treatment of industrial and municipal wastewater and biosolids for destruction of organic compounds (Maruthi et al. 2011; Wang et al. 2016; Trojanowicz et al. 2017; Wojnárovits and Takács 2017), disinfection (Swinwood et al. 1994; Borrely et al. 1998; Shin et al. 2002; Praveen et al. 2013; Engohang-Ndong et al. 2015, Kurilova et

al. 2017), sludge conditioning and processing (McKeown 1996; Meeroff et al. 2004; Wang and Wang 2007; Lemée et al. 2017), and flue gas purification (Gerasimov 2016). From this previous work, electron beam processing of wastewater or biosolids has demonstrated a potential to completely mineralize organic constituents of concern including pharmaceuticals, personal care products, endocrine disrupting compounds, pesticide residues, petroleum hydrocarbons, nutrients, toxic metals, nanoparticles, and disinfection byproduct precursors. The mechanism is by direct and indirect action of short-lived but powerful oxidants and reducers induced in the matrix including hydroxyl radical, hydrogen radicals, aqueous electrons, superoxides, peroxy radicals, and ozone, without requiring chemical additives (Cooper et al. 1998). Since initially introduced as a treatment option in the environmental sector many decades ago, electron beam technology has matured in other sectors including food safety, materials processing, cross-linking, coatings, grafting, flue gas treatment, and sterilization of medical instruments (Capodaglio 2017). In these fields, the technology has been shown to be robust and safe, so the time has come to reevaluate the shortcomings that have limited electron beam adoption in the utilities sector for environmental applications.

As noted in the 2015 Workshop, for water and wastewater treatment applications, electron beam units will be typically 0.6 MeV – 1.5 MeV, although accelerators up to 10 MeV have been used (Wang 2015; He et al. 2014). The generation of an electron beam with direct high voltage allows a beam power conversion efficiency of 95% or higher, which is much more efficient than a UV process at 30% (Trojanowicz et al. 2017). The 2015 workshop identified high-energy units (5.0 to 10 MeV) and mid-energy, high-current units (400 keV to 5.0 MeV) as having the most promise for treating water and/or biosolids in environmental applications of electron beam processing.

2.1.1 High-Energy Accelerators

Microwave linear accelerators (linacs) and radiofrequency (RF) Rhodotrons are the two types of high-energy (5.0 to 10 MeV) accelerators that have been used in industrial applications (Berejka and Cleland 2011). Linacs (Figure 3) are used for food irradiation, medical device sterilization, and even cancer treatment. The FDA limits are 10 MeV for Co-60, Cs-137, and e-beam and 7.5 MeV for X-ray. The Codex Alimentarius (FAO, UN, and WHO) limits are 10 MeV for Co-60, Cs-137, and e-beam and 5 MeV for X-ray.

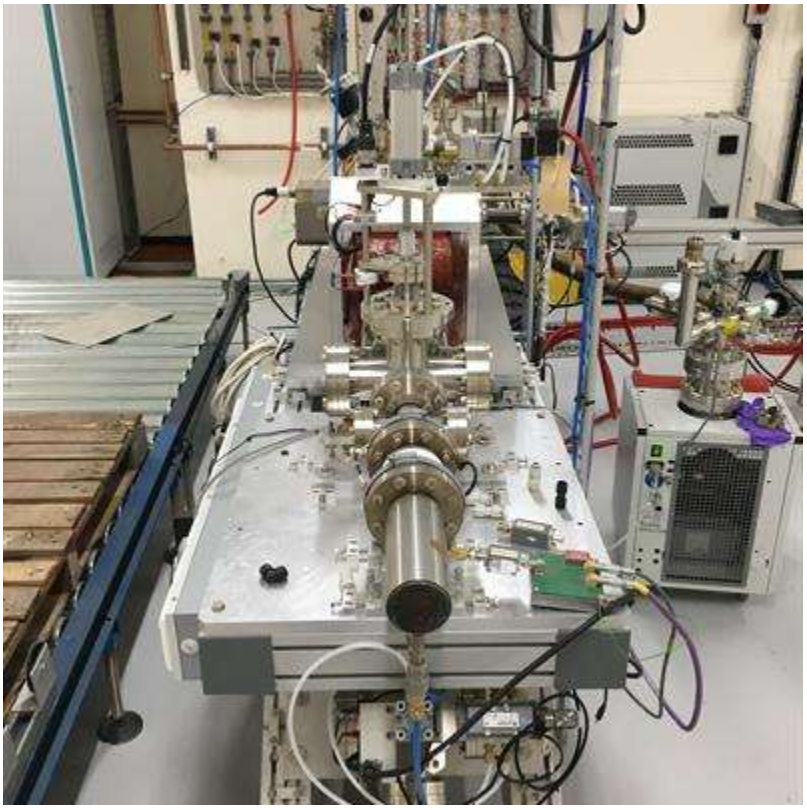


Figure 3. Compact linac (https://www.astec.stfc.ac.uk/Pages/AMICI-Compact-Linac.aspx)

Rhodotrons (Figure 4) operate at up to 700 kW at 7.0 MeV. Rhodotrons have the capability of having multiple beam lines and operate by bending magnets to accelerate electrons through a "figure eight" pattern (Berejka and Cleland 2011). For example, the US Postal Service uses a Rhodotron to sanitize critical US Federal government mail (Berejka and Cleland 2011).

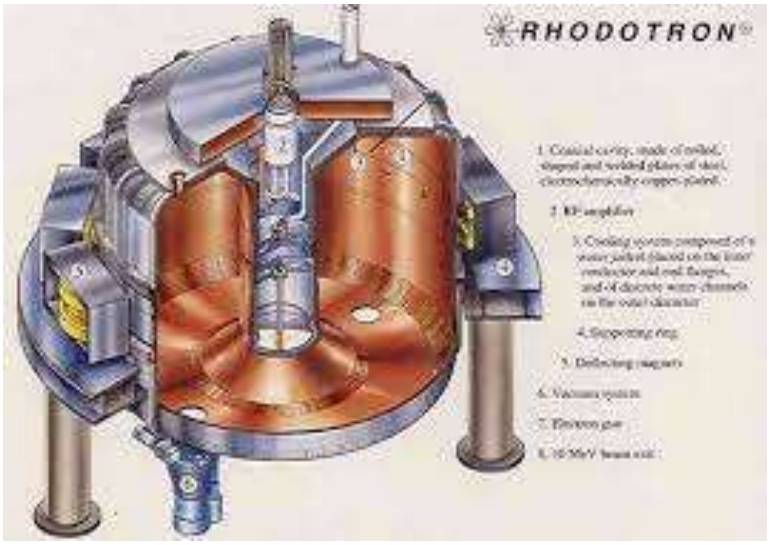


Figure 4. Rhodotron (https://www.phy.ornl.gov/eribs07/presentations/Tatum.pdf)

2.1.2 Mid-Energy Accelerators

Mid-energy electron accelerators produce scanned beams that range in energy from 400 keV to 5.0 MeV. Berejka and Cleland (2011) report that there are five electrical design systems that have been used in mid-energy accelerators. Berejka and Cleland (2011) report that these mid-energy systems (Figure 5) are used in cross-linking applications such as wire and cable, heat-shrinkable tubing and tire manufacturing, where electron beam processing is a routine and well accepted industrial manufacturing practice.

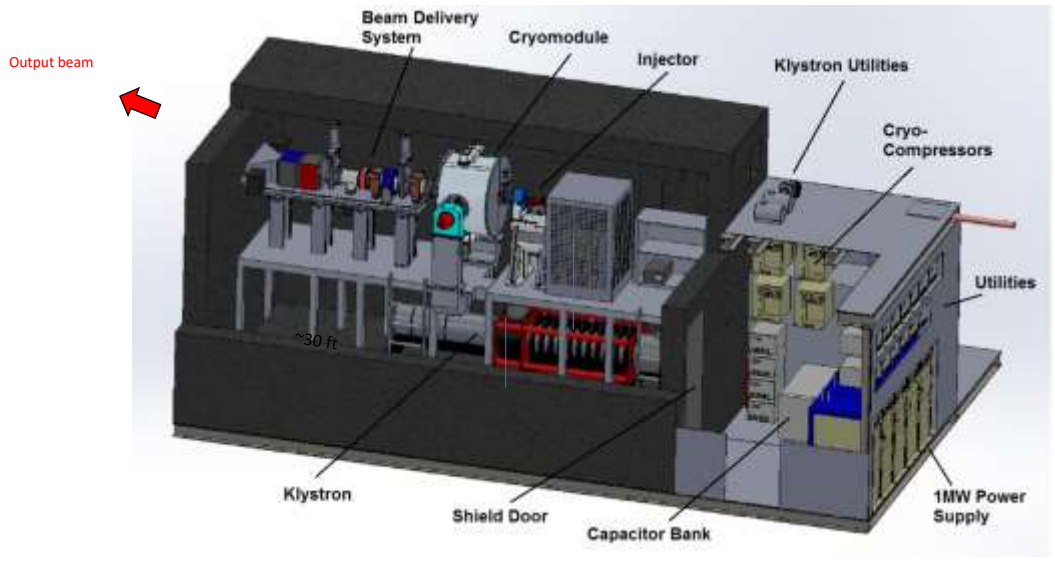


Figure 5. Typical schematic of mid-energy (1 MeV, 1 MW) electron beam unit (Thangaraj and Ciovanti 5/10/2018 presentation at Fermilab)

2.1.3 Emerging Accelerators

New accelerators include changes to the older designs to improve efficiency and reduce operating costs. The basic unit of acceleration in particle accelerators is the RF cavity. Conventional accelerators are made from copper cavities and referred to as warm accelerating technology. More recently, superconducting materials like niobium, referred to as cold accelerating technology because of the need to operate cryogenic temperatures, have gained favor because of their ability to operate more efficiently. Bulk materials processing applications require multi-MeV energy for penetration and thousands of kW (or even MW) of beam power. Inherent losses in copper accelerators limit their efficiency (heat vs beam power). Heat removal limits duty factor, gradient and average power. Superconducting radio frequency (SRF)-based accelerators, found typically only in big science, are huge with complex cryogenic refrigerators, cryomodules, etc. High wall plug power efficiency of these SRF accelerators (e.g. ~75%) allows a large fraction of the input power to go into the beam and ultimately the target.

Recent efforts at institutions like the DOE's Fermilab have incorporated several new technologies into superconducting RF accelerators to remove the need for liquid cryogens thus greatly reducing the size and complexity of the accelerator. This is in part made possible using cryocoolers to remove heat conductively. Since less heat removal is possible with conduction and the cryocoolers than convection and liquid helium, a bulk of the other technology advances like Nb3Sn thin films, low loss power coupling and accelerator operating parameters are made to reduce heat load which ultimately improves efficiency. The advantages of such an accelerator includes energy efficiency (lower operating cost), smaller foot print (portable and fits into existing operations more easily), less complexity and therefore more robust and higher power allowing for treatment of more mass per unit time. A summary of the key advances can be seen here:

1. Superconducting materials
2. Low loss power coupler
3. Accelerator design and operation

Minimize loss of power in accelerator, allow higher power, treat higher flow rates

4. Magnetron RF power supply

Minimize loss of power from e- source to accelerator, cheaper operating cost

5. Integrated electron gun
6. Cryocooler

Decreased complexity and size, portability, ease of incorporation into existing facility

The USDOE has provided funding to develop novel accelerator designs to address the needs for industrial application in the energy and environment sectors. Among the areas of interest are the elimination of pathogens in sludge and destruction of pharmaceuticals and personal care products that are environmental endocrine disruptors. The new design commonalities include: thermionic guns for high-current beams, cryostats with Nb_3Sn SRF cavities for efficient acceleration, cryocoolers for efficient temperature control, and coaxial input power couplers for efficient coupling of RF into the cavity. Potential applications for this next generation of high-energy units include catalyzing chemical reactions, in-situ cross-linking of materials, improving pavement resilience, instantaneous curing of coatings, medical sterilization and improving non-invasive inspection of cargo containers. Additional efforts to provide in-situ cleanup of contaminated soils (for example military bases), and spoils from dredging operations are coincident with these goals.

2.2 Markets for Commercial Field Applications

There are over 30,000 accelerators operating worldwide with sales of $3.5 billion/yr and impact of over $500 billion/yr (Henning and Shank 2010). These accelerators are predominantly warm/copper technology. Because there is a need to treat high volumes in the environmental applications, superconducting accelerators are needed. Design commonalities for such accelerators, include an electron generating thermionic gun that creates a high-current electron beam, a cryostat with a Nb3Sn SRF cavity for acceleration, cryocoolers to reduce power demand

and a coaxial input power couples for the RF cavity (Thangaraj and Ciovanti 5/10/2018 presentation at Fermilab).

It is expected that the new capabilities of compact superconducting RF accelerators will further the market reach of electron beam technology. The US market for wastewater applications is estimated to be on the order of $7.1 billion/year (Niowave 2018) but will take time to develop. For example, sludge thermal hydrolysis took 10 years to be implemented, membrane bioreactors took about 10 years to reach popular acceptance and almost 20 years to get to a commercially stable platform, UV disinfection also took about 20 years, and struvite systems for phosphorus management took about 12-14 years.

A new suggestion for the 2018 Workshop was the need for higher quality wastewater, pathogen elimination and destruction of micro-constituents for direct and indirect potable reuse applications. It was suggested that accelerator technology may increase reliability of destruction of these constituents to reduce the likelihood of pass-through from potable reuse applications in areas with limited water supplies. The removal of micro-constituents from wastewater is a fertile field of study and a current need in the water/wastewater industry.

Prior research from the 1970s and 1980s demonstrated that high energy electrons can alter the physical properties of wastewater sludge particles, thereby enhancing dewaterability and biodegradability through the action of free radical chemistry (Etzel et al. 1969; Kurucz et al. 1991; Sedlácek et al. 1985; Waite et al. 1997; Wang 1993). This research provided evidence that electron beams can be used to improve sludge quality to expand the ability to produce Class A biosolids for land application. The mechanism is via more consistent inactivation efficiency to eliminate potential human pathogens, a concern that resonates with potable reuse and beneficial reuse of biosolids in areas in contact with people, after NRC (2001) raised issues about resistant microorganisms such as viruses, protozoan cysts, and bacterial spores being applied to land application sites where vegetables are being grown.

Other industrial wastewater opportunities are ripe for investigation, especially in the use or catalysts for recovery of metals or destruction of compounds. Based on the previous work cited above, electron beam processing has demonstrated: 1) the ability to lower the strength of a variety of pollutants towards complete mineralization; 2) the ability to remove volatiles and semi-volatile organic compounds; 3) the ability to remove oils and grease of animal and vegetable origins; and 4) the ability to reduce pharmaceuticals and personal care products, such as carbamazepine, gemfibrozil, metformin, naproxen, sulfamethoxazole, and triclocarban, among others.

However, use of electron beam processing is not without challenges (to be further discussed in Chapter 4). These include the lack of ready-to-install equipment and the lack of education on the benefits of the technology in practice. In addition, there is little understanding in the operations and engineering fields for the physical size of equipment. Life cycle costs will be discussed in Chapter 6, but this has been a barrier since the Miami-Dade project was being tested in the

1980s-1990s. Power demands for the accelerators are perceived to be significant. The biggest challenge may be the lack of knowledge of the technology in the engineering industry - an example was one 2018 Workshop attendee who was a veteran of the water/wastewater utility sector for 42 years and had never heard of accelerators being used for wastewater applications. That means there is a lack of a clear message ("elevator speech" or TED Talk) that can be used to explain how accelerators can be integrated into larger treatment plant operations. From a regulatory perspective, measuring effectiveness remains an area of study.

2.3 Mechanisms

In water, wastewater, or biosolids applications, electron beam treatment is capable of generating both strong oxidants and reducers simultaneously in the water. In a wastewater or residuals matrix, the principal component is water. Therefore, it would be expected that high-energy electrons would be predominately be governed by aqueous electron chemistry. The ionization of water by high energy electrons is represented by the following equation:

$$H_2O \xrightarrow{e^-} \cdot OH + e^-_{aq} + \cdot H + H_2O_2 + H_3O^+ + H_2 \qquad (2.1)$$

In aqueous media, three highly reactive transient species are the predominant products generated. These are the oxidizing hydroxyl radical [·OH], the reducing aqueous electron [e^-_{aq}], and the hydrogen radical [·H]. The presence of oxygen and organic material results in the formation of activated intermediates and longer-lived, organo-radicals. Thus, the main effect is to generate a combination of reactive oxidizing and reducing species, free to interact with pollutants in the medium. These radical species are highly reactive with short half-lives on the order of 10 µs at 10^{-4} M.

Studies have shown (Cooper et al. 1992; Kurucz et al. 1995; Nickelsen et al. 1994) that this mechanism can efficiently destroy many organic compounds, including halogenated methanes, polychlorinated biphenyls, BTEX compounds, amines, organic color, and substituted aromatic compounds among others. Thus, the electron beam process can potentially remove metals and decompose organics to complete mineralization, under the right conditions, while at the same time, requiring no chemical additives (although O_3 or H_2O_2 could be used to enhance the generation of radicals).

Advanced oxidation processes (AOPs), including electron beams, are contaminant destruction processes that typically rely on *in-situ* formation of hydroxyl radicals. These processes generally involve two stages of oxidation: 1) formation of strong oxidants and 2) reaction of the oxidants with contaminants. Another byproduct of electron beams in aqueous solutions is hydrogen peroxide (H_2O_2), which results from radical recombination reactions or from superoxide radical disassociation in the presence of water and oxygen (Farooq et al. 1993). H_2O_2 treatment, unlike other chemical methods, does not produce toxic residuals or upset nutrient removal. Furthermore, peroxide application may also help restore microbial activity and effective operation by supplying dissolved oxygen, via the redox decomposition of peroxide in water.

The formation of reactive species from water and their subsequent interactions with particles in a wastewater or sludge matrix are described as indirect effects, caused by energy deposition in the medium leading to the formation of secondary reactants generated through free radical production, sensitizer reactions, and secondary ionizations. Indirect effects are rapid and typically occur within about 10^{-7} seconds of exposure (Setzer et al. 1983; Nickelsen et al. 2005). In addition, direct effects would also be expected due to the relatively high concentration of solids and organic material. Direct effects are induced through the energy deposition of high-energy electrons at sensitive target sites, typically vital sub-cellular components such as enzymes, nucleic acids, or genetic material. These primary ionizations are extremely rapid (10^{-16} seconds) (Setzer et al. 1983).

Electron beam technology is known to produce physical and biochemical interactions in microorganisms such as mutation, inactivation, or cell lysis (Nickelsen et al. 2005). Since the predominant component of activated sludge is water, aqueous electron chemistry mechanisms are important. The response to direct or indirect radiolysis is dependent upon many different factors such as moisture content and the biochemical nature of sludge particles. However, the ratio of indirect effects to direct effects can be estimated using the weight fraction of water to solids. Therefore, direct effects would be expected to be less significant than indirect effects, in wastewater or biosolids applications.

The Orange County Water Reclamation facility proposed electron beam pilot testing for nutrient removal to meet Title 22 guidelines for pathogens and to determine options for brine reuse or disposal. It was noted that the dosage does not make the targets radioactive in the process and easily inactivates *E. coli*. The electron beam is effective in reducing heterotrophic plate counts (Figure 6), seeded microorganisms (Figure 7) and *Cryptosporidium* (Figure 8) at the Orange County, CA facility. The electron beam also demonstrated effectiveness for reducing trihalomethane precursors as noted in Table 4.

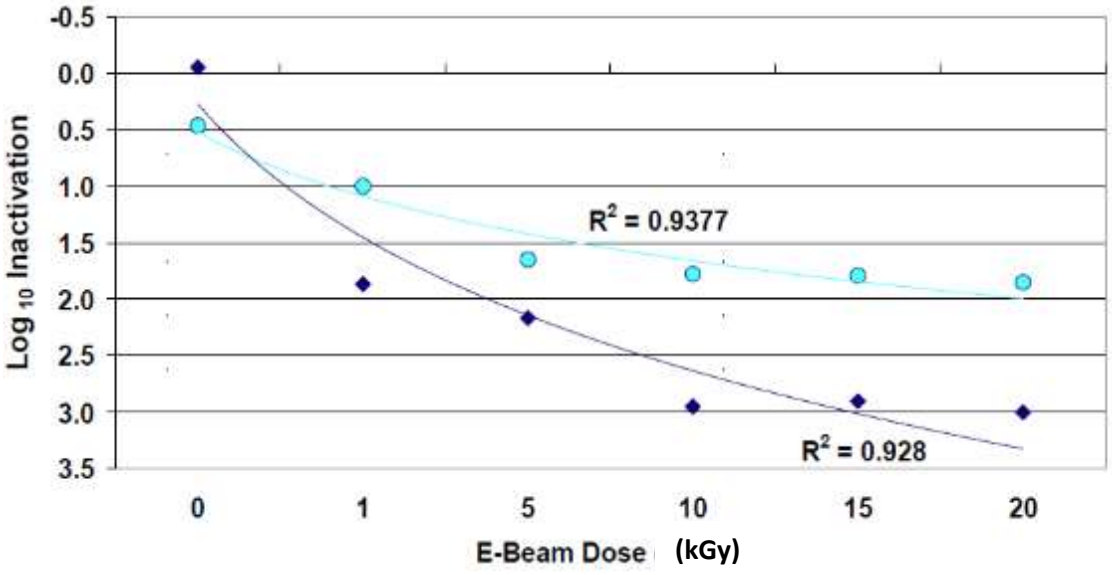


Figure 6. Efficacy of electron beam processing on HPC removal (Slifko, 5/10/2018 presentation at Fermilab)

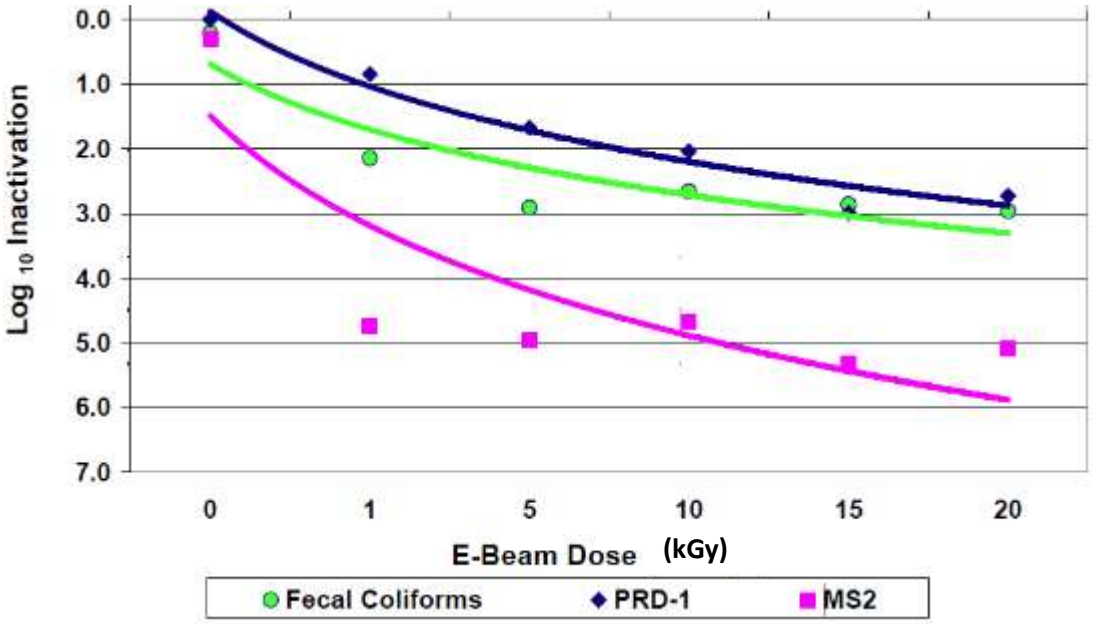


Figure 7. Efficacy of electron beam processing on removal of seeded microorganisms (Slifko, 5/10/2018 presentation at Fermilab)

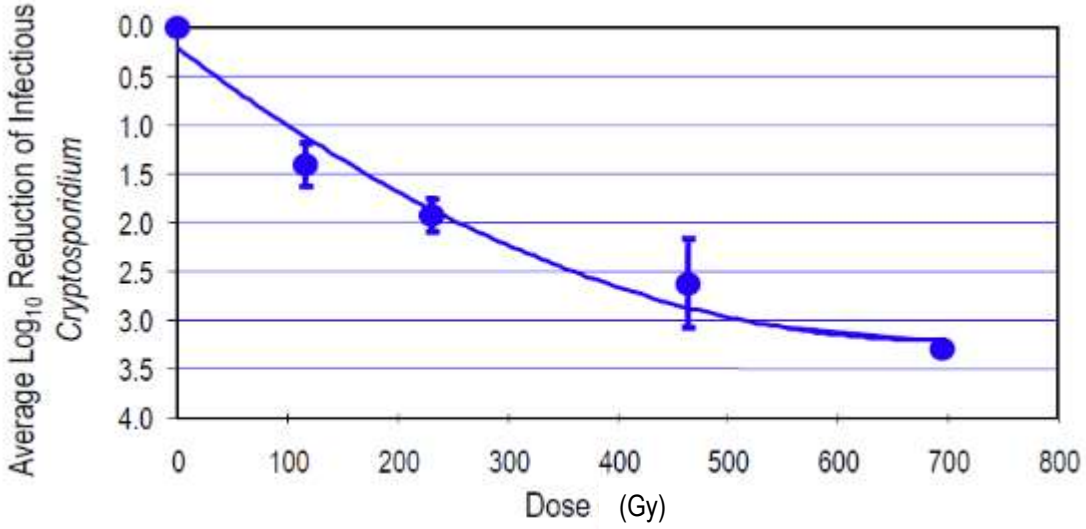


Figure 8. Efficacy of electron beam processing on *Cryptosporidium* removal (Slifko, 5/10/2018 presentation at Fermilab)

Table 4. Removal of trihalomethane precursors by electron beam treatment (Slifko, 5/10/2018 presentation at Fermilab)

Parameter	Percent Removal (%)				
	1 kGy	5 kGy	10 kGy	15 kGy	20 kGy
Dichloroacetic acid	0.0	52.9	77.9	80.4	85.3
Haloacetic acids (HAA5)	4.0	62.3	84.4	86.6	89.9
Tricholoacetic acid	12.9	82.9	>93.9	>93.9	>93.9
Bromodichloromethane	16.7	>94.4	>94.4	>94.4	>94.4
Chloroform	45.2	88.0	>99.1	>99.1	>99.1
Total trihalomethanes (TTHMs)	52.4	89.6	>99.3	>99.3	>99.3

2.4 Previous Experience in Wastewater and Biosolids Applications

Electron beam treatment has the potential to provide multiple beneficial effects with regards to wastewater treatment and biosolids management. At doses on the order of 2-6 kGy, this technique has been used successfully to achieve a variety of treatment objectives, including toxic chemical destruction and recalcitrant organics mineralization (Cooper et al. 1992; Kurucz et al. 1995; Nickelsen et al. 1994), flue gas treatment (Frank 1995), heavy metals immobilization and partitioning (Chaychian et al. 1998), and pathogen inactivation (Cooper et al. 1992; Maloof 1988; Sedlácek 1985; Suess and Kessel 1977; Waite et al. 1997). Based on previous research, the use of electron beam technology as a multi-purpose treatment tool within a wastewater treatment facility has the potential to beneficially impact several different aspects of operation. Therefore, it is expected that electron beam treatment would facilitate more complete biological degradation.

The need for higher quality treated wastewater effluent as well as enhanced pathogen disinfection in sludge and removal of micro-constituents in direct and indirect potable reuse applications provides a basis to evaluate the role that electron beam technology may play in the future. The removal of micro-constituents from wastewater is a fertile field of study and a current need in the water/wastewater industry. Based on the previous work cited above, electron beam processing has demonstrated: 1) the ability to lower the strength of a variety of pollutants towards complete mineralization; 2) the ability to destroy volatiles and semi-volatile organic compounds; 3) the ability to remove oils and grease of animal and vegetable origins; and 4) the ability to reduce concentrations of pharmaceuticals and personal care products, such as carbamazepine, gemfibrozil, metformin, naproxen, sulfamethoxazole, and triclocarban, among others (Slifko 2018).

It has also been demonstrated that high energy electrons can alter the physical properties of wastewater sludge particles, thereby enhancing dewaterability and biodegradability through the action of free radical chemistry (Etzel et al. 1969; Kurucz et al. 1991; Sedlácek et al. 1985; Waite et al. 1997; Wang 1993). Other potential areas for process improvements include the following: 1) improved sludge quality to expand the ability to produce Class A biosolids; 2) increased

inactivation efficiency to eliminate potential human pathogens, in particular, resistant microorganisms such as viruses, protozoan cysts, and bacterial spores; 3) enhanced sludge conditioning and thickening characteristics to increase process loading rate capacity; and 4) reduced waste sludge production by eliminating bulking events and improving dewaterability characteristics, without large amounts of chemical polymers that add mass to the waste sludge to be disposed (Meeroff et al. 2004).

There are two sites in the US that have investigated the use of electron beams for wastewater and biosolids treatment at utility scale. Both were successful, but the technology was not pursued beyond the demonstration stage due to changes in the sludge regulations promulgated in the early 1990s.

2.4.1 Deer Island, MA

The Massachusetts Water Resources Authority (MWRA) is a Massachusetts public authority established by an act of the Legislature in 1984 to provide wholesale water and sewer services to 3.1 million people and more than 5,500 large industrial users in 61 metropolitan Boston communities. MWRA operates the Deer Island Wastewater Treatment Plant to protect Boston Harbor against pollution from Metropolitan Boston's sewer systems. The plant removes human, household, business and industrial pollutants from wastewater that originates in homes and businesses in 43 greater Boston communities (MWRA 2018). Deer Island had one of the first applications of an electron beam in 1976, funded by the National Science Foundation. The system was designed to treat thickened sludge (2-8% solids) using a 50 kW beam of 850 keV electrons (Trump et al. 1977) and was applied for sludge disinfection at the facility in the late 1970s through the early 1980s before removal. The Deer Island demonstration project had a treatment capacity of 170,000 gallons per day (650 m^3/d) for a minimum dose of 4 kGy and found a dose of 0.5 kGy to be sufficient to disinfect municipal wastewater effluent and also to decompose organic pollutants (Cleland et al. 1984). They noted that electron beam processing was a practical method to disinfect liquid municipal sludges in large systems at a cost of $12/dry ton in 1977 dollars (Trump et al 1977). Capital and operating cost estimates were provided for continuous sludge disinfection on the order of $7.50 per 1000 gallons ($2.00 per cubic meter) for liquid sludge (Cleland et al. 1984). If an emerging accelerator technology, as described in Section 2.1.3, was used instead in this application, more than 1 million gallons per day could have been treated at 4 kGy, and the cost would have been closer to $5.00 per 1000 gallons.

2.4.2 Virginia Key, FL

Miami-Dade County operates three regional wastewater treatment plants, all of which have capacities that exceed 100 MGD:

- South District WWTP, 112.5 MGD
- Central District WWTP, 143 MGD

- North District WWTP, 120 MGD

In 1980, Miami-Dade County underwent a major regionalization that required taking many smaller plants off line to replace them with new master lift stations to facilitate the expansion of the three regional facilities with new wastewater disposal solutions, while dealing with a rapid influx of people. The Central District WWTP produced 100 dry tons of raw sludge per day, which after digestion left about 65 tons for disposal daily. Initially the facility used principally anaerobic digestion, then both aerobic and anaerobic digestion and composting. The County created an alternative solids plan that included use of an electron beam processing unit in which 95% of the funding was provided by the United States Environmental Protection Agency (USEPA). A prototype was employed to treat approximately 25% of the solids. The installation was a 75 KW unit implemented for pathogen reduction and organic priority pollutant reduction. Figure 9 shows the facility and the installation.

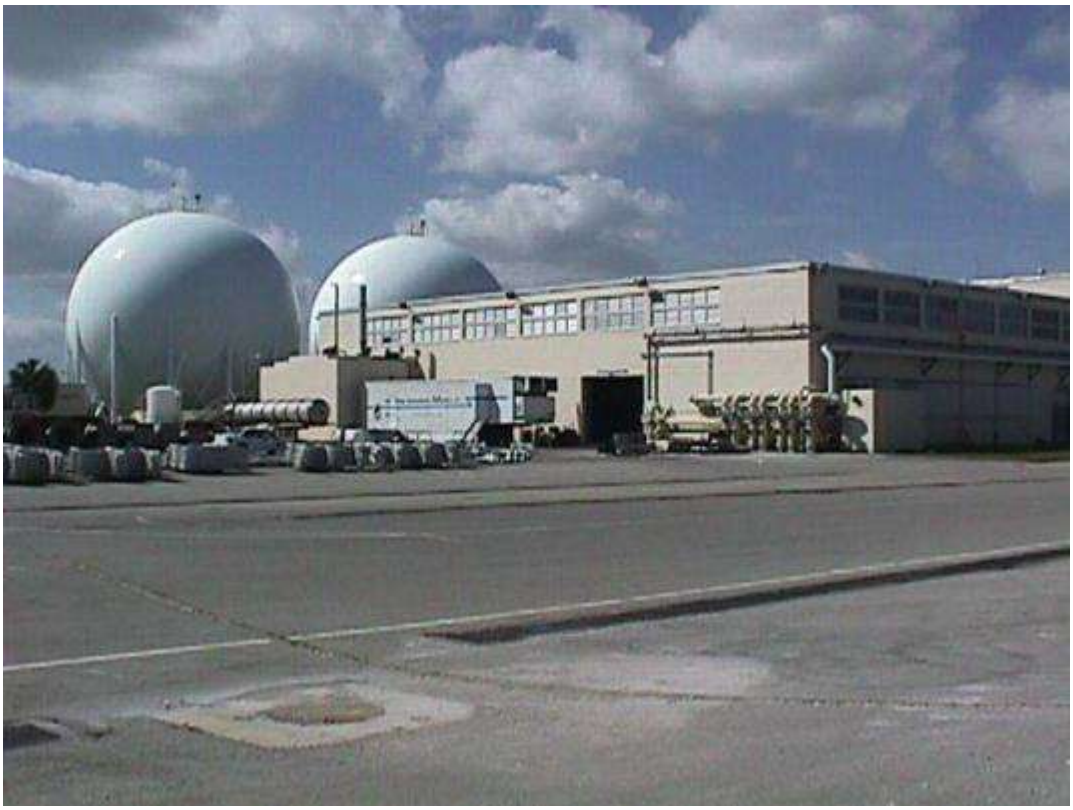


Figure 9. Electron beam installation at Central District WWTP (Slifko 5/10/18 presentation at Fermilab)

The prototype unit was installed, and both pathogens and viruses were tested in drinking water (Figure 10). The anaerobic digestion process at the time generated 10,000 mg/L of ammonia, which was sufficient in itself to inactivate certain pathogens and viruses. The goal was to pilot test the process prior to implementing a full scale system. Sludge rules were under development

at the time, but finalization was uncertain. Based on the data, electron beams were proposed for disinfection. Two issues ended up stalling the project. First, the facility experienced a 5-7 log reduction in bacteria, but it could not demonstrate effectiveness on *Ascaris* or viruses because there were no measurable helminth eggs or viruses in the feed sludge. The Florida Department of Health did not allow the researchers to spike the sludge with viruses or helminth eggs to be able to test the removal efficiency. With respect to organic priority pollutants, they were detected consistently, but the removal efficiency could not be determined because the feed concentrations were near zero and spike tests were not performed.

Figure 10. Electron beam treatment unit at the Central District WWTP (Slifko 5/10/18 presentation at Fermilab)

Second, USEPA had established an electron beam dosage in CFR 257, so the process was perceived to have minimum risk. However, the rules were changed, and the required dosage increased by 4 fold. This had the effect of increasing the number of units from 4 to at least 16-20 additional units. As a result, the electron beam was no longer deemed economically feasible.

Comparison laboratory and pilot tests were conducted in 1998-2001 to compare the use of cobalt-60 ionizing radiation and electron beam treatment at an activated sludge wastewater treatment facility with residuals processing (Meeroff et al. 2004). Operational enhancements were investigated with respect to bulking control, thickening enhancement, anaerobic stabilization processes, and dewaterability. Both technologies caused permanent effects in measured sludge parameters including solids content, chemical oxygen demand, ammonia-nitrogen, zeta potential, specific surface area, resistance to filtration, sludge volume index, pH, organic acid production during anaerobic digestion, and digester gas evolution. Findings from sludge parameter analyses indicated that treatment should enhance certain flocculation and settling mechanisms by permanently altering electrokinetic sludge properties, rupturing cells, and increasing biodegradability of recalcitrant material. However, a clear dose-response relationship was not demonstrated for many of the parameters tested, and the observations were sometimes the result of competing mechanisms. Within these limitations, a number of measured parameters showed sufficient sensitivity to detect differences with respect to dose. For doses higher than 10 kGy, pilot testing generally showed a reversal of dose-response trends indicating usually undesirable effects. At moderate doses (3-4 kGy), pilot testing demonstrated several benefits:

- Ammonia nitrogen stayed below toxic levels (<1000 mg/L as N)
- COD solubilization increased slightly (3%)
- Surface charge became more neutral by 40%
- Specific surface area decreased by 30%
- Resistance to filtration was reduced in half

Taken together, these results indicated that treatment induced more efficient compaction and improved filterability; however, the rate of water release did not necessarily show a corresponding improvement, and bench scale settling tests were not sensitive enough to detect any differences, such that surface area requirements and loading rates in settling column studies were not affected, indicating no adverse impacts to sludge thickening (Meeroff et al. 2004). With respect to bulking control, feasibility was deduced from relative inactivation kinetics. Since the indicator filament *Sphaerotilus natans* (D_{10} = 0.66 kGy) was inactivated at a lower dose than the bulk flora (D_{10} = 0.94 kGy), selective elimination of bacterial filaments is possible (Meeroff et al. 2004). In summary, pilot testing results suggest that treatment will enhance operational efficiency of certain processes within an activated sludge wastewater treatment with residuals processing. Preliminary cost analyses showed that a dose of 2-3 kGy, the potential for substantial savings for the application of integrated bulking control with electron beam treatment (Meeroff et al. 2004). According to these results, a centralized electron beam accelerator could be applied

economically in an integrated approach at an estimated annual savings of $0.2-2.7 million depending upon the application. Considering that the annual cost of operating an accelerator unit was estimated at $2.4 million ($2.16/m^3), this might translate into an important savings for a large-scale wastewater treatment facility (Meeroff et al. 2004).

As of 2018, Miami-Dade County views the electron beam as a potential technology to replace thermal hydrolysis to address the pending ocean outfall legislation and reuse of effluent, but the cost today to install the original test system for the Central District WWTP is estimated at over $5 billion dollars, a hefty cost that appears to be beyond the County's budget. As a result, there is a need to:

- Procure a pilot electron beam processing unit
- Test for pathogen reduction and priority pollutant reduction
- Establish dewatering characteristics
- Decide to expand or cancel and demolish

If an emerging accelerator technology, as described in Section 2.1.3, was used instead in this application (10 kGy), then 5-6 accelerators would be needed, instead of 16-20 of the type of accelerator used in the study. This would make the application more feasible.

CHAPTER 3

UNDERSTANDING THE PRIORITY APPLICATIONS OF ELECTRON BEAM TECHNOLOGY

According to the 2018 Workshop participants, several priority applications of electron beam technology were identified. Among those were wastewater, potable reuse, biosolids, industrial waste, and others.

3.1 Wastewater Management

Based on the comments in Chapter 2, the field of wastewater treatment appears ripe for adoption of electron beam technology applications for use on large scale processes for sludge, disinfection and recalcitrant emerging constituents. To that end, a brief introduction to the current state of wastewater management follows.

Wastewater is the used water discharged from homes, businesses, and industries. Typically, this water will contain constituents such as organics, suspended solids, salts, metals, pharmaceuticals, personal care products, endocrine disrupting compounds and many other constituents depending on the source, which make this water not suitable for most uses without proper treatment. In 2015, the Department of Homeland Security recorded 16,576 publicly owned treatment works (POTW) in the United States. Nearly 80% of POTWs are classified as small (<1 MGD). However, many large urban areas, such as Cleveland, Milwaukee, Detroit, Chicago, Miami and Los Angeles are served by a very large regional wastewater system. The size of a POTW is based on the permitted capacity of the facility. A summary of the numbers and sizes of facilities in the United States is provided in Table 5 (data provided by Department of Homeland Security, 2015).

Table 5. Numbers of POTWs and system sizes in the United States

Classification	Flow Range	Approximate Number in the US
Small	< 1 MGD	13,158
Medium	1 – 10 MGD	2858
Large	10 – 100 MGD	509
Extra Large	>100 MGD	51

A typical wastewater management system consists of the following physical infrastructure:

- Collection system
- Liquids treatment unit processes
    - Preliminary treatment (headworks)

    - Primary treatment
    - Secondary treatment
    - Additional treatment
    - Disinfection
    - Effluent discharge
- Solids handling unit processes
    - Residuals and biosolids management
- Ancillary systems

The wastewater collection system is a network of pipes, conduits, tunnels, pressurized force mains, lift stations, and pumps that convey the wastewater from the source where it was generated to the POTW for subsequent treatment and disposal. Sanitary sewers are gravity driven - the wastewater travels downhill by gravity until a point where the line becomes too deep. Then a lift station or pump station is installed to lift the sewage back to the surface. In many communities, natural topography can be used to transport the sewage. In flat areas, the use of lift stations is much more likely. Some systems also combine stormwater with wastewater in combined sewers.

Figure 11 outlines some of the typical unit processes commonly found at a POTW, noting that the use or discharge of the treated wastewater determines the processes and configuration of a wastewater treatment plant. The amount of treatment needed is entirely dependent on how the treated wastewater is discharged. Over 85% of treated wastewater is discharged into a surface water receiving water body (e.g. rivers, lakes, streams, ocean outfalls, etc.). The remaining portions are primarily used for irrigation (e.g. golf courses, fire supply, dual distribution systems, landscaping and agriculture), water features (ex. Las Vegas fountains), deep injection wells, wetlands augmentation, aquifer recharge and even indirect or direct potable use. The use of very highly treated wastewater for drinking purposes (indirect or direct potable reuse) may seem forbidding, but since nearly 60% of the US population's water demand is supplied from those same lakes, river and streams that are receiving water bodies for treated wastewater, in essence, most wastewater is "reused" for potable purposes albeit with far more control when treated in a treatment facility.

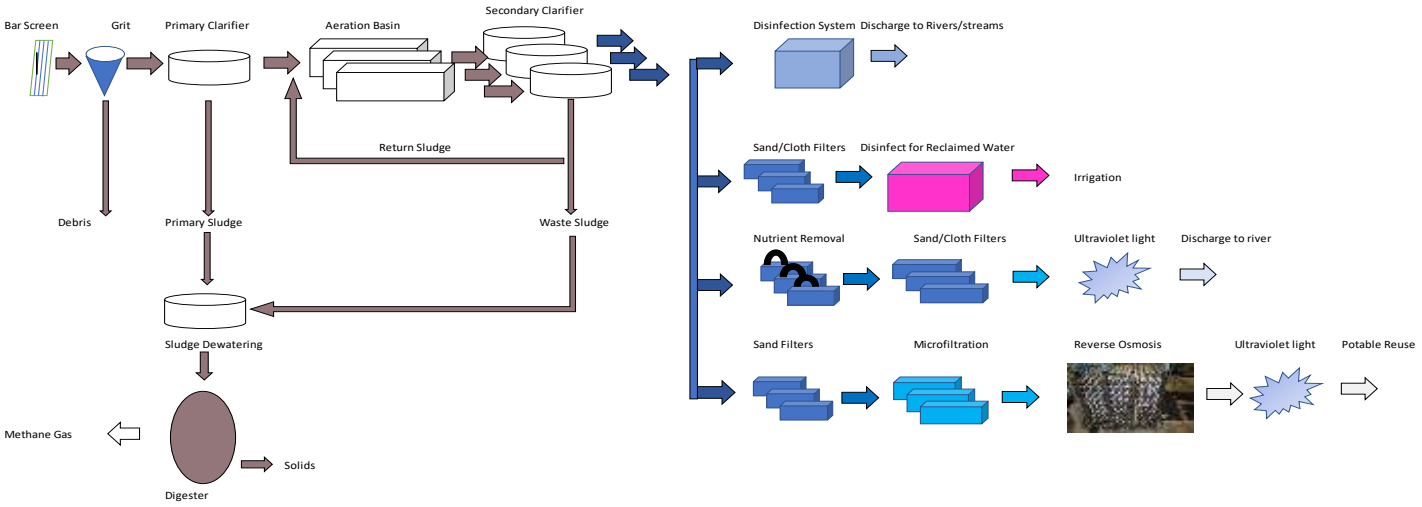


Figure 11. Typical POTW Process Flow Diagram (note the discharge point determines the treatment needed)

According to USEPA (2005), the goals of a sanitary sewer management program should include:

- "Protection of public health
- Prevention of unnecessary property damage
- Minimization of infiltration, inflow and exfiltration, and maximum conveyance of wastewater to the wastewater treatment plant
- Provision of prompt response to the number of people and service interruptions
- Efficient use of allocated funds
- Development of a sewer use ordinance
- Identification of and remedy solutions to design, construction, and operational deficiencies
- Performance of all activities in a safe manner to avoid injuries"

The early sewer systems in the world were merely pipes that moved the waste directly to receiving water bodies. In most cases the storm drainage system was connected to allow the stormwater to flush debris accumulated in the sewer pipes to the nearby waterway. This worked for the most part when populations were relatively small. However, rapidly growing communities exceeded the carrying capacity of their discharge points, which necessitated treatment prior to discharge.

3.2 Wastewater Treatment Unit Processes

3.2.1 Preliminary Treatment

The first step after the raw wastewater is delivered to the centralized treatment plant by the collection system is known as preliminary treatment or headworks. This typically consists of bar racks, screens, grit chambers and/or primary clarifiers (Figure 12). The goal of these systems is to remove large solids, such as sticks, rags, and other debris from the raw wastewater by physical straining processes. Bar racks are designed to remove particles greater than 0.25-inch, and fine screens can remove particles from 0.02-inch to 0.25-inch. These solid materials are collected and generally disposed of in landfills. Figure 12 shows the bar screen on the top right of the structure, with the screenings falling into the dumpster underneath.

Figure 12. Bar screen and grit chamber at the headworks of a WWTP

Grit consists of sand, gravel, cinders, or other heavy solid materials with much higher settling velocities compared to putrescible organic material. Grit removal reduces formation of deposits in downstream unit processes and protects mechanical equipment and pumps from accelerated wear due to abrasion. A grit chamber is located on the left side of the structure in Figure 12 (these are virtually always enclosed).

Primary clarifiers (Figure 13) are used to collect settleable solids, but also to equalize flow to address the peaks caused by rain and daily variations in usage. The goal of a primary clarifier is to remove readily settleable and floatable material to reduce the suspended solids content that would otherwise impact the downstream pumps and equipment in the subsequent treatment processes. Typically, primary sedimentation tanks provide a detention time of 10-30 minutes Depending on the design, up to 35% of the biochemical oxygen demand (BOD) and a large portion of suspended solids can be removed. Prior to World War II, primary treatment was the extent of treatment in the US (and remains so for much of the world, if any treatment is actually performed).

Figure 13. Aerated, primary clarifier, also used for flow equalization

Shortly after World War II, a focus on the construction of wastewater treatment plants began when the Federal Water Pollution Control Act in 1948 and its updates (the most famous of which was known as the Clean Water Act of 1972) were passed. The new treatment plants that were constructed at that time were designed to handle the average daily flows, which meant problems occurred when it rained if the sanitary sewer system was not sealed from surface flooding. This meant that primary clarifiers had to be converted to equalization basins. Major effort has been underway for the last 40 years to de-couple combined storm/sanitary sewer systems.

3.2.2 Secondary Treatment

After World War II, larger communities realized that primary treatment was insufficient to protect public health. So instead of just targeting suspended solids for removal, a new emphasis

was placed on removing dissolved organics using a biological reactor following preliminary and primary treatment but prior to disinfection. The initial goal of the Clean Water Act of 1972 was to restore the nation's fishable, swimmable, and navigable rivers and streams through the removal of untreated industrial and domestic wastewater discharges. Biological treatment became the minimum standard for POTWs with effluent standards developed nationally, as follows (note some states have stricter standards):

- BOD_5 <20 or 30 mg/L
- TSS <20 or 30 mg/L
- Fecal coliforms 0 CFU/100 mL most of the time

The concept of biological treatment is to use microorganisms to convert the soluble organic waste (sBOD) to particulate BOD (cell biomass), which can be settled out by gravity. The biological community in a wastewater treatment plant is highly efficient at removing most organic contaminants from the wastewater when flows are constant and the hydraulics are consistent (Tchobanoglous et al. 2014).

A common technology to achieve secondary wastewater treatment is the activated sludge process. The basic concept is soluble BOD (food) in the influent wastewater enters an aeration basin and gets mixed with air and activated sludge (microorganisms), which contains a concentrated mixture of microorganisms acclimated to breaking down the organic material when provided with oxygen from air. The microorganisms form flocculent particles that are subsequently separated out in a clarifier as activated sludge. This material is either returned to the aeration basin (return activated sludge) to provide microorganisms for further degradation or wasted (waste activated sludge) to maintain an appropriate sludge age in the aeration basin. Figure 14 is a typical activated sludge process (an aeration tank that mixes oxygen with solids and microorganisms for treatment).

Figure 14. Activated sludge process

Figure 15 shows a diffuser system, which is highly efficient for dispersing air. Figure 16 shows a photograph of a mechanical mixer, which is less expensive to construct, but is far less efficient.

Figure 15. Diffusers for air in the activated sludge basin

Figure 16. A mechanical mixer or sparger for adding air to the WWTP

Figure 17 is an example of an extended aeration system that uses rotating brushes to impact the oxygen to the water. Note that there are many different configurations for the aeration basin in an activated sludge process.

Figure 17. Extended aeration basin

In the activated sludge process, the food:microorganism ratio (F/M ratio) and sludge age are the key operating parameters for maintaining healthy bacterial populations. Too much or too little food will create significant changes in the bacterial population and destabilize treatment. Treatment systems do not want to wash out the microorganisms that convert the soluble organics into biological sludge, so the hungry microorganisms are captured in a secondary clarifier using gravity sedimentation (see Figure 18). Activated sludge is the material that settles at the bottom of the secondary clarifiers within a detention time that is on the order of 2-4 hours. Some of the biological solids captured in the clarifier are returned to the aeration basin as return activated sludge (RAS), while the remaining portion is removed as waste activated sludge (WAS) to maintain the appropriate sludge age in the system. When WAS is removed from the liquids processing train at the POTW, it is comprised mostly of cell biomass and minerals – not the organic material that comes into the wastewater treatment plant.

Figure 18. Secondary clarifier

Secondary clarifiers are designed to achieve an effluent prior to discharge containing not more than 30 mg/L of carbonaceous biochemical oxygen demand over 5 days ($cBOD_5$) and 30 mg/L total suspended solids (TSS), or 85% removal of these pollutants from the wastewater influent, whichever is more stringent. The TSS is a measure of the carry-over solids, which are the microorganisms that do not settle and escape the clarifier by overflowing the weirs. To eliminate solids carry-over, membranes can be used to replace the function of the secondary clarifier, particularly if space is limited. An example is the process known as a membrane bioreactor (MBR), as shown in Figure 19.

Figure 19. MBR process that uses membranes instead of clarifiers

Typically, the final step for liquids processing is disinfection to inactivate the potentially pathogenic microorganisms remaining in the effluent. Small systems often feed chlorine as a solution similar to household bleach. Larger systems obtain the chlorine as a gas in cylinders (Figure 20) and feed it into the water using a chlorinator (Figure 21). Chlorination equipment can be automated to work unattended, with proper safeguards to prevent freezing and vandalism. Chlorine is moderately priced, relatively easy to use, and effective as a disinfectant.

Figure 20. Chlorine cylinders (gas)

Figure 21. Chlorinator equipment

3.2.3 Advanced Secondary Treatment

In the early 1970s, a number of states began to realize water shortages given that demand for irrigation water was putting increasing pressure on water supplies. Therefore, substituting reclaimed wastewater for irrigation, cooling water and other non-potable purposes was pursued. The concern was the particles that escaped disinfection as a part of secondary processing might represent a threat to public health, so regulations were developed to reduce contaminants further as follows (note that states may have stricter standards):

- BOD_5 5 mg/L
- TSS 5 mg/L
- Fecal coliforms 0 CFU/100 mL
- Chlorine residual (often >1.0 mg/L leaving the plant)

To meet these standards, sand filters (Figure 22) or cloth filters, and high level disinfection were required. Gravity filters use media that is typically a combination of sand, anthracite, or other filter media materials. Water is loaded from the top and allowed to filter though the sand by gravity. Periodically the filter will start to plug, which requires backwashing (Figure 23). The filter then has water or a mixture of water and air flushed through it in the reverse direction. When this happens, the sand bed expands, and the solids on the surface are flushed into collection troughs for removal. The filter is then ready to operate as a clean filter again.

Figure 22. Typical gravity sand filter

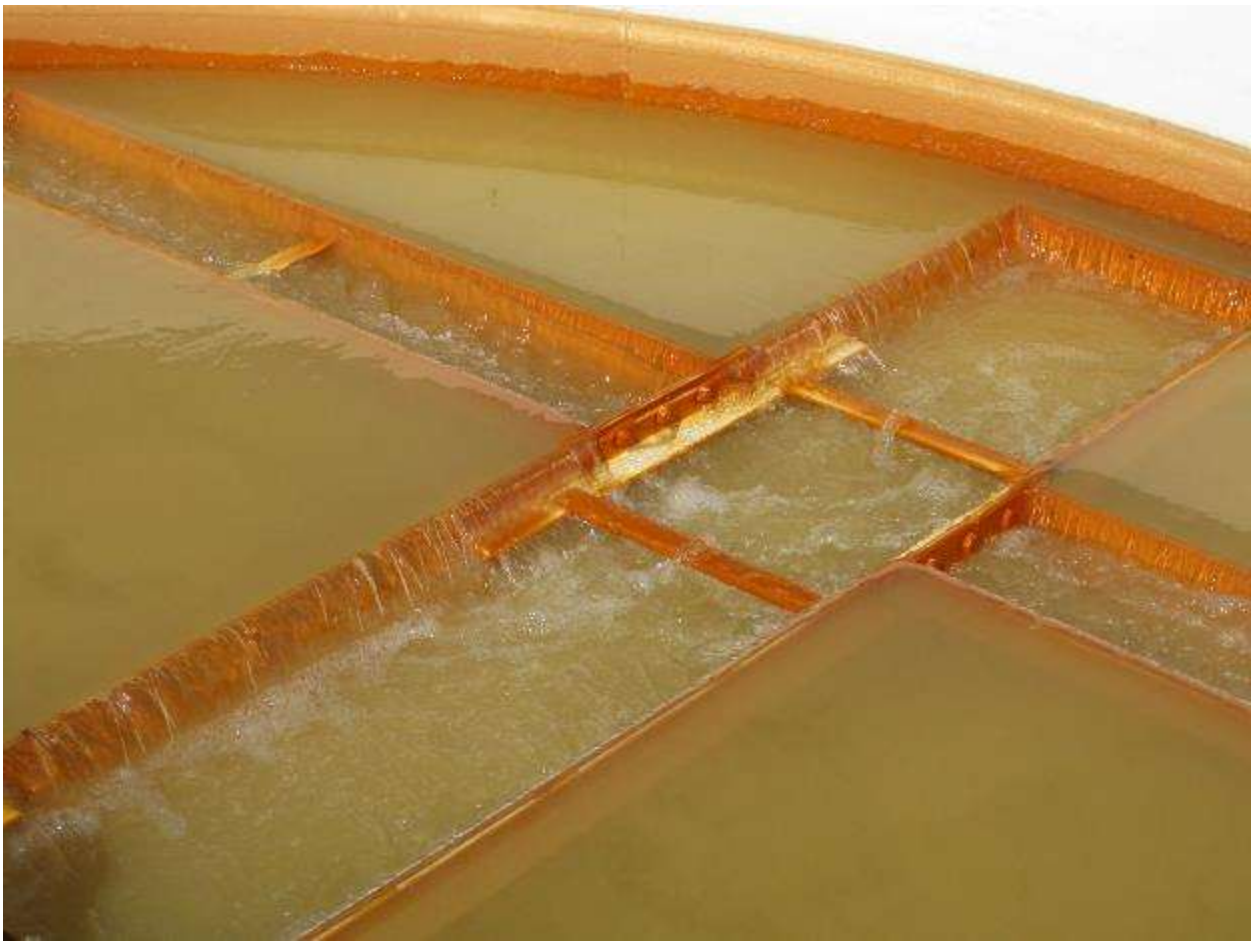


Figure 23. Backwashing filter

Some systems use pressure filters, which operate in a similar manner to gravity sand filters, except that the flow is often upward, as opposed to downward for gravity filters. They are totally enclosed (Figure 24) and are comparable in performance to gravity filters.

Figure 24. Pressure filters

Adin and Asano (1998) concluded that because removal varies by particle size, particle size must play a major role in the effectiveness of wastewater filtration. Figure 25 outlines the size of the particles of interest in the wastewater and the pores size or grain size for filtration processes.

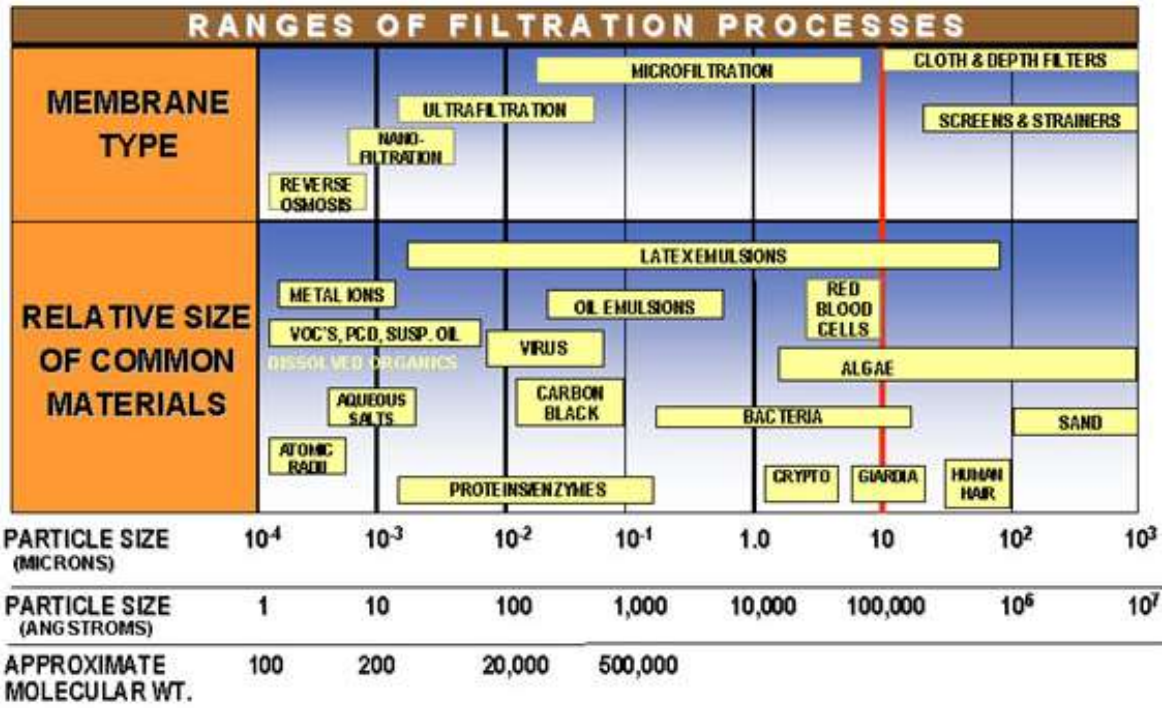


Figure 25. Particle size and filtration processes (http://www.hwea.org/events/02_reuse/slides/sl_arnold.htm)

3.2.4 Nutrient Removal (Advanced Wastewater Treatment)

If treated effluent with elevated levels of nutrients (e.g. nitrogen and phosphorus) is discharged to a slow moving receiving water body, the nutrients can trigger explosive growth of algae in a process called eutrophication. The natural eutrophication process can be accelerated by anthropogenic activities, which results in overgrowth of algae, septic conditions, and fish kills from a lack of dissolved oxygen (Figure 26).

Figure 26. Algae overgrowth on a eutrophic pond

Wastewater discharges encourage algae growth because the treated wastewater naturally contains elevated levels of nitrogen (in the form of ammonia and organic nitrogen) and phosphorous. As a result, effluent standards were developed nationally as follows (note some states have stricter standards):

- BOD_5 <5 mg/L
- TSS <5 mg/L
- Total Nitrogen 3 mg/L
- Total Ammonia 2 mg/L
- Total Phosphorous 1 mg/L
- Fecal coliforms 0 CFU/100 mL most of the time
- Chlorine residual 0 mg/L

Removal of nitrogen can be accomplished by biological nitrification/denitrification processes. These are typically in the form of anoxic zones in an aeration basin or specific treatment processes like rotating biological contactors (RBCs). There are many configurations, but the goal in all cases is to sequentially convert the ammonia to nitrite then to nitrate and then release the nitrogen to the atmosphere in the form of nitrogen gas. Because this is a biologically-mediated process, it is very similar to secondary treatment but with extended solids retention times or alternating oxic and anoxic zones. Some systems require two sludge recycling, so there will be a clarifier involved and filters after the process.

More difficult is phosphorous removal, which is typically a chemical precipitation unit process. Alum as a precipitation agent is an option, but it increases the amount of sludge produced substantially, while making the sludge residuals harder to dewater and of less value as an energy source. Conversion to struvite (magnesium ammonium phosphate) is an option pursued by some utilities as there is some indication that the world has passed its peak phosphorous mining levels, making recaptured phosphorous a potentially valuable commodity. Struvite precipitation technology for nutrient recovery has provided an example of a technology that has achieved commercial success in a relatively short (12 to 14 year) time span. For example, the Pearl Ostara System chosen for the Stickney plant removes 80-90% of phosphorus, while generating up to 9000 metric tons of useful commercial fertilizer per year (MWRD 5/10/2018 presentation at Fermilab). The benefits of large scale production at a large treatment plant is shown to provide an economy of scale for improved cost efficiency.

3.2.5 Full Treatment

Recovery of wastewater to supplement potable water supplies is a major conservation initiative in water-limited environments. Because few existing undeveloped or underutilized high-quality water sources exist in the United States, many utilities are considering to utilize impaired water sources to meet increasing demands and regulations requiring the investigation of alternative water supply sources such as reclaimed water for aquifer recharge and land application projects as well as desalination technologies in an effort to offset potable water withdrawals. The evolution of those processes offers significant promise to meet future water supply needs.

Because aquifer recharge requires much more treatment than reuse, it could provide a source of supply to meet increasing demands. In addition, aquifer recharge would permit continuation of the use of current water treatment processes (and many plants have capacity that is unused due to raw water supply limitations). The main obstacle is not technical, it is public perception and the potential for waterborne illness issues due to operator error, treatment process failure, or monitoring issues.

The Centers for Disease Control and Prevention (CDC) and USEPA have maintained a collaborative surveillance system for collecting and reporting waterborne disease outbreaks since 1971. For the ten-year period of 1997 – 2006, 137 waterborne disease outbreaks were reported to the CDC, with a total of 8,498 illnesses and 17 deaths (Barwick et al. 2000; Blackburn et al. 2004; Lee et al. 2002; Liang et al. 2006; Yoder et al. 2008). Of the outbreaks with a known cause (101), 17 were attributed to chemical or toxin poisoning and 84 to pathogens. Bacteria were the most commonly implicated pathogen; however, the highest number of outbreaks were due to *Legionella, Giardia, Campylobacter,* norovirus and *E. coli* O157:H7. The next update is due after 2020.

Wastewater treatment plant secondary effluents contain measurable concentrations of more than 1000 man-made compounds, including a variety of pesticides, herbicides, cleaning solvents, laundry detergents, household products, surfactants and emerging micro-constituents like hormones and pharmaceutically active substances, only a portion of which have been identified

(Harries et al. 1997). The term "emerging micro-constituents" describes two categories of contaminants: 1) biological constituents and 2) endocrine disruptors. The biological constituents are not new – but they appear to pose a greater risk to consumers today than they have in the past. Among the over 90 currently regulated contaminants in drinking water, seven are categorized as "microorganisms" by the USEPA. These include the pathogenic microorganisms *Cryptosporidium, Giardia lamblia, Legionella,* enteric viruses, and several indicators of microbial risk and treatment system effectiveness, including heterotrophic plate count, total coliforms, and turbidity. While a significant literature database has been established on these regulated parameters, waterborne disease outbreaks in the past decade have been attributed not only to the regulated microorganisms, but also to unregulated pathogens (Bloetscher and Plummer 2011).

Section 1412(b)(1) of the Safe Drinking Water Act requires the USEPA to publish a Contaminant Candidate List (CCL) every five years. The CCL outlines a series of contaminants of concern, including unregulated microbial and chemical contaminants that are not subject to any proposed regulations, but are known to occur in potable water supply systems and may require regulation in the future. The list is used to prioritize research initiatives, and to develop sufficient datasets such that regulatory decisions can be made about contaminants on the list. A contaminant may move from the CCL list to regulation if the USEPA determines that: 1) the contaminant may have an adverse health risk on people drinking the water, 2) the contaminant is likely to occur in potable water systems at a level that is a concern to public health, and 3) there is an opportunity to reduce human health risk by regulating the contaminant.

USEPA (1998, 2005, 2009, 2016 – CCLs) created a comprehensive list of 1,425 pathogens, called the CCL Universe, that was established based on waterborne illness occurrence. Information on waterborne diseases is obtained through voluntary reporting from state and local health departments to the CDC. The Final CCL 4 published in 2016 includes 97 chemicals or chemical groups and 12 microbial contaminants (USEPA 2016). Included in the chemical list are pesticides, biological toxins, disinfection byproducts and pharmaceuticals, some of which are considered to be endocrine disrupting compounds (EDCs).

EDCs are a group of chemicals, mostly man-made, which are released into the environment through normal daily activities, and they interact with normal human and animal metabolic processes. EDCs are found in most common, everyday household products, like pharmaceuticals, shampoos, detergents, sunscreens, pesticides and industrial chemicals. They enter the public waste stream through household sinks and drains. Not all are liquids, some are dusts, and comprise the major portion of household dust, like poly-brominated flame retardants (PBDE), which are in every seat cushion, drapery, and plastic item found in most households. Normal usage creates dust. Some EDCs, like pesticides and herbicides, enter the sanitary sewer system through common housekeeping. Eventually, most EDCs end up at the wastewater treatment facility, where they will need to be treated before the water can be made suitable for reuse. Their impacts are discussed more fully in Bloetscher and Plummer (2011) and references therein.

In the early 1990s, Ternes (1998) tested for 32 drug residues in municipal sewage treatment plant effluents in Germany. Greater than 80% of the tested drugs were found in at least one treatment plant effluent. Heberer (2002) found blood lipid regulators, analgesics, sulphonamides, and anticonvulsants at concentrations up to µg/L in sewage treatment plant effluents in Berlin, and he further determined a direct correlation between effluent discharges and receiving water concentrations of pharmaceuticals. A similar study was conducted by USGS in US waters (Koplin et al. 2002).

Some of these EDCs have been found to induce endocrine mediated changes in aquatic life at concentrations as low as one part per trillion (Carollo Engineers, 2008; Daughton and Ternes 1999; Bloetscher and Plummer 2011 and references therein). Some interactions are detrimental, some toxic, and some are lethal. Many EDCs have long environmental half-lives, on the order of decades, which means that once they are released, they can persist for years without degradation. Unfortunately, removal of these contaminants is poor in most typical wastewater plants. The removal rate of emerging contaminants is 34–83% as compared between influent concentrations and effluent from the conventional activated sludge step (Daughton and Ternes 1999; Ternes 1999). Reverse osmosis removes 95% of hormones (Daughton and Ternes 1999). A problem with pharmaceutical breakdown is that the concentrations may be below that needed to initiate the enzyme affinity of the organisms, so treatment may never begin (Daughton and Ternes 1999; Ternes 1999). If a pharmaceutical manufacturing facility is present in the service area, careful consideration of using an industrial pretreatment program to limit the discharge to the sewer is warranted.

A number of options have been studied with an eye toward treatment of endocrine disruptors, and pharmaceuticals in particular. These are categorized as follows:

- Facilities that have ultraviolet disinfection may reduce pharmaceuticals and EDCs, especially if double carbon bonds are present. Ultraviolet light experience seems to provide reduced pharmaceutical occurrence (in very limited testing) with advanced oxidation (UV/H_2O_2 – Carollo Research Solutions 2008; Weinburg et al. 2008).
- Breakpoint chlorination may also render some compounds nonfunctional. However, because the activity of an organic compound is often increased by chlorination, modest chlorine dosages may increase the activity of the effluent above nonchlorinated levels. Breakpoint chlorination of an effluent would also likely generate disinfection byproducts, some of which may violate water quality standards (Snyder et al. 2007).
- Chemical coagulation using ferric salts and/or alum were reported as having only limited effectiveness in laboratory studies (Bloetscher and Fergen 2001; Fergen and Bloetscher 2001). However, successful removal of dissolved organic compounds may occur only at a narrow range of coagulant dosage, pH and polymer dose (Bloetscher and Fergen 2001; Fergen and Bloetscher 2001).
- Ozone appears to destroy certain organic compounds (Weinburg et al., 2008) particularly by oxidizing the double bonds to render the compound less active. However, partial ozonation may produce increased activity in the compound and disinfection byproducts or partially oxidized products such as aldehydes and ketones.

- Nanofiltration and reverse osmosis appear viable for the removal of many trace contaminants including pharmaceuticals (Snyder et al. 2007; Huber et al. 2003; Carollo Research Solutions 2008; Bloetscher et al. 2011; Bloetscher and Fergen 2001; Fergen and Bloetscher 2001), but without UV/AOP, do not achieve 3 logs of removal (Bloetscher et al. 2011)

While the body of literature on effective treatment has grown, no one method seems to resolve all issues. However, more certainty and reliability is required for treating wastewater for groundwater recharge and potable reuse applications. The standard-bearer for such recharge projects is Water Factory 21 in Orange County, CA. A 1996 study found no measurable differences in the incidence of diseases in water users between Orange County and the Los Angeles basin, where the water supply is not recharged with reclaimed water (Sloss 1996). The City of Pembroke Pines, FL pilot tested the Water Factory 21 process for 9 months. From a public health perspective, reverse osmosis is employed as part of a multi-barrier system, as seen in Figure 27 (installed). While the membrane treatment results are described elsewhere (Bloetscher et al. 2011), one of the concerns generated during the pilot testing was about under-saturation of the effluent resulting from the reverse osmosis treatment, including the potential to dissolve the aquifer formation, and to leach metals into the raw water. As a result, effort was put toward developing post treatment stabilization.

Figure 27. Installed reverse osmosis system

Figure 28 shows a flowchart for treating domestic wastewater to drinking water standards and using it to recharge groundwater with the goal of enhancing source water recovery. RO precedes the ultraviolet advanced oxidation process (UVAOP). The City of Pembroke Pines piloted such a process based on the Orange County project, and the results of the pilot study mimic the full-scale facility in California (Bloetscher et al. 2011).

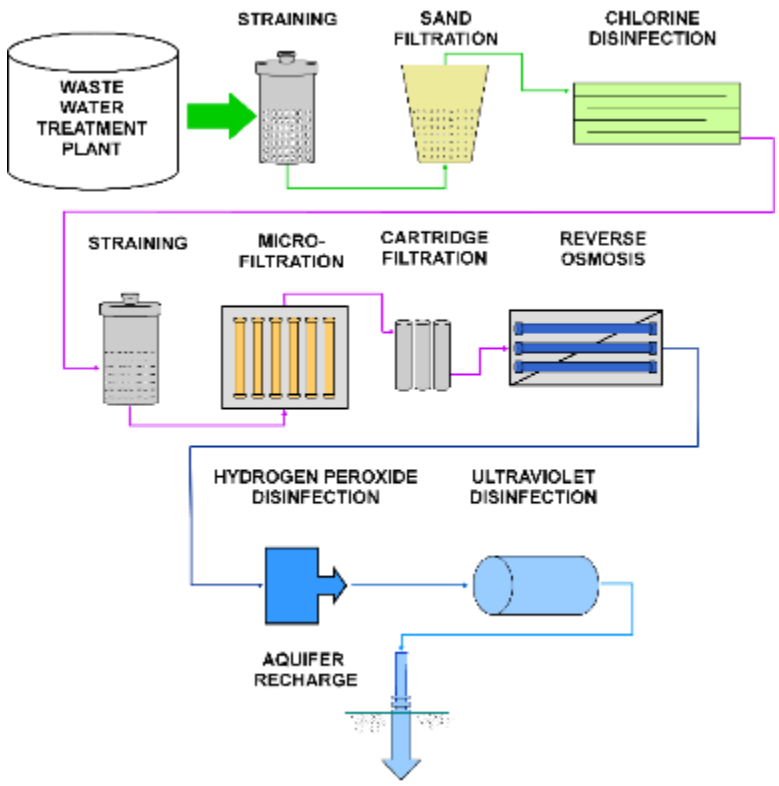


Figure 28. Full treatment process diagram

In this configuration, the membranes rejected over 97.5% of salts, had recoveries approaching or exceeding 66-73% with two stage flux of 15.7-21.5 gpd/sf, while still providing excellent permeate water quality. Since salt is not the issue of concern, other parameters such as phosphorous must be evaluated to determine if the process was sufficient. Table 6 and Table 8 shows summaries of performance data indicating successful removal of the regulated constituents when compared with the local (Broward County - BC) and State (FAC) regulatory requirements.

Table 6. Summary of Nutrient and Coliform Average Results Post RO and UV-AOP for the Pembroke Pines Full Treatment Demonstration Project (Bloetscher et al. 2011)

Analyte	Units	BC Limit	FAC Limit	Effluent
Nutrients and Microbiologicals				
Phosphorous	mg/L	0.01	NS	U
Turbidity	NTU	10	NS	U
Total Coliforms	CFU/100 mL	1000	4	U
Fecal Coliforms	CFU/100 mL	800	1	U
TSS	mg/L	*	NS	U
Enterovirus	IU/100L	1/gal	<1	U
Cryptosporidium Oocysts	Oocysts/100L	1/gal	<1	U
Giardia Cysts	Cysts/100L	1/gal	<1	U
Viable Helminth Ova	Ova/100L	1/gal	<1	U
Organics				
BOD	mg/L	5	NS	U
COD	mg/L	10	NS	I-U
Oil & Grease	mg/L	10	4	U
Phenolics	µg/L	0.1	NS	U
TOC	mg/L	NS	3	U
Pesticides				
Azinphos-methyl (guthion)	µg/L	0.1	NS	U
Demeton	µg/L	0.1	NS	U
Ethyl Parathion	µg/L	42	NS	U
Malathion	µg/L	0.1	NS	U
Hexachlorobutadiene	µg/L	10	NS	U
Hexachloroethane	µg/L	10	NS	U

NS = No Standard

U = Undetected based on method detection limit

I = Result is between lab method detection limit and practical quantification limit

** = None attributable to wastes*

Table 7. Summary of Post RO and UV-AOP Inorganic Water Quality Results for the Pembroke Pines Full Treatment Demonstration Project (Bloetscher et al. 2011)

Analyte	Units	BC Limit	FAC Limit	Effluent
Sodium	mg/L	160	160	BL
Antimony	µg/L	6	6	U
Arsenic	µg/L	50	10	U
Barium	µg/L	2000	2000	U
Beryllium	µg/L	4	4	U
Cadmium	µg/L	5	5	U
Chromium	µg/L	100	100	U
Lead	µg/L	15	15	I
Mercury	µg/L	2	2	U
Nickel	µg/L	100	100	U
Selenium	µg/L	50	50	I-U
Thallium	µg/L	2	2	U
Cyanide, Total	mg/L	0.2	0.2	U
Fluoride	mg/L	2	4	U
Nitrate as N	mg/L	10	10	BL
Nitrate + Nitrite as N	mg/L	10	10	BL
Nitrite as N	mg/L	1	1	I-U

NS = No Standard
U = Undetected based on method detection limit
I = Results is between lab method detection limit and practical quantification limit
BL = Below regulatory limit

In addition, a suite of unregulated contaminants listed in monitoring rule 2 (UCMR2) were analyzed after treatment and none were detected. The suite included: BB, BDE-100, BDE-153, BDE-47, BDE-99, dimethoate, terbufos sulfone, 1,3-dinitrobenzene, 2,4,6-trinitrotoluene (TNT), RDX, *n*-nitrosodiethylamine, *n*-nitrosodimethylamine, *n*-nitroso-di-n propylamine, *n*-nitrosodi-*n*-butylamine, n-nitrosomethylethylamine, n-nitrosopyrollidine, acetochlor, alachlor, and metolachlor. Virtually all of these compounds were found in small concentrations in the influent (see Table 8). Because they were close to the detection limit, the project team decided to spike 8 substances at 1000 times the detection limit to determine if 3 logs of removal could be attained.

Table 8 presents the maximum, average, and minimum concentrations of substances of interest analyzed in 3 different spike tests. Samples were collected at 4 different locations in the treatment train: 1) at the influent, 2) before Phase 1 (SP-1), 3) after Phase I (SP-2), and 4) after reverse osmosis (SP-3). A 3-log reduction was obtained for all analytes except TCEP and 1, 4-dioxane, which had a combined percent removal equivalent to 99.83 and 97.80%, respectively.

Table 8. Summary of EDCs Removal for the Pembroke Pines Full Treatment Demonstration Project (Bloetscher et al. 2011)

Compound	Influent				SP-1				SP-2				SP-3			
	High Value	Average	Low Value	Count	High Value	Average	Low Value	Count	High Value	Average	Low Value	Count	High Value	Average	Low Value	Count
PHARMACEUTICALS																
Acetaminophen	150000	90,813	8500	8	180	127	100	3	180	180	180	1	0	0	0	0
Azithromycin	1700	938	130	8	350	247	170	6	380	233	140	6	0	0	0	0
Caffeine	94000	47,800	5900	8	2600	838	220	4	1400	450	160	5	0	0	0	0
Carbamazepine	420	217	32	8	370	204	24	7	370	207	26	8	0	0	0	0
Cotinine	2500	930	43	8	1800	426	15	5	130	100	71	4	0	0	0	0
Diltiazem	540	322	35	8	290	205	29	8	230	144	15	8	0.86	0.67	0.47	2
Fluoxetine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gemfibrozil	3800	2,576	280	8	600	480	310	6	470	418	360	6	0	0	0	0
Ibuprofen	18000	12,413	1500	8	1300	678	210	6	1200	605	230	6	0	0	0	0
Iopromide	4700	1,385	140	4	510	229	81	3	620	227	71	4	0	0	0	0
Lincomycin	15	6	1.2	5	10	6	1.7	5	19	11	3.8	2	0	0	0	0
Naproxen	19000	12,813	1700	8	3100	1,580	500	6	1800	1,193	500	6	0	0	0	0
Sulfamethoxazole	3300	2,140	330	8	900	595	76	8	830	538	71	8	0	0	0	0
Trimethoprim	920	566	91	8	320	236	40	7	340	243	170	6	0	0	0	0
Tylosin	54	26	12	3	42	28	12	2	26	19	12	2	0	0	0	0
ANTIBACTERIALS																
Triclocarban	1200	928	110	8	290	178	39	7	280	233	160	6	6.6	5	3.3	4
Triclosan	3600	1,506	86	8	150	98	69	6	120	110	100	2	110	110	110	1

Continued

Table 19 *Continued*

Compound	Influent				SP-1				SP-2				SP-3			
	High Value	Average	Low Value	Count	High Value	Average	Low Value	Count	High Value	Average	Low Value	Count	High Value	Average	Low Value	Count
STEROIDS/HORMONES																
17α-Estradiol	10	9.6	8.9	3	0	0	0	0	0	0	0	0	0	0	0	0
17α-Ethinyl Estradiol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17β-Estradiol (E2)	23	17.8	14	5	0	0	0	0	0	0	0	0	0	0	0	0
Equilenin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Estriol (E3)	210	113.3	56	7	0	0	0	0	0	0	0	0	0	0	0	0
Estrone (E1)	41	35.6	27	7	22	18.5	15	2	0	0	0	0	2.6	2.6	2.6	1
Progesterone	17	14.3	11	3	0	0	0	0	0	0	0	0	0	0	0	0
Testosterone	96	70.7	40	7	0	0	0	0	0	0	0	0	0	0	0	0
PROTEIN DEGRADATION																
NDMA	29	19.33	7.3	7	9	5.43	2.6	8	130	30.1	6.5	8	8.3	3.8	2	8
NDPA	4.4	4.40	4.4	1	0	0	0	0	0	0	0	0	0.54	0.54	0.54	1
FLAME RETARDANTS																
TCPP	1200	827	78	7	1600	963	120	8	1500	939	89	8	33	33	33	1
TCEP	990	483	200	4	1400	598	190	5	1200	508.333	220	6	190	112	34	2
TDCPP	610	610	610	1	800	800	800	1	1100	1100	1100	1	0	0	0	0

Notes

All units are in ng/l

In all cases of biological wastewater processing outlined in this section, there is a residual of sludge that must be disposed of properly. Sludge is basically bacteria removed from the process to control the age and population of microorganisms. The disposal of sludge has become an increasing challenge over the past 30 years. Accelerator technology, as outlined from previous experience at Deer Island and Miami-Dade County (refer to Section 2.4), has demonstrated potential to improve treatability and disinfection of sludge residuals in a utility setting.

3.3 Biosolids Management

Wastewater residuals processing generally deals with less than 1% of the total waste volume, but typically accounts for nearly half the total capital and operating costs of a wastewater treatment facility (Tchobanoglous et al. 2014). To offset these costs, domestic sewage sludge from biological wastewater treatment is sometimes reused for beneficial purposes. Since the sludge is rich in nutrients and organic material, it can be applied as a soil conditioner. However, sludge derived fertilizers may contain concentrations of pathogens, water-soluble toxic chemicals, and trace metals that are not trivial. Thus, sewage sludge must be treated, disinfected, and rendered harmless before disposal.

Waste activated sludge is typically withdrawn from the bottom of secondary clarifiers. It is a dilute material (<0.5% solids), comprised of bacterial flocs and fine inert solids. Withdrawn sludge is pumped to either a storage area or directly to the first stage of the sludge processing train, which is usually sludge thickening. Thickening processes serve to initially increase the solids content of the sludge to around 2%. A slight increase in sludge solids will result in a substantial decrease in the volume of thickened sludge produced for further processing. Thickening can be accomplished by several different methods including dissolved air flotation, centrifugation, gravity drainage belts, perforated rotating drums, or most commonly gravity concentration. In most instances, waste activated sludge will not thicken readily. Therefore, some sort of sludge conditioning practice is typically employed to achieve more efficient thickening.

Conditioning techniques alter the physical and chemical characteristics of the sludge through a variety of methods including polymer addition, elutriation, electro-acoustic processes, thermal treatment, or irradiation. Sludge conditioning processes are also utilized to facilitate the further consolidation of sludge solids and aid in the removal of water in subsequent treatment processes, such as stabilization and dewatering.

Sludge stabilization methods are typically included in wastewater residuals processing to reduce pathogen density, eliminate odor-producing components, and inhibit the potential for putrefaction. Stabilization can be accomplished by biological, physical, or chemical methods (Stoll 1996). Common sludge stabilization processes include biological treatment, in the form of anaerobic digestion, aerobic digestion, or composting, and also chemical treatment, generally in the form of lime stabilization or pH adjustment. Alkaline stabilization can produce a soil amendment with substantially reduced pathogen counts capable of meeting Class A requirements, but the lime addition requires chemical costs and also increases the mass of solids.

Depending on the process, stabilization may also yield sludge volume reduction, biogas generation, and even dewaterability enhancement. Most commonly, anaerobic digestion stabilization methods are used in large installations. It accomplishes the biological reduction of volatile solids in the absence of molecular oxygen. The process, carried out in an airtight reactor vessel, converts biological solids into a variety of end products including CH_4 and CO_2. Electron beam treatment to enhance anaerobic biological stabilization and improve digester performance would seek to achieve more complete volatile solids destruction, increase biogas production at lower solids retention times (SRT), accelerate biological degradation by breaking down sludge particles into more soluble materials, and reduce polymer demand for subsequent dewatering through the action of free radical chemistry.

Sludge dewatering (Figure 29) involves processes to improve the physical sludge handling characteristics by removing excess moisture. By decreasing the final sludge volume, the costs for transporting sludge to the ultimate disposal site may be substantially reduced. Simple dewatering methods involve the application of wastewater solids to sand drying beds or lagoons, where gravity sedimentation, drainage, and evaporation processes remove moisture. Because of the lower space requirements, more commonly, dewatering involves mechanical equipment, such as direct dryers, vacuum filters, belt filter presses, or centrifuges.

Figure 29. Dewatered sludge

Biosolids can also be treated with advanced thermal oxidation or incineration. Some utilities run a pelletizing plant to turn the material into a granular fertilizer product, such as Millorganite or Green Edge. Another final stabilization process could be composting.

Changqing and Min (2012) used electron beam processing of biosolids to increase the fraction of substrate that was bioavailable as a precursor to enhancing methane production potential in downstream anaerobic digestion. Laboratory scale studies (Meeroff et al. 2004; Shin and Kang 2003) suggested that pre-treatment of waste activated sludge (WAS) prior to anaerobic digestion could reduce the solid retention time, depending on the conditions.

The final step in biosolids processing consists of disinfection, which is performed to sterilize remaining sludge residuals, rendering it safe from a human health perspective. In practical terms,

this means the inactivation of human pathogen indicator organisms. Selection of the most appropriate decontamination technology is dependent upon the physical properties of the sludge solids, the microbiological characteristics of the sludge to be disposed, and the final disposal option selected.

The USEPA regulates the disposal of municipal sewage sludge (biosolids) to the environment in the US in 40 CFR Part 503. The key pollutants are microbial pathogens, nutrients (nitrogen and phosphorus) and minerals (potassium, calcium, magnesium and sulfur). Heavy metals are generally not an issue in wastewater sludge streams in the US since they are regulated at sources under the USEPA's National Pollutant Discharge Elimination System (NPDES) permitting program, except where heavy industry is located. Emerging contaminants such as norovirus, adenovirus, perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS), EDCs, and pharmaceuticals and personal care products have also raised concerns. More information on the federal rules that govern biosolids reuse and disposal are discussed in more detail in Section 3.6.

High-energy electron beam sterilization of biosolids is of particular interest because of demonstrated success in inactivating pathogenic microoorganisms in sludge (Cooper et al. 1992; Maloof 1988; Sedlácek 1985; Waite et al. 1997) at absorbed doses in the range of 2.7-10 kGy. Using electron beam technology, a total absorbed dose of 4.0 kGy has been found effective for inactivation of bacterial pathogens, although microorganisms with higher resistances, such as viruses, may require larger doses to achieve the desired level of disinfection (Sedlácek 1985; Suess and Lessel 1977; Wickramanayake and Sproul 1990; McKeown et al., 1998). In Poland, Skowron et al. (2013) demonstrated the efficiency of electron beam treatment for inactivating *Ascaris suum* eggs from cattle and swine waste. Capizzi-Banas and Schwartzbrod (2001) reported a D_{10} value = 0.8 – 1.1 kGy for ova from slaughterhouse sludge. Using a 3 MeV electron beam system at 50 gpm, Engohand-Ndong et al. (2015) reduced viable *Ascaris* ova to below detection limits at 14.5 kGy. Pillai and Reimers (2010) and Praveen et al. (2013) demonstrated that electron beam treatment of sewage sludge at 10 kGy achieves the approximate log reduction of specific pathogen indicators using a 10 MeV S-band linac. The 10 kGy level has been adopted by USEPA as a process to further reduce pathogens (PFRP) in stabilized municipal sludges. This energy level was cited by Miami-Dade County as 4 times what they were expecting during their testing, and concerns remain that this level or energy imparted to sludge will remain a barrier to electron beam technology adoption. To the best of our knowledge, there does not appear to be any electron beam facilities in operation for biosolids treatment. Unlike wastewater applications, biosolids treatment will be a batch process, which means that the redundancy factor may not be as critical. Therefore, the opportunities for market entry for electron beam processing in this space are related to the following:

- Conditioning to improve thickening and dewaterability and to reduce viscosity to lower pumping costs, polymer demand, and hauling costs
- Pre-stabilization improvements to enhance biodegradability/bioavailability of organics and nutrients for downstream digestion and to enhance methane production potential for a more stable soil amendment product with higher energy generation

- Destruction of emerging contaminants to reduce risk of exposure after final disposal
- Disinfection

3.4 Industrial Pretreatment

Typically, most wastewater treatment facilities are designed to manage sanitary sewage generated from households and light commercial activities. They are not generally designed to treat toxic pollutants from industrial sources without pretreatment to remove harmful constituents before being discharged. Industrial wastewater can contain acids/metals from a plating process, coloring agents (paints or dyes), oils and fats from food processing, or pesticides, detergents, pharmaceuticals, etc. Many of the components of these kinds of wastes are known to be biotoxic and therefore would be expected to upset the biological treatment process of secondary wastewater treatment at a POTW.

Pretreatment can include processes such as chemical addition for acid neutralization, precipitation of metals, or mineralization of recalcitrant organics. If the matrix and the constituents are complex, then integration of multiple unit processes for a complete wastewater treatment system may be called for. The USEPA has a national pretreatment program that focuses on general/specific prohibitions, categorical pretreatment standards, and local limits, often expressed as numerical limits, narrative prohibitions, and best management practices.

Since the pretreatment requirements are locally-based and heavily influenced by industry-specific and site-specific issues, there is no one size fits all approach. In this space, there are many potential applications for electron beam processing of waste prior to sewer discharge. Several presentations at the 2018 Workshop focused on these opportunities, including a cheese factory, textile mill, brewery, and a solid waste facility.

3.4.1 Leachate Management

According to 40 CFR Part 257, leachate is defined as any liquid that has passed through or emerged from solid waste and contains soluble, suspended or miscible materials removed from such wastes. Leachate is the liquid that percolates through the landfill and is captured by the leachate collection system. Leachate consists of: 1) primary leachate, which is the liquid content of the waste placed in the landfill that percolates through the waste by the force of gravity, 2) secondary leachate, which is formed when water entering the landfill (principally from precipitation) percolates through the portions of the landfill that are not capped and becomes contaminated via contact with the contents of the landfill, and 3) metabolic water, which is created by the microbial degradation of waste materials over the active life of the landfill (Meeroff and Teegavarapu 2010).

The management of leachate is critically important to eliminating pollution of groundwater, which may be a source of drinking water for the local population. A number of alternatives have

been proposed to manage the leachate that is collected from sanitary landfills. These include: 1) leachate recirculation (bioreactor landfill), 2) evaporation, 3) natural attenuation (e.g., deep well injection, treatment wetlands, reed beds, etc.), 4) hauling off-site, 5) municipal sewer discharge, and 6) on-site pre-treatment prior to discharge.

Modern landfills are engineered facilities that are located, designed, operated, and monitored to ensure compliance with federal regulations. Solid waste landfills must be designed to protect the environment from contaminants that may be present in the solid waste stream. This is accomplished by the use of a liner system. Essentially, a double liner and leachate collection systems are constructed at the base of the landfill. Waste placement begins; a small amount of leachate may result from free liquids found in the incoming waste. During early operation, rainfall events result in relatively large volumes of leachate production since much of the runoff from the waste will enter the leachate collection system and mix with stormwater. The waste that became wet in lower layers of the landfill will serve as a continuous source of steady leachate production as the landfill cell fills up. When the landfill reaches its final elevation, a low permeability cap will be constructed to prevent rainfall intrusion. Thus, leachate volumes will steadily diminish over time. Once leachate is generated by liquid percolating through the waste layers, it is collected in the leachate collection system via perforated pipes and removed by gravity laterals to a sump. The laterals are connected by a header pipe for the cell to combine the leachate from one cell and discharge to a pumping station or wet well. From the pumping station, the leachate is pumped through a force main to its ultimate management option location, be it on-site storage, on-site treatment, off-site discharge, deep well injection site, etc.

The quantity of leachate that is formed is related to the amount of external water entering the landfill, the type of landfill construction (degree of compaction), its age (degree of decomposition), size (physical area), waste composition (type of waste disposed and moisture content), inflows (surface runoff, infiltration, and ground water intrusion), and climatic conditions (rainfall, humidity, temperature, evaporation, evapotranspiration) (Lema et al. 1988; Méndez-Novelo et al. 2005; Renou et al. 2008). For example, a large operating landfill site will produce a greater amount of leachate than a small closed site. The South Dade landfill in Miami-Dade County, with an area of 142 acres (of which 46 acres are closed, 46 acres are at final elevation and are undergoing closure, and 50 acres are actively receiving solid waste), generates an average flow of approximately 25,000 gpd with a range of 0 to 40,000 gpd during the dry season. However, during the wet season, the average flow is approximately 150,000 gpd per day with a range of 75,000 to 320,000 gpd, and up to 1.0 million gallons per day (MGD) of leachate during extraordinary rain events.

The Class I landfill of the Solid Waste Authority of Palm Beach County has a surface area of approximately 2260 acres in 2010. During the period from October 2004 to August 2005, the average daily volume of leachate was 214,500 gallons. Leachate generation varied from 130,900 gpd in December 2004, up to 323,000 gpd in July 2005. However, for the period from October 2006 to April 2007, the average volume of leachate produced per day was only 179,500 gallons

with a variation from 89,500 gpd in January 2007, up to 244,300 gpd in October 2006. An urban landfill in Brazil (Gramacho Municipal Landfill in Duque de Caxias) located in a tropical climate region reportedly produces 800 m^3/d (210,000 gpd) (Bila et al. 2005).

Leachate generation data is generally not routinely recorded (Winthelser 1998); therefore, leachate quantities are difficult to predict and volumes are highly variable (Méndez-Novelo et al. 2005). The major issue with leachate management is the contamination of both ground water and eventually surface water. With sanitary landfill design guidance, risks of contamination are limited by multiple engineered liners (clay and/or geosynthetic liners are commonly used). But historically, most landfills (or open dumps) were built without liners or leachate collection systems, and leachate still continues to be discharged directly into the ground from those older facilities.

The liner is an important part of the leachate collection system, which is designed to collect and remove the leachate from the base of the landfill. It should also prevent the contamination of the surrounding environment. Holding and treatment facilities are also an important part of the leachate collection system. Great care must be taken to connect these elements to an enclosed system to prevent any seepage from contaminating the ground water or soil beneath the liner.

To better understand how to predict leachate volumes, Tedder (1997) obtained leachate flow data from 9 active double-lined sanitary landfills (24 active cells). These cells ranged in size from 4.5 – 20 acres. The amount of rainfall recorded over the period correlates well with the observed average leachate generation. Averaging the primary and secondary liner values provides 770 gpd/acre of leachate. Leachate generation is typically calculated based upon the worst case scenario when the lined portion of the landfill has completed construction and has placed the first lift of garbage in the cell with no cover material and the highest rainfall event ever recorded in the area hits the opened faced landfill. The site runoff and the rainfall that percolates through the waste are considered leachate in this scenario. The HELP model can provide a theoretical value in the South Florida area (for example) of 2,000 to 3,000 gpd/acre to be used for design purposes; however, most landfills do not have calibrated flow meters for recording actual leachate volumes, and some are generating leachates from partially lined cells or older systems.

A classification scheme has been proposed by Amokrane et al. (1997). They compared various types of landfills according to their age and leachate water quality. This classification is worth mentioning because they also specified the efficiency of different treatment techniques according to the types of landfill generating the leachate in their study. Table 9 summarizes their findings. The pH of leachate is typically in the range of 5.8–8.5, which is due to the ongoing biological activity. The ratio of BOD/COD, from 0.70 to 0.04, decreases rapidly with landfill age. This is due to the release of large recalcitrant organic molecules from the solid wastes. Consequently, older landfill leachate is characterized by its low BOD/COD ratio and relatively high NH_3-N (Renou et al. 2008).

Table 9. Leachate classification, adapted from Amokrane et al. (1997)

Characteristic	Young Leachate	Medium Leachate	Mature Leachate
Landfill age (years)	< 5 yrs	5 – 10 yrs	>10 yrs
Landfill type	Biodegradable	Intermediate	Stabilized
pH	< 6.5	6.5 – 7.5	> 7.5
COD (mg/L)	>10,000	5000 – 10,000	< 5000
BOD_5/COD ratio	> 0.5	0.1 – 0.5	< 0.1

When liquid water percolates through MSW that is undergoing decomposition, both biological and chemical constituents are leached into solution. Several reviews have been conducted with the goal of collecting information regarding leachate composition according to the location (i.e. the climate and especially the precipitation rate), the age of the landfill, or the type of wastes. Different data sets are available from different parts of the world (Åkesson and Nilsson 1997, Al-Yaqout et al. 2005, Amokrane et al. 1997, Bekbölet et al. 1996, Bernard et al. 1997, Bila et al. 2005, Calli et al. 2005, Geenens et al. 2001, Gonze et al. 2003, Hickman 2003, Imai et al. 1998, Ince 1998, Kim et al. 1997, Kjeldsen et al. 2002, Lin et al. 2000, Meeroff and Teegavarpu 2010, Mohammad et al. 2004, Moraes and Bertazzoli 2005, de Morais and Zamora 2005, O'Leary and Walsh 1995, Oweis and Kehra 1998, Tammemagi 1999, Tatsi et al. 2003, Tchobanoglous and Kreith 2002, Tchobanoglous, Theisen, and Vigil 1993, Reinhart and Grosh 1998, Reinhart and Townsend 1998, Silva et al. 2004, Statom et al. 2004, Steensen 1997, Ward et al. 2002, Westlake and Phil 1995, Wichitsathian et al. 2004, Wu et al. 2004, Youcai et al. 2002) and are summarized in Table 10.

Table 10. Typical leachate water quality data from young and mature landfills (Tchobanoglous, Theisen, and Vigil 1993)

Constituent	Units	Young	Mature
Ammonia-nitrogen	mg/L as NH_3-N	10 – 800	20 – 40
BOD_5	mg/L as O_2	2000 – 30,000	100 – 200
COD	mg/L as O_2	3000 – 60,000	100 – 500
Iron (Fe)	mg/L	50 – 1200	20 – 200
pH	pH units	4.5 – 7.5	6.6 – 7.5
Alkalinity	mg/L as $CaCO_3$	1000 – 10,000	200 – 1000
TSS	mg/L	200 – 2000	100 – 400

Other important constituents include:

- Dissolved natural organic matter from methane (CH_4) to volatile fatty acids (VFA) to more refractory humics and fulvics
- Inorganic constituents, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), ammonium (NH_4^{+}), iron (Fe^{2+}), manganese (Mn^{2+}), chloride (Cl^{-}), sulfates

(SO_4^{2-}) and bicarbonates (HCO_3^-) with heavy metals (arsenic, cadmium, chromium, cobalt, copper, lead, mercury, nickel and zinc), in the microgram per liter range

- Xenobiotic organic compounds from domestic and industrial sources, comprised of a broad variety of aromatic hydrocarbons, phenols, endocrine disrupting compounds (EDCs), pharmaceuticals, personal care products, pesticides, and chlorinated aliphatics among others

More than 100 hazardous chemicals have been isolated and identified in landfill leachate including aromatics, halogenated organics, phenols, pesticides, heavy metals, endocrine-disrupting compounds, pharmaceuticals, personal care products, and ammonium (Foo and Hameed 2009). Many of those are capable of bioaccumulation, persistence, and reactivity in the environment. Toxicity studies confirmed the presence of 133 different chemicals, of which 24% were carcinogenic, 16% were mutagenic, and 8% were teratogenic (cited in Foo and Hameed 2009). However, toxicity tests conducted with *Daphnia* (Atwater 1983), freshwater fish (Wong 1989), luminescent bacteria (Devare and Bahadir 1994) and other organisms found that ammonia-nitrogen is the dominant constituent with regards to toxicity. Table 11 summarizes the variability of constituents found in leachate. Specific conditions are not indicated in the table, as the summary serves point out the wide variety of leachate water quality that can be found.

Table 11. Extreme values for the composition of leachate developed through review of technical literature

Parameters	Units	Concentration Range	Average	Median
Ammonia	mg/L as NH_3-N	BDL* - 8750	830	750
BOD_5	mg/L as O_2	BDL* - 80,800	4000	190
COD	mg/L as O_2	0.4 – 152,000	10,300	4200
Conductivity	µS/cm	5.2 – 95,000	13,100	8,600
Lead (Pb)	mg/L	BDL* - 5.0	0.1	0.1
pH	pH units	2.0 – 11.3	7.5	7.5
TDS	mg/L	0.1 – 88,000	11,000	7600
TSS	mg/L	10 – 45,000	840	950

BDL* = below detection limit

References: Åkesson and Nilsson 1997, Al-Yaqout et al. 2005, Amokrane et al. 1997, Bekbölet et al. 1996, Bernard et al. 1997, Bila et al. 2005, Calli et al. 2005, Geenens et al. 2001, Gonze et al. 2003, Hickman 2003, Imai et al. 1998, Ince 1998, Kim et al. 1997, Kjeldsen et al. 2002, Lin et al. 2000, Meeroff and Teegavarpu 2010, Mohammad et al. 2004, Moraes and Bertazzoli 2005, de Morais and Zamora 2005, O'Leary and Walsh 1995, Oweis and Kehra 1998, Reinhart and Grosh 1998, Reinhart and Townsend 1998, Silva et al. 2004, Statom et al. 2004, Steensen 1997, Tammemagi 1999, Tatsi et al. 2003, Tchobanoglous and Kreith 2002, Tchobanoglous, Theisen, and Vigil 1993, Ward et al. 2002, Westlake and Phil 1995, Wichitsathian et al. 2004, Wu et al. 2004, Youcai et al. 2002.

Given that the starting concentrations are highly variable, and the ultimate disposal options are as well, it is no surprise that the treatment targets are also variable. To determine an expected water quality goal for treatment of leachate parameters, the most straightforward approach

would be either pump or haul the leachate to a municipal wastewater treatment facility (or publicly owned treatment works-POTW) followed by safe discharge to the environment, or if the POTW is relatively far away, then some form of "black box" on-site pretreatment, to reduce the toxicity of the leachate, followed by discharge to the sanitary sewer network for eventual treatment and discharge by the POTW to the environment. For either option, the leachate may not meet the POTW's sewer discharge limits; therefore, some form of targeted pre-treatment may be required. Table 12 shows details from a medium-sized POTW (City of Boca Raton, FL) sewer discharge limits, as an example.

Table 12. Example of allowable public sewer discharge concentrations for the City of Boca Raton, FL (2006).

Parameter	Units	Maximum Allowable Value over any 24-hr Period
Lead	mg/L	0.37
Total dissolved solids (TDS)	mg/L	2000
Total suspended solids (TSS)	mg/L	400
Chemical oxygen demand (COD)	mg/L	800
Biochemical oxygen demand (BOD_5)	mg/L	400
pH	mg/L	6.0 – 8.5
Iron	mg/L	21
Ammonia	mg/L as NH_3-N	Not listed
Conductivity	µS/cm	Not listed

Over 50 leachate management and disposal scenarios have been studied and discussed in detail using engineering alternative analysis criteria of treatment performance, residuals, footprint, cost and other categories, in Meeroff and Teegavarapu (2010). However, electron beam processing was not included in that analysis. Potential issues related to treatment of leachate will include variable concentrations and treatment requirements, high conductivity/TDS, low transmittance, recalcitrant organics, variable treatment volumes, corrosivity, and others. Potentially, none of these will be an issue for electron beam processing.

3.4.2 Grande Cheese Company

Grande Cheese Company is a 77 year old, privately held company headquartered in Fond du Lac, Wisconsin. It specializes in Italian cheese products sold to independent pizzerias and Italian restaurants. A second division called the Custom Ingredient Group sells dairy ingredients to the global market. All production facilities are located in Wisconsin as well as a new LEED Gold Home Office.

Grande operates some of the largest cheese plants in Wisconsin. A large cheese plant can utilize 3 million pounds of milk per day (360,000 gallons or 65 trucks) to produce 150 tons per day of cheese and 37.5 tons per day of dry whey products. The cheese manufacturing process is water-

intensive. For example, the 150 ton per day facility will use 700,000 gallons of water per day and generate approximately 800,000 gallons of wastewater per day (mostly from daily equipment cleaning activities).

Like many processing facilities located in the Midwest, water is generally available at no or low cost. The current paradigm of "pull water out of the ground, use it, treat it, and send it to a small stream where it ends up in the Gulf of Mexico," is no longer sustainable. The challenges noted by the industry are to consistently meet the allowable discharge requirements, as follows:

- 1 ppm P
- pH ~ 7.9
- BOD_5 < 6 mg/L
- Chlorides < 400 mg/L
- Suspended solids < 8 mg/L
- Total ammonia-nitrogen < 0.08 mg/L
- DO > 9 mg/L

In addition, the freshwater aquifers are being depleted due to increased demand for irrigation, particularly along the eastern part of the State and throughout other parts of the State. Water withdrawal costs are increasing because shallow wellfields are no longer productive, requiring new deeper exploration to meet demands. Deeper aquifers have lower water quality, so additional costs are required for treatment. Wastewater treatment costs are increasing due to more stringent permissible receiving water quality standards, particularly for phosphorus and thermal. In the future, costs will increase $1,000 per day from additional chemicals to achieve the proposed new phosphorus limits from 1 ppm to 0.075 ppm. Total treatment costs are over $15/1000 gallons. Although Grande does recycle up to 100% of process water in some plants, an important flowrate of mostly equipment cleaning wastewater still remains that must be discharged to surface waters. Almost all of the water reused in the plant must meet Grade A and USDA requirements as well as the Clean Water Act. Water reuse within Grande facilities is regulated by the Pasteurized Milk regulations.

Because Grande is a business, it tends to make investment decisions based on financial return on investment (ROI) forecasting. Within the current paradigm described earlier, costs have increased to the point that investments in new technologies that can help to reach the goal of reducing/minimizing water consumption and reducing/eliminating discharge are justified. Technologies are evolving for treating and monitoring water usage. This is evident in drought stricken areas around the US. Potable water reuse projects in the US and around the world continue to demonstrate that reuse is a viable option. They are currently working on projects to capture waste solids and send them back to the farm as animal feed, eliminating waste treatment requirements and costs.

The major challenges Grande has with reuse are removal of trace organics, disinfection, and handling of secondary (side) streams (or recycle flows) within the facility. These include reverse

osmosis concentrate that could contain 3% inorganic compounds and cleaning water streams with trace inorganic compounds. The goal with electron beam processing of some or all of this waste material is to determine if the technology can cost effectively deal with one or more of these secondary streams. For adoption of electron beams in this sector, the impacts of prevalent compounds in the cheese manufacturing effluent and biosolids must be determined. Investing in research for alternative biosolids handling processes and conducting technology scans for promising remediation strategies would be part of the strategic plan.

3.4.3 Textiles

Anvari et al. (2014) note that textile effluent waters are typically heavily polluted with dyes and chemicals and have a broad range of pH, COD, and suspended particles. Color and turbidity removal was evaluated using a combined process of coagulation/ flocculation and electron beam irradiation. Alum was employed as coagulant (Anvari et al. 2014). The samples were irradiated by electron beam accelerator at different doses. According to their results, the alum was effective at removing turbidity and color, and allowed the E-beam to further treat the sample to reach 95% removal of color (Anvari et al. 2014). Their results indicate that the coagulation process eliminates suspended particles from disperse dyes, while destruction of soluble dye molecules happens by irradiation (Anvari et al. 2014).

3.5 Microgrid Water Treatment

Although not a session topic at the 2018 Workshop, there were many discussions on use of electron beam technology as part of a treatment system for treating water in a microgrid system, which parallels a power microgrid with many of the same benefits (Falco and Webb 2015), including resiliency, design to meet specific instead of broad needs, potentially cheaper installed and operating costs, and reduction of grid congestion and transportation costs. Electron beams could be the key enabling technology in microgrid water systems because of the capability to treat a wide range of contaminants and the scalability to meet different treatment demands. Another advantage of electron beam processing in a water microgrid scenario is the ability to treat contaminants at the point source and avoid secondary contamination in the transport process through leaky valves and pipes. In general, these smaller local solutions can lead to more flexible, manageable, decentralized and sustainable systems.

3.6 Regulatory Goals

Among the goals of the Clean Water Act was the suggestion to recycle nutrients back to the farms. 40 CFR Part 503, *Standards for the Use or Disposal of Sewage Sludge* (USEPA 1993), establishes “general requirements, pollutant limits, management practices, and operational standards, for the final use or disposal of sewage sludge generated during the treatment of

domestic sewage in a treatment works." A typical ton of dry sludge comprises about 80 pounds of nitrogen, 200 pounds of phosphate, and 10 pounds of potash, which explains why sewage sludge has value as a crop fertilizer. Sludge as such is very difficult to characterize in terms of microbiological and chemical loads, which are variable. Therefore, the rules include standards for sewage sludge applied to land, placed on a surface disposal site, or incinerated. Because sludge is primarily bacteria that are not returned to the aeration basin in the biological treatment process, the major concern for land application is to ensure that the biosolids 1) do not introduce pathogens to the environment, and (2) do not come into contact with the public.

The rules include general requirements for sludge processing, contaminant limits, best management practices, operational standards, requirements for monitoring and reporting, and pathogen and alternative vector attraction reduction requirements as they apply to "publicly owned treatment works (POTWs) with a design flow rate equal to or greater than one million gallons per day, and POTWs that serve 10,000 people or more are included" (USEPA 1993). Based on these rules, any sludge applied to the land must have concentrations for heavy metals below specified maximum concentrations and must also meet one of three additional criteria: 1) pollutant concentration limits for exceptional quality (EQ) or pollutant concentration (PC) options; 2) cumulative pollutant loading rate (CPLR) limits; or 3) annual pollutant loading rate (APLR) limits (USEPA 1993).

Sludge is regulated as either Class A or Class B, based on the level of pathogen reduction that must be achieved. According to 40 CFR Part 503, "Class A" is safe for direct human contact and "Class B" is safe for crop applications with site restrictions, according to the density of pathogen indicators. The criteria to achieve Class A or Class B are listed in Appendix A. The level of pathogen reduction generally involves demonstrating acceptable inactivation of enteric viruses, viable helminth ova, and *Salmonella* sp. or fecal coliform count. Processes that can be used to reach the Class B category are identified by USEPA as "Processes to Significantly Reduce Pathogens" (Cornell Law School, nd). 40 CFR Part 503 outlines options to achieve vector and pathogen reduction. These include aerobic digestion, air drying, anaerobic digestion, composting, lime stabilization, or any combination of processes that can reduce fecal coliform counts to less than 2,000,000 colony forming units per gram of total dry solids. The rules are included in Appendix B, which outlines the processes to significantly reduce pathogens and the process to further reduce pathogens in sludge, including beta ray irradiation as an approved process to further reduce pathogens (PFRP) at dosages of at least 1.0 megarad (10 kGy) at room temperature (~20°C). The origin of this value is from prior microbiological analyses conducted on municipal sewage sludge samples containing 15% solids treated in a pilot plant process utilizing an electron accelerator with a beam energy of 3 MeV. This requirement is effectively 10 times the dose that was tested during the Miami-Dade experience (Waite et al. 1998). However, the Miami-Dade County experiment could not verify inactivation of *Ascaris* ova due to lack of ova in the wastewater and the lack of authorization from the regulatory community to conduct a spike test to verify treatment performance.

In early 1993, the USEPA asked the National Research Council (NRC) to assist in finalizing its sludge standards and guidelines, entitled the *Standards for the Use or Disposal of Sewage Sludge*,

and to study the public health and public perception issues associated with the use of treated municipal wastewater and sludge in the production of crops for human consumption. In 1993, NRC agreed and formed a committee within its Water Science and Technology Board (WSTB) representing diverse expertise and perspectives to conduct the study. The WSTB committee produced a report called *Use of Reclaimed Water and Sludge in Food Crop Production* (NRC 1996). The committee highlighted public concerns and regulatory issues likely to be faced and also identified additional areas for research.

In 2001, USEPA again asked the NRC for an independent review – this time on the technical basis of the chemical and pathogen regulations for biosolids. Among the tasks were to determine if any evidence on human health effects related to biosolids exposure could be found, and to make recommendations for the periodic reassessment of the Part 503 rule. In 2002 the NRC released its report (*Biosolids Applied to Land, Advancing Standards and Practices*), which noted that land application of sludge was widely practiced with "no documented scientific evidence that the Part 503 rule has failed to protect public health" (NRC 2002). In addition, the NRC concluded that further research was needed and made recommendations for addressing public health concerns, scientific uncertainties, and data gaps in the science to ensure that the standards are supported by the most current scientific data and risk assessment methods (NRC 2002). The NRC specifically singled out pharmaceuticals and personal care products (PPCPs) as a category of compounds that has not been studied in sewage sludge and that is especially likely to be present in domestic sewage sludge. Thus, a new hazard assessment of sewage sludge to expand the suite of chemicals is called for. The Agency responded in 2003 to the NRC report in the form of a 14-project Action Plan (USEPA 2003). From FY 2004 through FY 2005, chemical analysis methods developed for PPCPs were adapted for sewage sludge and published in 40 CFR part 136.

A key roadblock for accelerator technology today is the cost to implement the 10 kGy requirement and the fact that only sludge appears to have a direct regulatory approval for the use of accelerators. Accelerators could potentially be used for disinfection, especially since the PPCP issue arises with potable reuse projects and the ova cyst issue is avoided due to the use of reverse osmosis membrane treatment. However, demonstration research is lacking in this area. One option is to include the accelerator as a part of a multi-barrier approach, like ultraviolet is included in potable reuse. The concept is to demonstrate removal of the treatment steps as a whole, as opposed to one specific process. Since UV demands decrease dramatically with clean membrane treated water, the potential exists for a demonstration of larger scale disinfection and PPCP destruction for potable reuse projects.

CHAPTER 4

PERCEIVED BARRIERS THAT ARE NOT

Based on discussions at the 2018 Workshop, there were five areas where concerns were raised in the past, but where the concerns appear to be unfounded. These are:

- Regulatory hurdles
- Dose requirements
- Power demands
- Patents and markets
- Misconceptions about ionizing radiation

4.1 Regulatory Hurdles

A number of regulatory hurdles with particle accelerators is a long-standing concern. There are two issues that impact regulations. The first is the absence of full scale installations that demonstrate compliance with regulations. Secondly, the compliance constituents are unclear. As noted in Chapter 3, potential applications for the electron beam appear to be favorable for biosolids processing (for improved digestion and disinfection), and disinfection and destruction of emerging constituents in wastewater for other purposes. Unlike chlorine, which has over 100 years of testing and demonstration of compliance, accelerator technologies do not, and the potential for testing proof of concept requires long-term demonstration projects under differing conditions. The agency to fund such a program is not currently in place. However, avoiding the regulatory issue is possible. The application of accelerator technology for sludge conditioning does not require regulatory approval beyond a construction permit, as sludge conditioning has no regulatory limits in of itself. The use of an electron beam can improve disinfection by supplementing the current disinfection processes.

With respect to disinfection of wastewater and destruction of emerging contaminants, emerging contaminants are by and large unregulated. Hence an electron beam processing unit can only improve the treatment, while not affecting compliance. With respect to disinfection, accelerators used in conjunction with other technology (ultraviolet light or chlorine for example) can be used to maintain compliance with current regulations. With such “paired” treatment, much data can be gathered on the benefits of the accelerator, perhaps leading to the future reliance solely on the accelerators.

As a result, the regulatory hurdle appears to be one created to discourage accelerator demonstrations. The regulations are relatively silent on treatment with accelerators which is

why pairing with known treatment methods may benefit the long-term usage of accelerators, while reducing costs of implementation in the short-term.

4.2 Dose Requirements

The key regulatory hurdle relates to the dose required for disinfection in the federal regulations for sludge. There are a number of unanswered questions about the dose. The current USEPA rules note that the required minimum dose is 10 kGy with the possibility of 20 kGy for destruction of emerging constituents. If they need different doses, the design of a multi-dose delivery system that can operate reliably in a plant is a challenge. The basis for this value needs to be reviewed because depending on the constituent of concern, the correct dose could be different than the regulatory requirement, which would potentially open up more innovation possibilities. Based on previous work cited in Chapter 2, the most appropriate dose for wastewater and biosolids treatment could be on the order of 0.4 - 10 kGy with contact times from 10^{-3} to 10^{-6} minutes. As a result, the dose regulations for sludge disinfection via high energy electron treatment needs to be revisited before any system can be properly designed. The suggestion is a demonstration program to test actual removal performance with varied applied doses in wastewater and sludge for substances like PCBs, PCP, fragrance/odors, explosives, nutrients, cyanobacteria, asphalt, oocysts, pharmaceuticals, PAHs, organic compounds, daughter products, and other key constituents of concern to determine if a lower dose can be equally effective or if the current standards are too conservative.

4.3 Power Demands

Power use is directly related to the required dose. During the 2018 Workshop, a representative from ComEd (Sekou Sidime, 2018 presentation) provided perspective on service requirements for proposed installations, as follows:

- 1 MW load > one 12 kV feeder
- 10 MW load > two 12 kV feeder > one 34 KV line
- 20 MW load > four 12 KV > two 34 KV lines
- 1 MW solar plant > 5 acres of land

For most municipal applications, the power grid should not be a limiting factor, and the cost in many places is relatively inexpensive. It was noted that most medium and large treatment facilities have standby power arrangements whereby they can go off the grid if needed by the power companies. That means they get power at a lower cost throughout the year if they have backup power at the plants. The added demands would need to be considered.

There were a series of questions that still require further research however:

- What else can be done to improve beam power and wall power efficiency (from 75 to over 90%)?
- How to reach net zero power with electron beam technology?
- Can the demand from the power grid be reduced?
- What is the impact on backup power needs?

These are local issues that affect individual facilities and grids.

4.4 Patents and Markets

Patents can be a barrier to developing competition, but it is unclear if patents are stifling innovation given the number of companies involved with accelerators. A search of the internet indicates that there are thousands of patents, from 2016 back to the 1940s, and across the globe, with the Unites States, Japan, China and Germany having the most involvement based on a cursory review (a Google search indicated 673,000 hits). Virtually all of the recent patents are by private corporations building on prior work they have done. However, much of the original effort came from university or federal labs. Private firms use the federal lab technology and develop it further for their purposes. As technology develops commercially, firms will file patents to protect their intellectual property and research and development efforts. The concern is that patents may limit competition and create a challenge in differentiating between products. Competition is limited because comparisons between machines is difficult. Sharing of data, information and technology is limited because the number of vendors is likewise limited. Hence the ability to develop cooperative partnerships, a la Detroit in the early 20th century for cars, is unlikely. The development of accelerator technology and the associated economy-of-scale to reduce costs is thwarted as a result.

A series of questions were raised for this issue:

- Is there a scale-up issue from pilot to full scale?
- What is the demand for electron beam systems?
- What is the solution to the perceived lack of reliable equipment and maintenance?

Working with federal agencies, especially for demonstration projects, would seem to minimize this concern, but may reduce private investment, innovation and interest in further developing and promoting the technology.

Despite these questions, a further issue identified by the participants was reliability of the equipment. Covanta Environmental Solutions (Bleach 5/10/2018 presentation at Fermilab) notes a series of recent projects that would appear to counteract this concern:

- Their 800 kW unit had an average life of 138,000 hours
- Their cryocoolers at 1.5 W at 4K have an average life of 44,000 hours and 30,000 for the compressor
- Their 20 Amp thermionic gun cathode had an average life of 40,000 hours

New units are now available at 1-10 MeV, and 1 MW are available now. In parallel, modules may be capable of achieving 10 MW but may need liquid helium cooling although a hot spare 1 MeV, 1 MW is needed and maintenance intervals are important.

Nevertheless, developing new technologies with a currently limited market involves four steps that take time:

- **Level 1:** A university or research lab that can assist with bench-scale work but is not dedicated to piloting new technologies
- **Level 2:** A water resource recovery facility that is interested in innovation and willing to host a full-scale demonstration project, but does not have a dedicated test facility
- **Level 3:** A water resource recovery facility or research lab with a dedicated physical space available for piloting innovative water technologies at near full scale
- **Level 4:** A staffed facility dedicated solely to R&D/piloting of new technologies (can be housed at a functioning water resource recovery facility)

For the better part of the last decade, the municipal water sector has seen an increased focus on innovation, especially in the transition from a waste disposal mindset to one of resource recovery from wastewater. There are substantial barriers to modernizing the water infrastructure, including historical underinvestment, regulatory barriers, social and behavioral challenges, technology deployment and validation obstacles, and a conservative, risk-averse industry mindset where technology diffusion tends to be slow. Efforts like the Leaders Innovation Forum for Technology (LIFT), a joint program from the Water Environment Federation and the Water Research Foundation, seek to increase the rate of technology implementation.

Empirical data is used to create the technology adoption “S curves” from the 2017 LIFT Water Technology Survey and from BlueTech Research. The LIFT survey broadly covers the municipal water sector (wastewater, stormwater, drinking water, desalination, and water reuse facilities) and identifies trends around the deployment of innovative technologies at utilities. To date, over 100 respondents have completed the survey—representing many of the largest water and wastewater utilities in North America and abroad. In the past two years, BlueTech Research has published technology adoption curves on technology categories including capacitive deionization, ceramic membranes, struvite recovery, thermal hydrolysis, and advanced oxidation. Their research has shown that a new technology needs nearly 20 years to achieve adoption by the “early majority” cohort. The story of struvite precipitation technology for nutrient recovery has provided a welcome example that the sector can move faster, as that technology has achieved commercial success in a relatively short 12 to 14 years.

4.5 Misconception of Ionizing Radiation

The perception of being exposed to ionizing radiation was a comment from the participants that was not expected. This came from several utility personnel who expressed concern that the technology was so poorly understood by staff and decision-makers that they assumed the electron beam was an ionizing radiation process that involves nuclear chemical reactions. This was perceived as a barrier to implementation but is a mischaracterization of the process. As noted in Chapter 2, accelerators propel charged particles to higher energies. Therefore, it is clear that education is required to dispel the myth so that the electron beam can be decoupled from the misconception that it involves residual radiation. Particle accelerators are simply tools designed to speed up and increase the energy of a stream of particles by generating electric fields that switch from positive to negative at a given frequency, using radiofrequency cavities spaced to accelerate the particles forward by using magnetic fields to steer and focus the beam to a target. In treatment of wastewater or biosolids, a large part of the matrix (>92%) will be water. Thus, it is most likely that the accelerated electrons will interact with water to form oxidants as explained in Chapter 2 or act directly upon unwanted constituents in the water. As a result, there are no toxic residuals with no secondary waste generation and no nuclear radiation generated.

The results of this discussion raised the following issues:

- Lack of knowledge and education on processes that rely on high-energy electrons without residual radiation (activation) vs. traditional ionizing radiation processes like cobalt-60
- Lack of training for engineers
- Decision makers seem to mistakenly have the impression that electron beam technologies involve ionizing radiation and that all radiation is dangerous

One solution is to avoid the use of the term "*radiation*" when referring to the electron beam. For example, ultraviolet light providers have dropped the term from their products even though it really does rely on ultraviolet radiation.

CHAPTER 5

NEEDS FOR IMPLEMENTATION (BARRIERS THAT ARE)

A number of strategies were identified during the 2018 Workshop and refined during the breakout discussion groups. These included education, building a mobile demonstration unit, demonstration projects, dose requirements (efficacy studies), costs, and funding for research or demonstration projects.

5.1 Moderated Group Discussion Summaries

As a part of the 2018 Workshop, the participants were subdivided into small groups and were asked to identify questions that arise when discussing the implementation of electron beam technology for wastewater applications. Over 50 questions were raised by the participants, which were grouped into 6 basic areas. The following sections outline the questions developed and solutions suggested to address these concerns.

Area 1 – EDUCATION

1. An introduction video to show how accelerator technology has developed since the 1930s, and how it can be approached for future market adoption within the water/wastewater sector is needed
2. An industry journal article such as Journal of the American Waterworks Association (AWWA) summarizing the workshop is needed
3. A way must be found to get electron beam technology into the curriculum for civil/environmental engineers
4. A list of success stories is needed
5. The impact of failures of electron beam technology implementation in Russia, Poland, and elsewhere must be documented
6. The radiation issue must be addressed

The solutions to these concerns involve outreach. Chapter 2 of this report should serve to address the first issue in the list. People are truly unaware of the history or uses of electron beam technology. They fail to understand that this technology is already in use, for example in the fruit and vegetable industry. A YouTube-style video could be developed with background information from the Fermilab and manufacturers included. A small grant to create this video is needed.

Engineers, operators, administrators and others associated with the water and wastewater industry are largely ignorant of the technology. This is because the engineering design textbooks do not cover the subject, there is a lack of installed facilities for case studies, and there is a lack of performance data in the literature. It was suggested that an article in the Water Environment

Federation journal, the Journal of the American Water Works Association, or other similar trade journal is needed to publicize potential benefits of the technology. The authors of this report propose that the cost and background documentation could be developed into such literature in the next year.

To get this into the environmental engineering curriculum, it was suggested that one of the most widely used textbooks in wastewater engineering is the Metcalf & Eddy book authored by Dr. George Tchobanoglous, H. David Stensel, R. Tsuchihashi, and F.L. Burton. The potential audience of this book should reach a large majority of future engineers and allow them to have a credible introduction to the technology if a chapter could be added to the next edition. Since the authors of this report have worked in the past with Dr. Tchobanoglous, an approach will be made to see if this is feasible. Potential contributors to assist in development of this book chapter were solicited at the 2018 Workshop.

The success of demonstration projects, placed into academic and public literature would boost the visibility of the technology and provide engineers with design guidance for implementation. Such successes could be contrasted to reported failures in Europe (that require more research). YouTube and popular literature like Popular Mechanics might be appropriate outlets for public education. Several attendees volunteered to assist in these efforts. It needs to be made clear that ionizing radiation is different than the electron beam technology.

Area 2 – BUILD A MOBILE PILOT UNIT

1. What does a 20 MGD electron beam processing facility look like?
2. How long would it take to build a mobile unit that could be shipped to an implementation project site?
3. What are the components, critical spare parts, performance limitations?
4. Where to use it in within the treatment train in a POTW setting?
5. What is the price point for a mobile demonstration unit that meets market demand?
6. How much power would be needed?

The belief from the 2018 Workshop participants was that now is a good time to reevaluate the use of electron beam accelerators for treatment of wastewater and residuals. Biosolids and potable reuse disinfection appeared to market potential. The science would seem to indicate that sludge characteristics could be improved along with reductions in emerging constituent concentrations. The latest generation of accelerator designs (with cryogenics) now allow for cheaper operating costs and could potentially unlock new applications. But are there engineering/technology companies working to develop electron beam technologies into feasible applications for the wastewater sector, and if so, who are these entities? Will NSF or the federal government participate in leading this R&D effort? Leased space, public-private partnerships or other solutions are needed to demonstrate the value added of electron beam applications.

Area 3 – DEMONSTRATION PROJECTS

1. What are the design criteria for a viable large-scale demonstration/proof of concept?
2. What is the highest leverage proof of concept demonstration (low hanging fruit)?
3. What are the factors that influence the tipping point related to adoption of the technology?
4. What are the small victories that can influence these factors in a positive way?
5. How do we overcome the redundancy hurdle (a single facility is too risky for industry to rely on)?
6. How do we deal with interconnectivity and service life hours issues?
7. What are the impacts on downstream treatment units?

Of importance is completing the first demonstration project where useful design and performance data can be gathered on a fully operating electron beam facility. The proposed solutions for this are to start with a small industrial installation – maybe with design/build/operate options or with an externally funded research project at an existing facility. As will be noted, most of the utilities present at the 2018 Workshop were willing to host a pilot project for biosolids or potable reuse purposes. If private funding, via a public-private partnership, were proposed, the allocation of costs would likely be based on the amount or volume of water treated. A suggestion was to install a demonstration system at a large facility at a nominal fee to cover operational costs and publish the results to promote success. As a part of any experimental unit treatment process, there is a need to prove the reliability and redundancy of the technology; and determine how to handle the situation when the unit fails. Chapter 7 outlines several protocols for potential demonstration projects.

Area 4 – DOSE REQUIREMENTS

1. What is the appropriate design dose, and if there are multiple doses for different applications, how do you design a multi-dose delivery system that can operate reliably in a POTW?
2. What is the appropriate exposure time for 10 MeV vs. 1 MeV vs. 400 KeV? Is it on the order of 10^{-3} to 10^{-6} seconds or longer?
3. Can we test actual removal in wastewater vs sludge for substances like (PCB, PCP, fragrance/odors, explosives, nutrients, cyanobacteria, asphalt, oocysts, pharmaceuticals, PAHs, organic compounds)?
4. What do we know are the byproducts or secondary pollutants formed after treatment?
5. How does electron beam technology at various doses compare in terms of treatment performance to other similar or conventional technologies?
6. What more do we need to know about electron beam disinfection?

For the most part the issues within this area of concern involve determination of the design dose (time vs. intensity). As noted in Chapter 2, work has been done on this, but the feeling was that the data was not robust enough for either the regulatory agencies or the public. In addition,

there was concern that virus inactivation might be incomplete. The goal would be to take uncertainty out of the dose question and define the useful dose to achieve defined wastewater treatment goals. In addition, the regulatory suggestion was to use the electron beam technology as a part of a current process, not as a standalone, as the latter requires far most robust information to achieve regulatory approval.

Area 5 – COST OF IMPLEMENTATION

1. What would it cost to build a mobile pilot scale system?
2. What are the capital and O&M expenses for my facility?
3. What is the cost per kGy?
4. What are the actual costs compared to other conventional or competing approaches?
5. Which processes are no longer necessary in the treatment train if electron beam technology is implemented (avoided costs)?

Chapter 6 begins to address much of the questions about costs and comparisons. The ultimate question is how to provide the investment needed to drive the cost of accelerator technology down, and what steps need to be taken to promote the technology better. The roadmap to developing the data needed to begin convincing the market starts with a mobile pilot scale unit that can be used to conduct demonstration experiments at large scale wastewater treatment facilities. With this data, researchers can determine the dose requirements and develop more accurate cost models for scaleup.

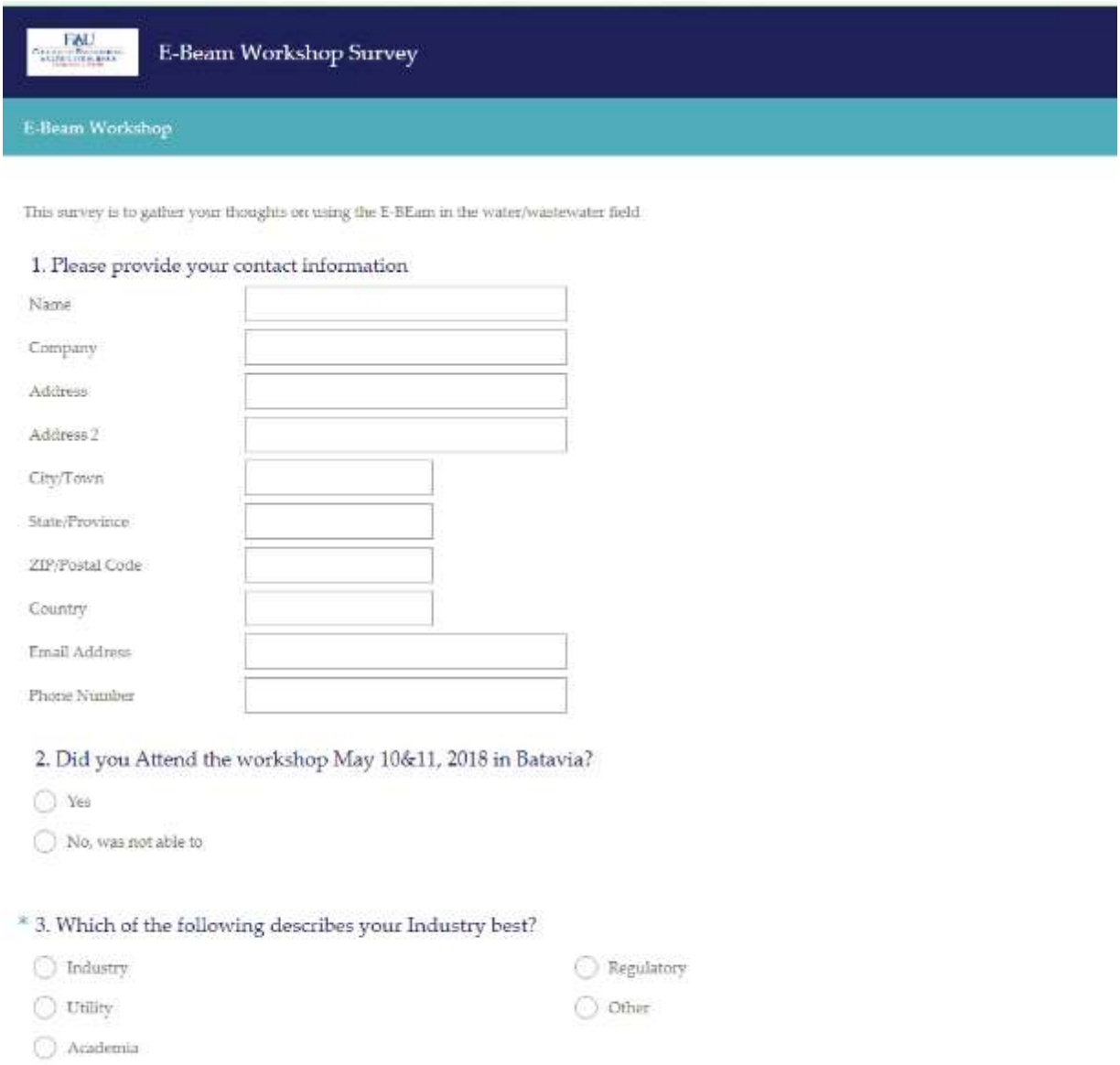
Area 6 - FEDERAL FUNDING

1. NSF should continue doing combinational studies on how to optimize electron beam technologies with other AOT technologies.
2. Other sources of federal funding, such as Department of Energy, Department of Defense, USEPA, etc. should be explored.

The consensus is that the National Science Foundation should continue to fund accelerator research projects. NSF seems like the best option for a multi-year, longer-term pilot or demonstration project funding as this mitigates the risk-aversion issue with adoption of new technology, reduces the financial risk for the user, and provides a robust platform to collect the needed science. Chapter 7 outlines suggested demonstration projects, but the idea would be to create several demonstrations, focused on different water quality issues (biosolids, potable reuse, leachate, etc.) and fund long-term projects that would employ pilot units developed in conjunction with USDOE-funded national labs to provide answers to the questions on dose, cost, reliability and removal performance for selected constituents of concern.

5.2 Participants Follow-up Survey

The organizers created a post-workshop survey sent to all attendees and invitees, which consisted of the following 10 questions:



E-Beam Workshop Survey

E-Beam Workshop

This survey is to gather your thoughts on using the E-BEam in the water/wastewater field

1. Please provide your contact information

Name
Company
Address
Address 2
City/Town
State/Province
ZIP/Postal Code
Country
Email Address
Phone Number

2. Did you Attend the workshop May 10&11, 2018 in Batavia?

- Yes
- No, was not able to

* 3. Which of the following describes your Industry best?

- Industry
- Utility
- Academia
- Regulatory
- Other

* 4. In terms of first adoption of electron beam technology, rank these potential applications (with 1 being of highest interest).

- Biosolids Treatment
- Biosolids Disinfection
- Emerging Contaminant Removal
- Wastewater Disinfection
- Soil/Groundwater Remediation
- Potable Reuse
- Industrial Wastewater Pre-treatment
- Leachate
- Flue Gas Treatment
- Nutrient Removal
- TDS Removal
- TSS Removal

* 5. In terms of barriers to first adoption, rank these engineering/technical issues in order of importance (with 1 being most important).

- E-Beam Reliability
- Redundancy
- Capex
- Fouling/aging
- Flow Distribution
- Shielding
- Monitoring
- Treatment performance
- Other

* 6. Rank these workshop outcome recommendations in order of importance (with 1 being most important).

- E-Beam Prize
- Demonstration Projects
- Engineering Textbook chapter
- Industry workshop
- Other scholarly publications
- White Paper
- Other technical papers
- Public outreach on social media
- Other

7. Demonstration projects were recommended at the workshop, please rank these in order of importance (with 1 being most important).

- Biosolids conditioning before anaerobic digestion
- Reclaimed water for potable reuse
- Military site remediation
- Leachate treatment for solid waste management
- Other - please specify
- Other

8. Describe how you envision electron beam technology being utilized in water/wastewater treatment applications?

9. Are you willing to host a demonstration project at your facility?

- Yes
- No

10. If yes, provide details (open ended question)

11. Do you want us to keep you on the contact list going forward?

- ○ Yes
- ○ No

12. Please provide any information that you think would be useful

The response rate was 20% of the attendees. The first three questions were asked to gain contact information for future follow-up. The respondents were evenly distributed between private industry, water/wastewater utilities, academia and other. Of concern was that there were no respondents who self-identified as representing any of the regulatory agencies that were invited. However, this reflected the fact that although it was a stated goal of the 2018 Workshop, no one from USEPA, NSF, or state regulatory agencies was in attendance. Travel restrictions (especially at the federal level) was cited as a barrier to attendance.

In terms of first adoption of electron beam technology, the respondents were asked to rank potential applications for the electron beam (with 1 being of highest interest). Those receiving the highest scores were: 1) emerging contaminants removal, 2) biosolids processing/disinfection, and 3) leachate treatment. These were among the demonstration projects that were further developed in Chapter 7. In terms of barriers to first adoption, the respondents were asked to rank a series of engineering/technical issues in order of importance. Reliability and operational parameters (shielding, monitoring and overall performance) were ranked as the most important.

Respondents were also asked to rank the following 2018 Workshop outcome recommendations in order of importance:

- E-beam prize
- Demonstration projects
- Engineering textbook chapters (Metcalf & Eddy)
- Industry workshops
- Other scholarly publications
- White papers
- Other technical papers
- Public outreach on social media
- Other

Of these options, the highest rated were white papers and other scholarly publications. Immediately behind these were other technical publications (i.e. not peer reviewed literature), a chapter in the Metcalf and Eddy textbook, and the E-beam prize. There was much discussion about demonstration projects at the 2018 Workshop. The focus of these discussions were ranked in order of importance to determine the highest impact application for implementing a proof of concept demonstration:

1. Biosolids conditioning before anaerobic digestion
2. Reclaimed water for potable reuse
3. Military site remediation
4. Leachate treatment for solid waste management
5. Other – please specify

Biosolids conditioning prior to anaerobic digestion received the most votes, although all options listed in the question received at least one first place vote. One reason that biosolids conditioning received such high interest is because much of the work on municipal wastewater to date has been conducted in this area (Cleland et al. 1984, Waite et al. 1998, Kurucz et al. 1991, Meeroff et al. 2004), and much of the conversation at the 2018 Workshop centered around solids treatment, particularly from the Metropolitan Water Reclamation District of Greater Chicago, Orange County California, Miami-Dade County, and the City of Milwaukee, who were represented in person at the 2018 Workshop. However, substantial discussion also focused on potable reuse and other applications.

The remaining questions were more open ended. Respondents were asked to describe how they envisioned electron beam technology being utilized in water/wastewater treatment applications. With respect to biosolids treatment, the use of high-power accelerators for pretreatment of regulated disinfection/sterilization was noted first. For sludge conditioning, the suggestions were to use the technology to replace polymers and thickening agents. The belief was that this would improve digestion and stabilization. However, the respondents to the biosolids treatment/disinfection discussion noted that the electron beam is unlikely to get regulatory traction by itself. Therefore, the electron beam in conjunction with other treatment methods would appear to be a path forward. Another potential secondary application was related to odor control.

Another set of comments focused on the use of electron beam in conjunction with membrane treatment technologies to maximize reuse potential by increasing recalcitrant contaminant removal and enhancing effluent disinfection. A benefit noted was the potential removal of emerging contaminants, simultaneously. Electron beam accelerators are viewed as having the potential to be less costly to employ in the case of replacing UV/AOP, while providing superior treatment efficiency. But from a regulatory perspective, this integrated approach may need to be combined with membranes to achieve regulatory compliance.

Initial applications utilizing existing, commercial equipment by industry were to treat low flow wastewater discharges containing recalcitrant organics. However, this has not been verified at

the municipal scale. Additional testing is needed to determine if the electron beam technology has the potential for nutrient removal. Demonstrating/ensuring reliability in performance as conditions worsen in water quality is also needed. However, there is only limited science available regarding reliability and performance at full scale. Demonstration projects should be developed in the key areas identified by this 2018 Workshop, which are all high-value potential applications that should be tested at the pilot, then facility scale. These demonstration projects are needed to validate efficacy of meeting the treatment requirements on a consistent basis to regulatory agencies to gain acceptance that electron beam technology can be listed as a treatment technique for environmental applications.

The respondents noted that electron beam technology has the potential to provide trace chemical destruction for emerging contaminants such as perfluoridated compounds, PCBs, explosives, PCPPs, etc. A suggestion was made that the industry might want to analyze the potential for a powerful, mobile unit for the application of treating water for flood victims.

Taking all of the open-ended responses, a word cloud, which gives greater prominence to the words or phrases that appear most frequently, was created as follows:

Sludge Conditioning Industry Water

Removal Disinfection Treatment

When asked directly, 64% of respondents are willing to host a demonstration project. This included all 4 utilities present at the 2018 Workshop. For those who responded "yes," they were asked to provide details in an open-ended question. Responses were as follows:

- "The accelerator stewardship program at USDOE could be a vehicle to fund a demonstration of a pretreatment system at an accelerator facility" or possibly to create a mobile treatment unit."
- "Conduct testing as part of our new recycled water demonstration project some time after the initial MBR approval is obtained."
- "We would be happy to connect with our industry partners/contacts for those who may be willing to demonstrate/test the technology."
- "MMSD is listed under the WRF FAST Network as a stage II test bed facility."
- "Willing to have FERMI set up an on-site system to test various applications ranging from biosolids treatment to effluent disinfection."
- "IARC could have floor space for small to medium scale demonstrations."
- "In partnership with Broward County OES or Boca Raton or Palm Beach wastewater (ECR or SCR)…"
- "We could host an accelerator but not a demonstration project, since we do not have a treatment problem. We could participate in one at a local WRRF or industrial site."

- “We don’t have a facility but would be happy to participate in one locally.”

A summary of the open ended responses was created in word cloud format to determine the words or phrases that were most commonly used, as follows:

The final question asked if the respondent wished to remain on a contact list going forward, and if they responded affirmatively, they were asked to provide any other comments. All respondents asked to remain on the contact list to receive further information. Four other comments were received. Two were appreciative of the information provided in the 2018 Workshop and noted that they gained an exceptional amount of knowledge about the technology and its path forward in the environmental sector. A third comment was that the respondent understood the market conditions much better than before attending. And finally, one respondent echoed the comments from the live sessions at the 2018 Workshop that routine electron beam stakeholder workgroup meetings should be scheduled to keep the momentum moving forward. A dropbox has been created to disseminate documents from the 2018 Workshop to participants and interested parties.

CHAPTER 6

ECONOMICS OF WASTEWATER/BIOSOLIDS TREATMENT BY ELECTRON BEAM TECHNOLOGY

6.1 Introduction

In 2017, there were 14,748 wastewater treatment plants in the United States (ASCE 2017) treating around 32 – 40 billion gallons of wastewater per day, generating approximately 5.6 – 7.0 million dry tons per day of treated sewage sludge. The vast majority of systems (80%) treat less than 1 MGD, but an important fraction (17%) of the wastewater treatment plants in the US treat 1 – 10 MGD, while over 500 facilities treat between 10 – 100 MGD and 51 treat over 100 MGD (USEPA 2015). Treatment plants in large US cities such as Miami, Chicago, Dallas, Los Angeles, and Washington D.C. routinely treat between 150 – 400 MGD. Theoretically, facilities that process greater than 100 MGD have the manpower, infrastructure, and budgetary capacity to be able to manage electron beam systems, but to process this amount of flow, the number of accelerators and the electrical power needs would be extremely cumbersome without major innovations in the technology. Therefore, the target market given the current state of the technology would more likely be the large-sized facilities that treat 10 – 100 MGD ($n \approx 500$) and generate between 8 – 80 dry tons per day of biosolids.

6.2 Objectives

The goal is to investigate the cost breakdown, key design considerations, and opportunities for innovation for electron beam treatment in wastewater and biosolids applications. The unit cost of treatment (cost per unit volume treated) can only be estimated when the required dose (either power or chemical addition) to achieve a treatment goal is known. In the case of electron beam processing of water and wastewater, the dose can vary from 0.4 up to 20 kGy or more based on previous pilot scale testing to achieve treatment goals for disinfection, oxidation of recalcitrant organics, and removal of inorganics.

6.3 Methodology

In the 1980s, an electron beam system was installed and operated at the Miami-Dade County Central District Wastewater Treatment Plant in Virginia Key, FL. This system was a 1.5 MeV, 75 kW (50 mA) unit capable of delivering 8.3 kGy at 120 gpm, which was only 0.1% of the plant's capacity at the time. The beam was scanned out to a window with dimensions of approximately 60" × 2" in a horizontal configuration that passed through a constant flow over a weir. The wastewater fell by gravity through the electron beam with treatment achieved in less than one

second exposure. The efficiency of this system was measured to be 66% (Kurucz et al. 1995). The published performance data from this treatment unit served as the basis for the cost estimates calculated here. A series of scenarios will be calculated for a wastewater treatment plant capacity of 10 – 100 MGD and a biosolids processing capacity of 5 – 65 dry tons per day. Scenarios with different assumptions for power efficiencies, electrical power rates, and applied dose were analyzed. The cost analyses were evaluated using the annualized capital cost and the operations and maintenance costs at 4% interest for a projected 15-year lifetime, and the unit cost of treatment for wastewater applications was reported on the basis of US$/kgal, while the unit cost for biosolids processing was reported in US$/dry ton.

6.3.1 Capital Costs

The capital cost for an electron beam facility include the accelerator unit, the control systems, installation, shielding, and ancillary equipment including pipes, pumps, weirs, bypass, back-up power, etc. Capital cost estimates are based on the power requirements of the unit. If the dose is known, the required power of the accelerator can be estimated as follows:

$$P = \frac{QD}{\eta}$$

Where *P* is power in kW, *Q* is flowrate in kg/s, *D* is dose in kGy (kJ/kg), and η is efficiency of energy transfer from the accelerator. Using this equation, a 1.0 MW unit capable of delivering 20 kGy at an efficiency of 0.48 (0.6 wall power × 0.8 beam power) would theoretically only be able to treat a wastewater flow of 0.55 MGD. At the Virginia Key facility in Miami-Dade County, a 75 kW unit was used to treat 0.14 MGD at an applied dose of 8.3 kGy. However, if scaling up to treating the current design flowrate of 143 MGD at a dose of 20 kGy is calculated using a linear model, then the power requirement would need to be on the order of 385,000 kW (385 MW).

$$P_2 = \frac{P_1}{\eta}\frac{Q_2 D_2}{Q_1 D_1} = \frac{75kW}{(0.6\times 0.8)}\frac{(6265kg/s)(20kGy)}{(6.13kg/s)(8.3kGy)} = 384{,}798kW \; or \; 385MW$$

Using a redundancy ratio of one spare for every 4 units, this would require more than 450 accelerators of 1 MW capacity, which would be difficult to manage at this scale. For a 10 MGD facility, the number would be on the order of 34 units, which is more reasonable but still cumbersome.

According to one electron beam manufacturer (www.eb-tech.com, cited in Capodaglio 2017), installation costs in 2013 US dollars are estimated in Figure 30.

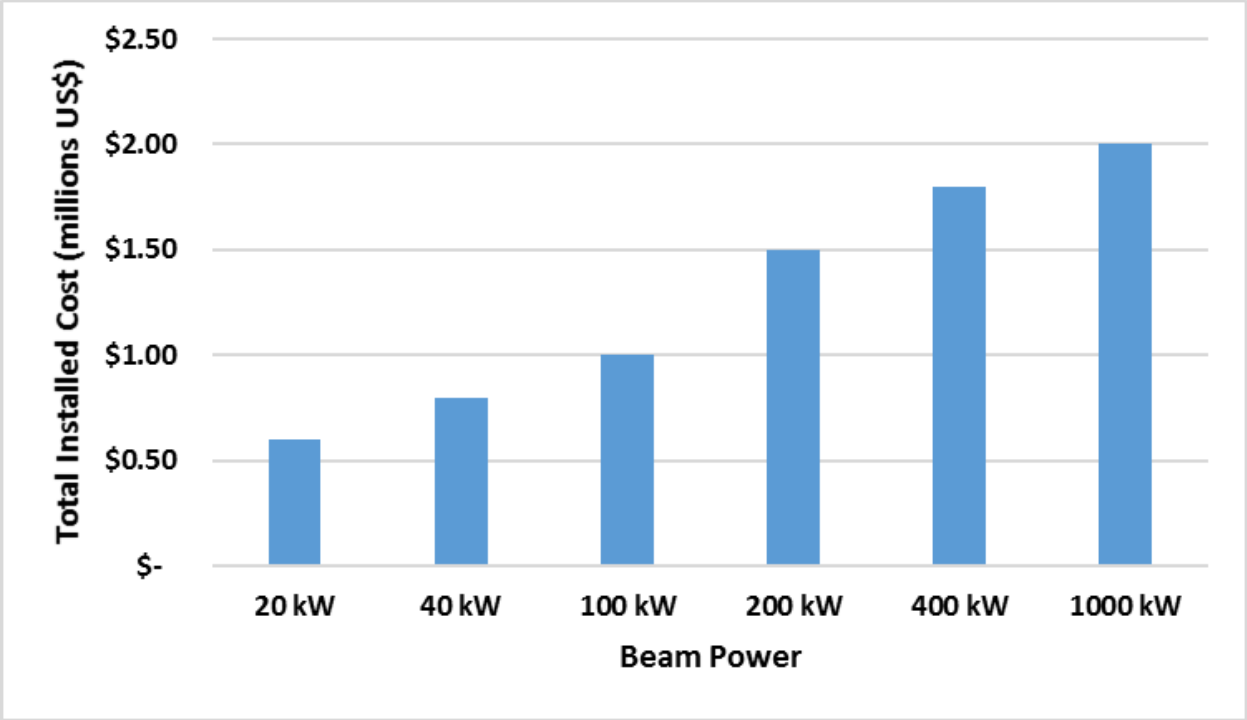


Figure 30. Electron beam pricing structure in 2013 US dollars for 1 MeV capacity as a function of beam power (cited in Capodaglio 2017)

Using the data provided in Figure 30, the installation cost equates to $2 – $30 per Watt. An alternate pricing scenario is proposed by Zimek and Kaluska (1998) and Emami-Meibodi et al. (2016). In this approach, the cost of an installed electron beam accelerator can be estimated as follows:

$$\$ = a \times b(1 \pm d)E\sqrt{P}$$

Where *$* is the cost of the installed accelerator in thousands of dollars, *a*, *b*, and *d* are related to the installation cost, accelerator type, and manufacturer, respectively, *E* is the electron energy in MeV, and *P* is the power in kW. Han et al. (2009) performed a regression analysis on 2009 accelerator cost data and reported that $b(1 \pm d)$ = 110. Adjusting for the consumer price index, the value increased to 121 in 2014 (Emami-Meibodi et al. 2016). The installation coefficient varies from 2.0 (Emami-Meibodi et al. 2016) to 2.4 ± 0.3 (Zimek and Kaluska 1998). Applying this model to the 10 MGD, 20 kGy, 60% wall power and 80% beam power efficiency scenario, the installed accelerator equivalent cost comes to $1.79 – $2.15/W, which is at the lower end of the range cited in the pricing structure in Figure 30 ($2 – $30/W).

To determine the capital costs for a given scenario, the power was estimated first, and then this value was rounded up to the nearest MW to determine the number of 1000 kW units required. A redundancy ratio of 1 for every 4 units was applied. The control systems, installation, shielding, water systems, and mechanical costs were estimated based on the equipment costs (Gehringer

2004; Temple-Bird et al. 2005; Han 2009; Han et al. 2012; IAEA 2007; Emmi and Takács 2008; USDOE 2015; Wojnárovits et al. 2017).

6.3.2 Operation and Maintenance Costs (O&M)

The annual costs include operator salaries, electricity, water usage, maintenance and repairs, etc. The USEPA (2013) has reported that water and wastewater treatment can represent over 35% of the total annual operating budget of municipalities. Electricity usage accounts for 25-40% of the annual budget of a wastewater treatment plant (NYSERDA 2008). Labor costs are based on operator salaries (Class C operator $18/hr, Class B operator $21/hr, and Class A operator $25/hr), assuming three Class A level operators (day shift, night shift, spare) with one working 24 hours per day, 7 days per week, and 52 weeks per year with 29% fringe benefits. An additional set of three operators for every 30 electron beam units is added. Supervisor costs are not included. Bulk electricity costs are typically between $0.06- $0.11/kWh for large commercial customers. Water consumption for water-cooled beam stopper use or routine cleaning is required, but no reports in the literature were found for estimating the use rate. The cost of water consumption is assumed to be negligible in this preliminary cost analysis since it is likely that treated effluent can be used for this purpose at no real cost to the utility. Finally, maintenance costs are estimated at a percentage of the capital cost per Temple-Bird et al. (2005).

6.3.3 Scenarios

According to the Virginia Key experience (Kurucz et al. 1995), the combined wall power and beam power efficiency was 0.68, roughly equivalent to 80% wall power and 85% beam power efficiency. To conduct a sensitivity analysis, the wall power efficiency and beam power efficiencies were varied from 50% – 100% for a range of 0.25 – 1.0. The dose was varied from 0.4 to 20 kGy, and the flowrate was varied from 10 MGD (438.1 kg/s) to 100 MGD (4381 kg/s) for wastewater and 5 – 80 DTPD (2.6 – 42 kg/s @2% solids) for biosolids. The bulk electricity price was assumed to vary between $0.06 – $0.11/kWh.

6.4 Results for Wastewater Treatment Scenarios

Conservatively assuming $2 per Watt for equipment, 1000 kW as the maximum beam power per unit, 80% beam power efficiency, and 60% wall power efficiency, a series of capital cost simulations were conducted. A proportional scaleup from the Virginia Key experience is used based on a 75 kW unit capable of treating 0.14 MGD at 8.3 kGy to a comparable scenario at 20 kGy for a facility sized to handle 10 – 100 MGD (Figure 31). This estimate includes a 4:1 redundancy ratio for spare units.

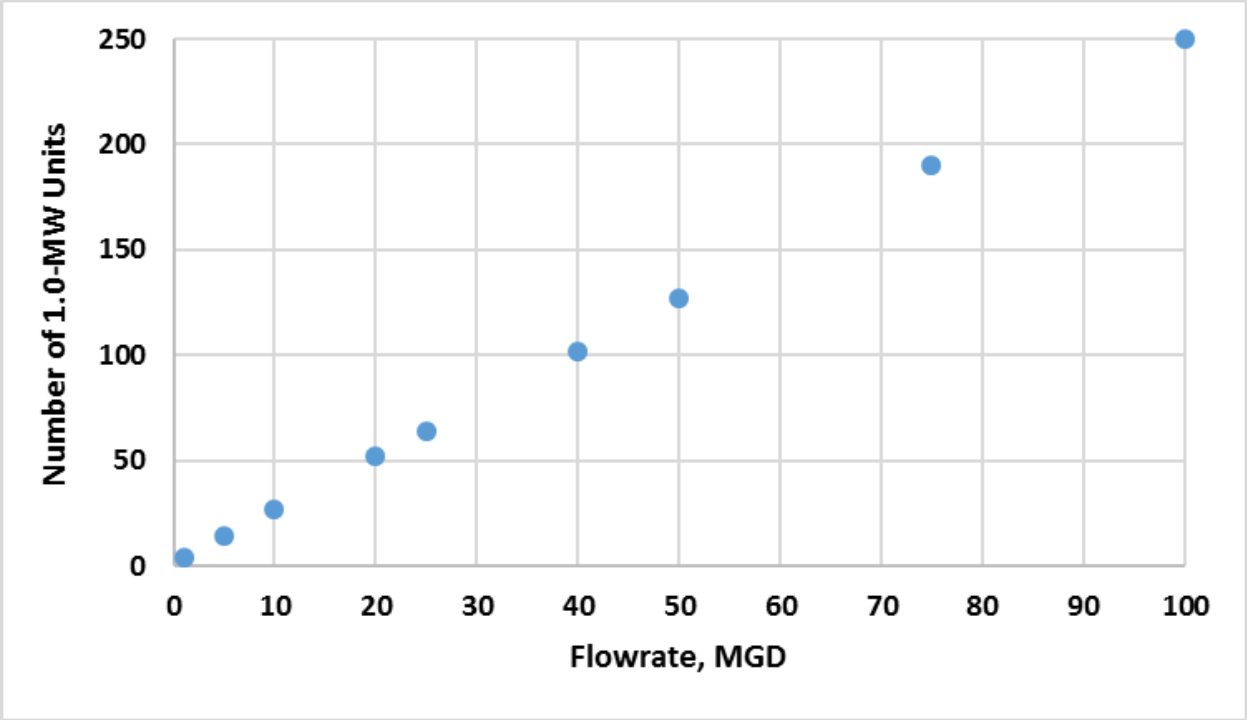


Figure 31. Simulated number of 1.0-MW beam power units needed for various wastewater treatment plant flow capacities at 20 kGy, based on the Virginia Key pilot facility data provided in Kurucz et al. (1995)

For a 10 MGD facility, this analysis shows that the number of 1.0-MW units required is on the order of 30. Thus, it would be more favorable in this scenario if accelerators with beam power in the range of 10-MW or greater were available. This would reduce the number of units down to 2-3 and make electron beam processing a more manageable prospect for utilities. Table 13 specifies the estimated capital costs and assumptions for the 10 MGD and 50 MGD scenarios.

Table 13. Capital cost breakdown based on 10 MGD and 50 MGD capacities for 1 MeV, 10 kGy with 80% beam power efficiency and 60% wall power efficiency

Cost Parameter	10 MGD	50 MGD
Power Requirements, kW	13,447	67,233
Number of 1.0-MW Units + Spares	18	85
Unit Cost (U) $2.00/W	$ 36,000,000	$ 170,000,000
Control Systems (5%U)	$ 1,800,000	$ 8,500,000
Installation (7.5%U)	$ 2,700,000	$ 12,750,000
Shielding, Water System (10%U)	$ 3,600,000	$ 17,000,000
Mechanical (2%U)	$ 720,000	$ 3,400,000
Total	$ 44,820,000	$ 211,650,000
Annual Cost at 4% interest for 15 yr*	$ 4,031,160	$ 19,036,034

*The annualized capital cost is based on 15-year lifetime at 4% annual interest [(A/P,4%,15) = 0.08994]

Table 14 summarizes the annual costs and overall unit cost for the 10 MGD and 50 MGD scenarios.

Table 14. Annual cost breakdown based on 10 MGD and 50 MGD capacities for 1 MeV, 10 kGy with 80% beam power efficiency, 60% wall power efficiency.

Cost Parameter	10 MGD	50 MGD
Unit Cost (U) $2.00/W	$ 36,000,000	$ 170,000,000
Personnel Required	3	5
Labor (@ $25/hr)	$ 282,704	$ 471,173
Power ($0.08/kWh)	$ 9,467,280	$ 44,706,600
Maintenance (2.5%U)	$ 1,120,500	$ 5,291,250
Total O&M	$ 10,870,484	$ 50,469,023
Total Annualized Capital	$ 4,031,160	$ 19,036,034
Total Annual Cost	$ 14,901,644	$ 69,505,056
$/kgal	$ 4.08	$ 3.81

Typically, the cost of conventional wastewater treatment is on the order of $2 – 3/kgal. The estimates listed here for electron beam processing for a 10 – 50 MGD facility are slightly higher than typical wastewater treatment options; therefore, engineers would likely not recommend this process from an economic perspective unless the cost of electrical power and efficiency can be improved substantially, or some value added benefits of electron beam processing are considered.

A sensitivity analysis was conducted on the variables of dose, efficiency, and price of electricity. The cost analysis was repeated for a range of doses from 0.4 – 20 kGy, while holding the efficiency at 48% and the price of electricity at $0.08/kWh (Figure 32). Then the analysis was repeated for overall efficiency from 25% – 100% at 10 kGy and $0.08/kWh (Figure 33) and for the price of electricity from $0.06 – $0.11 per kWh at 10 kGy and 48% efficiency (Figure 34).

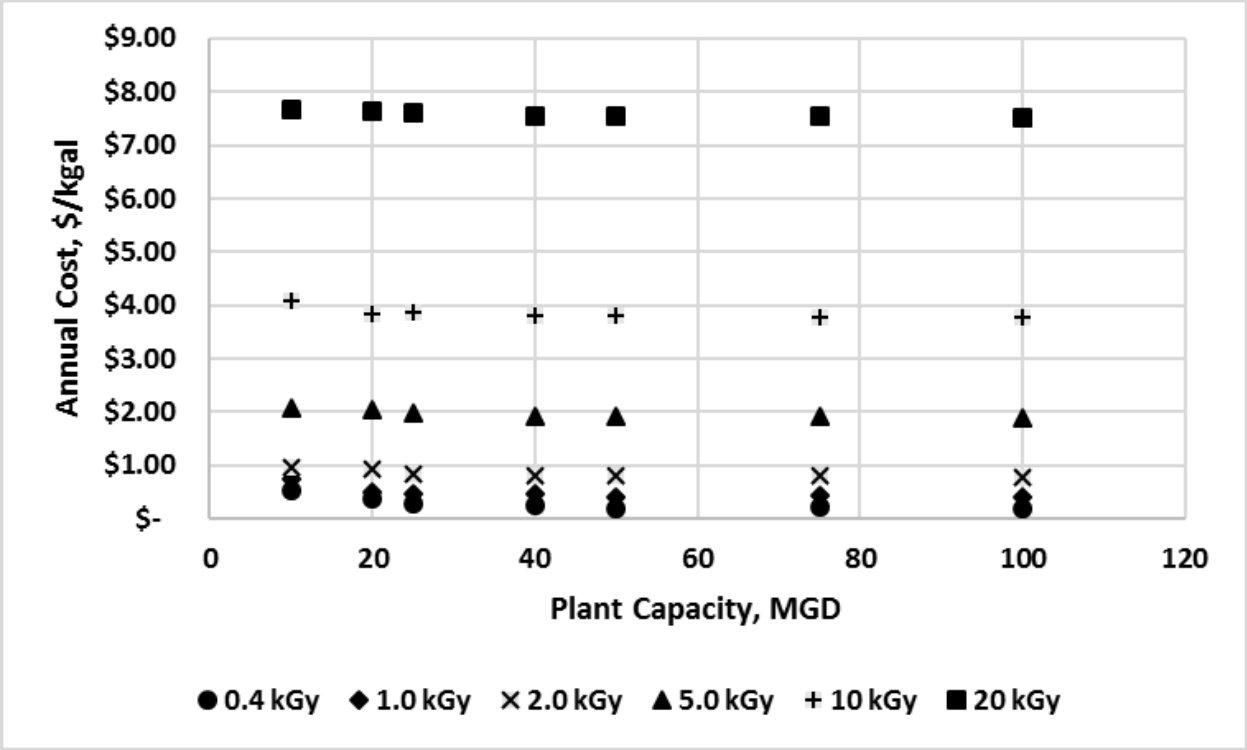


Figure 32. Sensitivity analysis by varying 1 MeV dose from 0.4 – 20 kGy at $0.08/kWh with 80% beam power efficiency, 60% wall power efficiency for 10 – 50 MGD capacities.

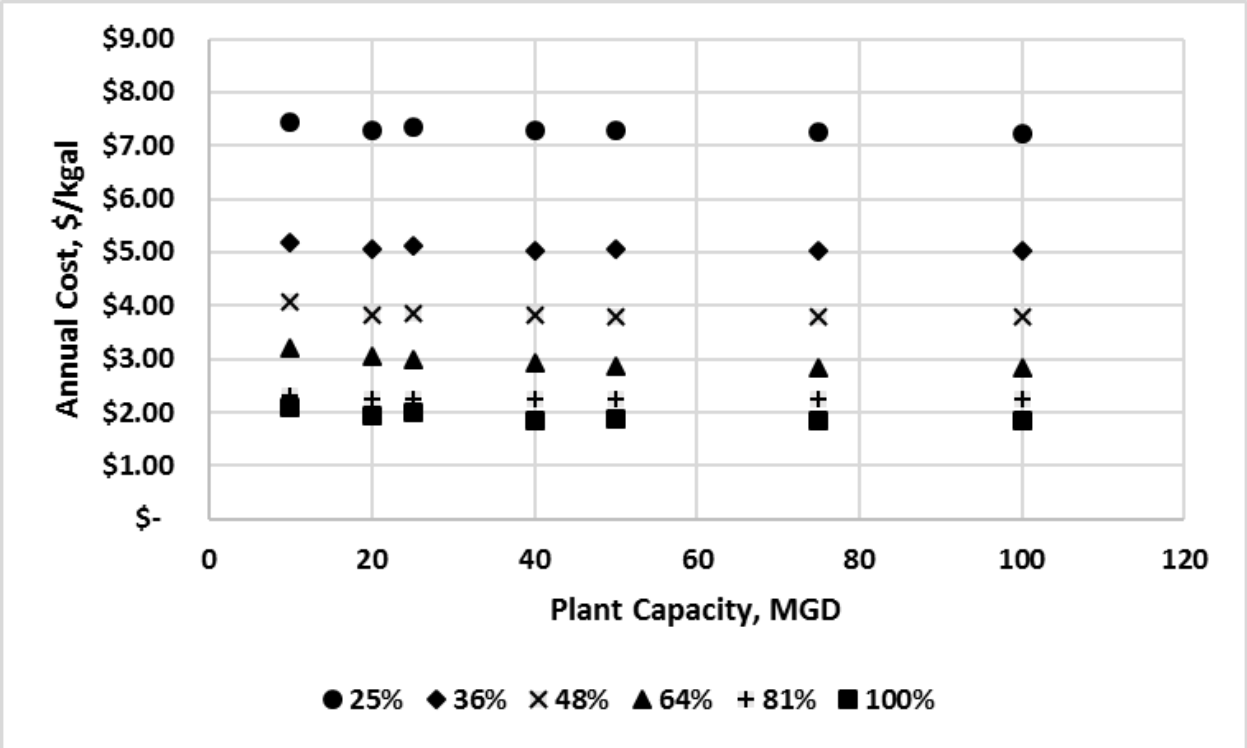


Figure 33. Sensitivity analysis by varying overall efficiency from 25% – 100% for 1 MeV, 10 kGy at $0.08/kWh for 10 – 50 MGD capacities.

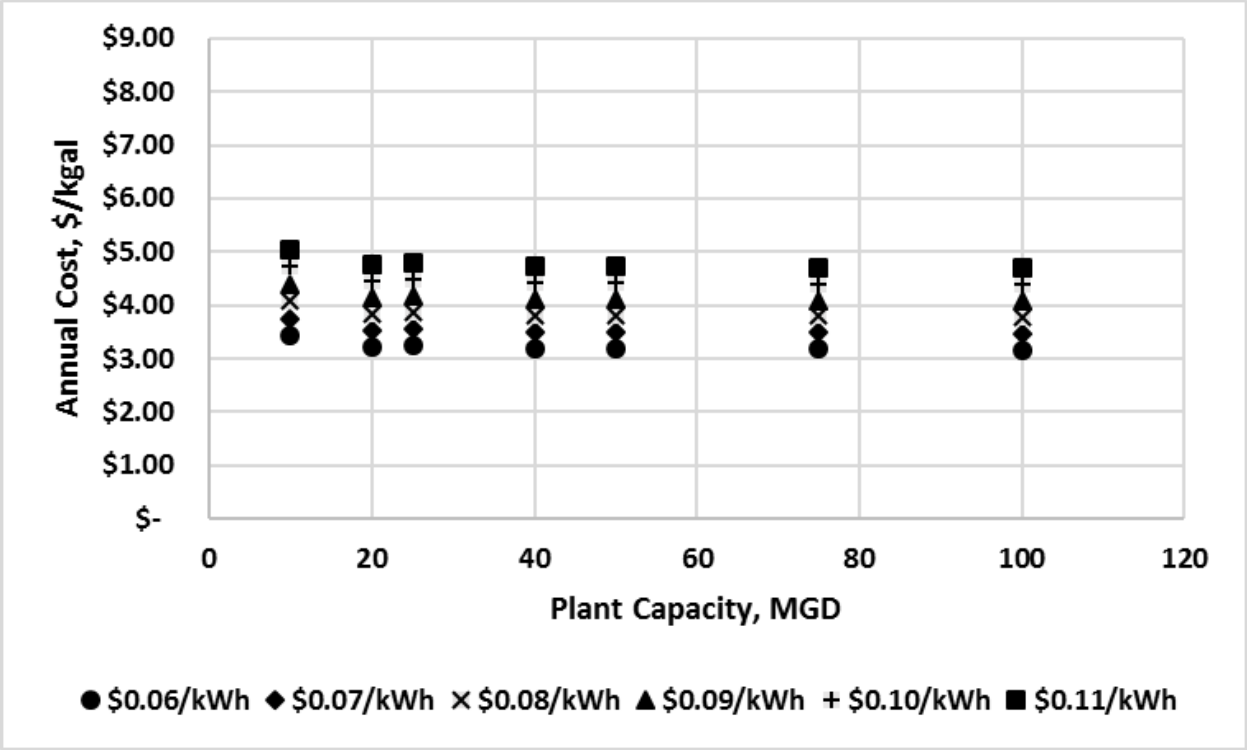


Figure 34. Sensitivity analysis by varying 1 MeV, 10 kGy dose from $0.06 – $0.11/kWh with 80% beam power efficiency, 60% wall power efficiency for 10 – 50 MGD capacities.

The variable with the most important impact on the wastewater treatment cost of the three investigated in the sensitivity analysis is dose, followed by wall power/beam power efficiencies and then by bulk electricity cost. For example, a 5 kGy dose at $0.08/kWh and 48% efficiency will have an annualized cost of approximately $2/kgal, which is on the order of expected costs for wastewater treatment processes. Increasing the dose to 10 kGy nearly doubles the cost. With respect to efficiency, if the wall power and beam power efficiencies can be increased to 90%, this would have the effect of cutting the annual cost in half compared to 80% beam power and 60% wall power efficiencies at 1 MeV, 10 kGy and $0.08/kWh. The bulk electricity price had the least impact on the overall cost. For a 1 MeV, 10 kGy dose at 48% efficiency, the annual cost is reduced by one-third if the price of electricity is reduced by nearly half from $0.11 to $0.06 per kWh.

6.5 Results for Biosolids Treatment Scenarios

For a biosolids facility, a large facility treating 10 – 50 MGD will generate 8 – 40 dry tons per day (DTPD) of sludge. Unlike wastewater effluent treatment, biosolids treatment is a batch process that does not generally require continuous operation if sufficient storage is available in the biosolids treatment train. Therefore, full process redundancy may not be required in some facilities. However, redundant systems were assumed for purposes of this cost analysis.

The capital cost component for a biosolids application consists of the electron beam unit, control systems, installation, shielding/water cooling systems, and mechanical (pumps/pipes/weirs) similar to the wastewater scenario. The main difference is batch run times and the solids handling

system instead of a liquid handling system. Also, because the beam power requirements are substantially less than for wastewater (because the mass flow in kg/s is much lower), the unit cost was increased to $10.00 per Watt, and the other ancillary capital cost ratios were also adjusted accordingly. Table 15 specifies the estimated capital costs and assumptions for the 8 DTPD and 40 DTPD plant capacities.

Table 15. Capital cost breakdown based on 8 DTPD and 40 DTPD capacities for 1 MeV, 10 kGy with 80% beam power efficiency and 60% wall power efficiency

Cost Parameter	8 DTPD	40 DTPD
Power Requirements, kW	100	500
Number of Units + Spares	2	2
Unit Cost (U) $10.00/W	$ 2,000,000	$ 10,000,000
Control Systems (15%U)	$ 300,000	$ 1,500,000
Installation (25%U)	$ 500,000	$ 2,500,000
Shielding, Water System (30%U)	$ 600,000	$ 3,000,000
Mechanical (10%U)	$ 200,000	$ 1,000,000
Total	$ 3,600,000	$ 18,000,000
Annual Cost at 4% interest for 15 yr*	$ 323,788	$ 1,618,940

*The annualized capital cost is based on 15-year lifetime at 4% annual interest [(A/P,4%,15) = 0.08994]

For the biosolids scenario, the maintenance cost multiplier increased due to the complexity of the solids handling system and conveyor belts operating in a highly corrosive environment. Table 16 summarizes the annual costs and overall unit cost for the 8 and 40 DTPD scenarios.

Table 16. Annual cost breakdown based on 8 DTPD and 40 DTPD capacities for 1 MeV, 10 kGy with 80% beam power efficiency and 60% wall power efficiency at 2% solids

Cost Parameter	8 DTPD	40 DTPD
Unit Cost (U) $10.00/W	$ 2,000,000	$ 10,000,000
Personnel Required	3	3
Labor (@ $25/hr)	$ 282,704	$ 282,704
Power ($0.08/kWh)	$ 64,000	$ 320,000
Maintenance (10%U)	$ 200,000	$ 1,000,000
Total O&M	$ 546,704	$ 1,602,704
Total Annualized Capital	$ 323,788	$ 1,618,940
Total Annual Cost	$ 870,491	$ 3,221,643
$/dry ton	$ 298	$ 221

Although the annual costs for biosolids treatment are much more reasonable compared to the wastewater scenario, typical sludge handling costs are on the order of $20 – $85/dry ton, according to 2018 Workshop participants.

Similarly to the wastewater treatment scenario, a sensitivity analysis was conducted on the variables of dose, efficiency, and price of electricity. The cost analysis was repeated for a range of doses from 0.4 – 20 kGy, while holding the efficiency at 48% and the price of electricity at $0.08/kWh (Figure 35). Then the analysis was repeated for overall efficiency from 25% – 100% at 10 kGy and $0.08/kWh (Figure 36) and for the price of electricity from $0.06 – $0.11 per kWh at 10 kGy and 48% efficiency (Figure 37).

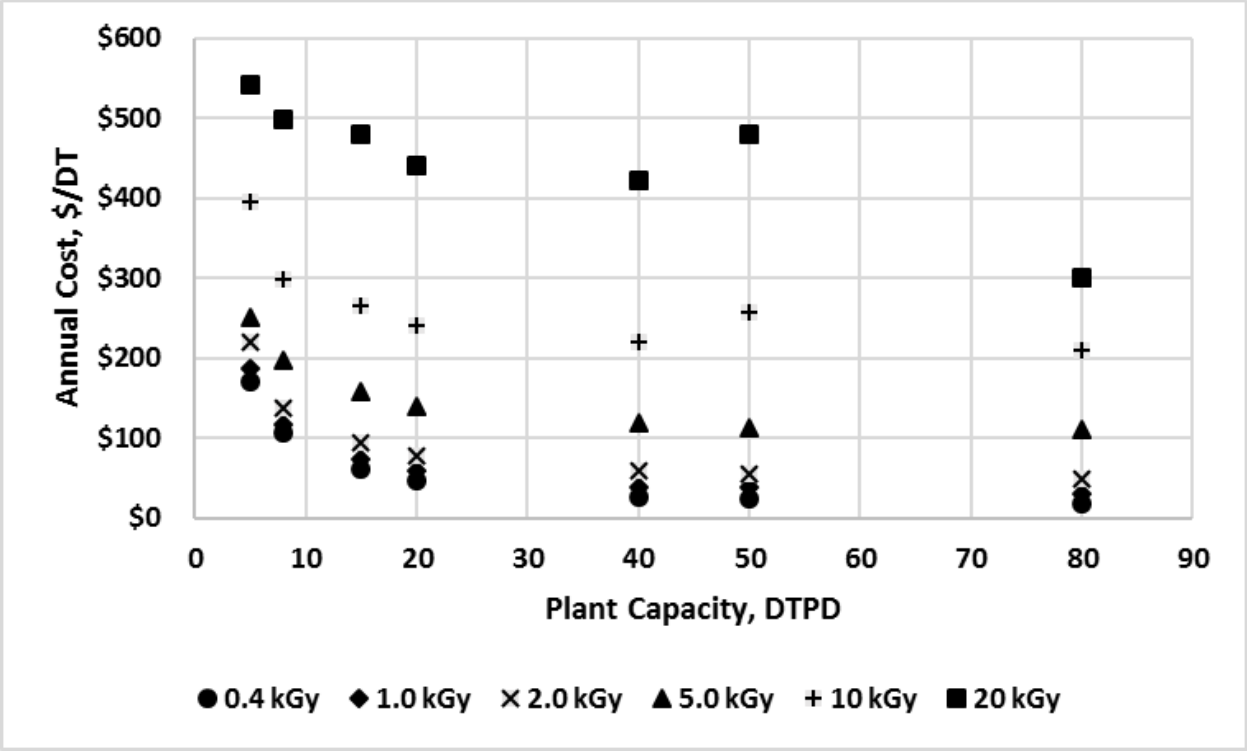


Figure 35. Sensitivity analysis by varying 1 MeV dose from 0.4 – 20 kGy at $0.08/kWh with 80% beam power efficiency, 60% wall power efficiency for 10 – 50 MGD capacities.

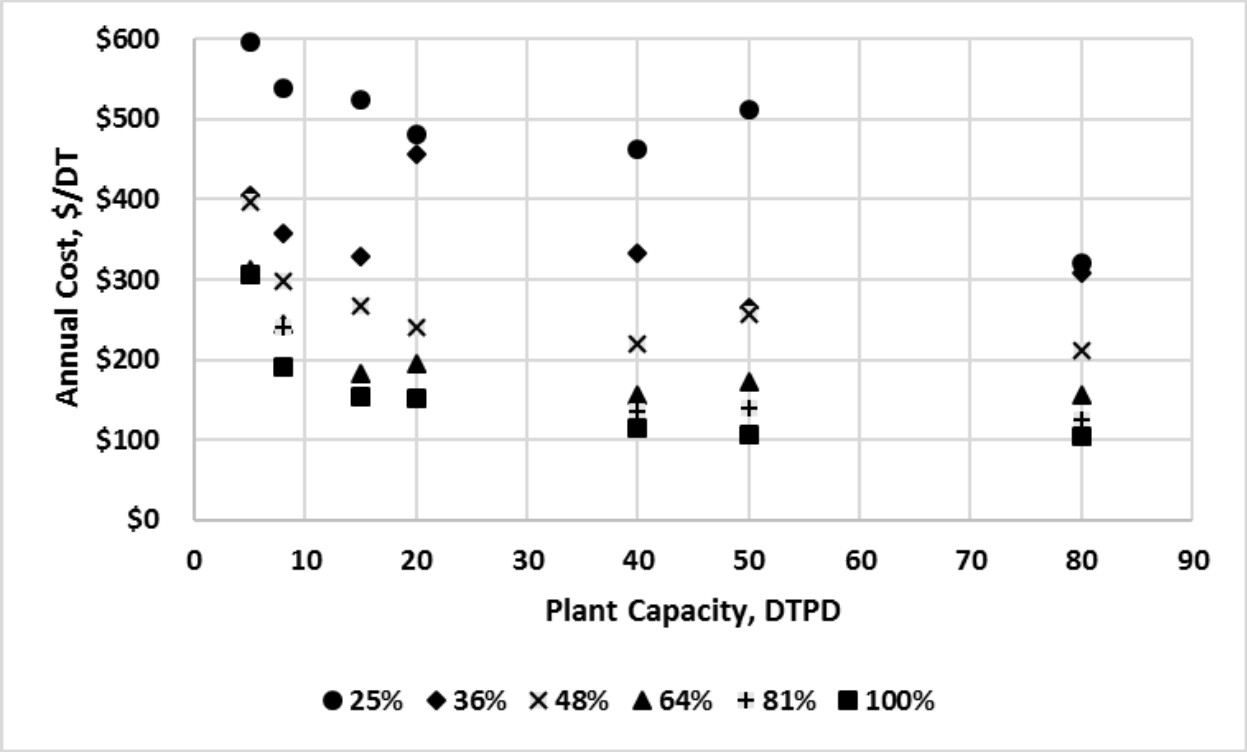


Figure 36. Sensitivity analysis by varying overall efficiency from 25% – 100% for 1 MeV, 10 kGy at $0.08/kWh for 10 – 50 MGD capacities.

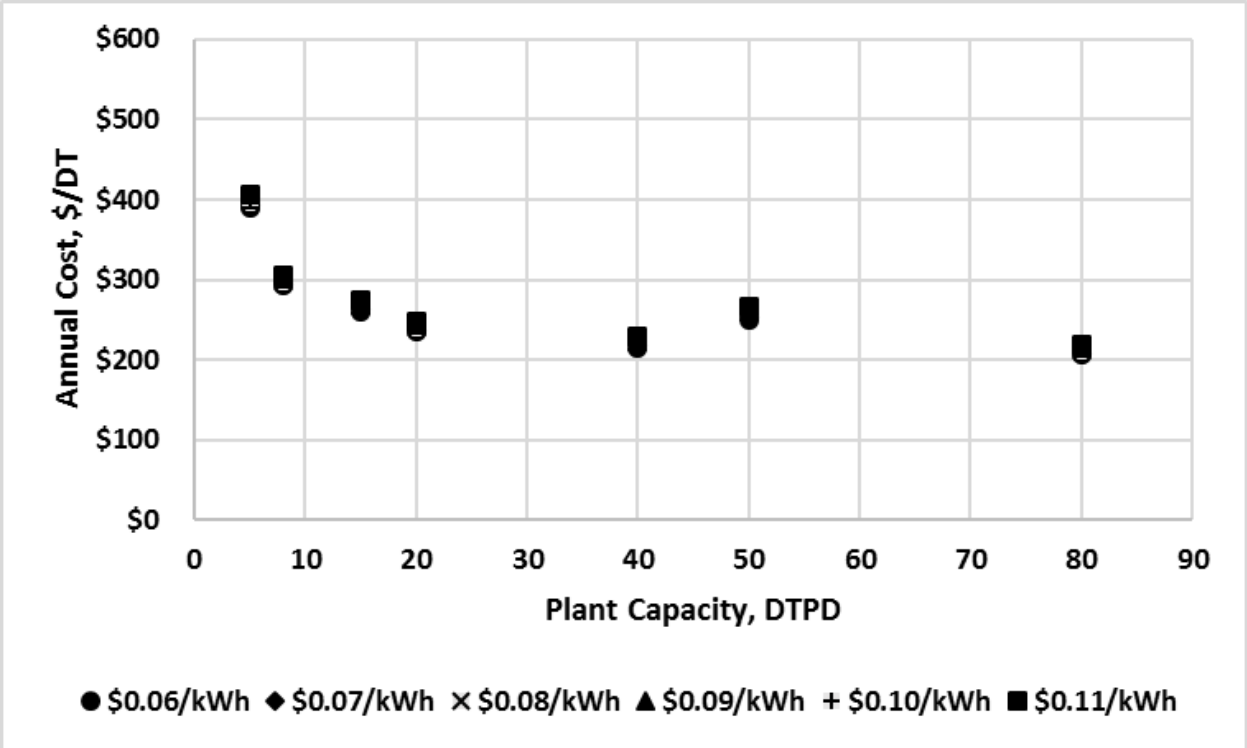


Figure 37. Sensitivity analysis by varying 1 MeV, 10 kGy dose from $0.06 – $0.11/kWh with 80% beam power efficiency, 60% wall power efficiency for 10 – 50 MGD capacities.

The variable with the most important impact on the biosolids treatment cost of the three investigated in the sensitivity analysis is dose, followed closely by wall power/beam power efficiencies. Similarly to the wastewater scenario, the bulk electricity cost did not make a noticeable difference.

To get the annual cost of treatment to meet typical biosolids cost targets (<$100/DT), the dose would need to be on the order of 2 kGy at $0.08/kWh and 48% efficiency to be competitive with current biosolids treatment processes. Increasing the dose from 5 kGy to 10 kGy nearly doubles the cost at 40 DTPD. With respect to efficiency, if the wall power and beam power efficiencies can be increased to 90%, this would have the effect of cutting the annual cost by about $100/DT compared to 80% beam power and 60% wall power efficiencies at 1 MeV, 10 kGy and $0.08/kWh. The bulk electricity price impact on the overall cost was minimal. For a 1 MeV, 10 kGy dose at 48% efficiency, the annual cost is reduced by about $15/DT (5%) if the price of electricity is reduced by nearly half from $0.11 to $0.06 per kWh.

6.6 Key Design Considerations and Opportunities for Innovation

Accelerators for industrial treatment have been in operation with 0.8 MeV (1.0 MW beam power per 100 MW plant); however, for both wastewater and biosolids treatment at large sized utilities (10 – 100 MGD), industrial scale, high beam power accelerators on the order of 1 – 10 MeV with 0.4 – 20 MW of beam power or more (Henning and Shank 2009) will be necessary. These hypothetical electron beam specifications are not widely available and have not been demonstrated at pilot scale specifically for these applications. Since utilities are fundamentally conservative when it comes to trying out unproven technologies, there is risk aversion with the perception that high voltage implies prohibitive energy costs and that the new technology has not been properly demonstrated at full scale to document reliability, stability, and performance.

In the 1990s, the most powerful industrial accelerators were on the order of 100 kW. This means that in order to treat only a fraction of the flow for even a small treatment plant, installation of 10 – 30 or more units would have been necessary. In the US (Deer Island, MA and Virginia Key, FL), Germany, Australia, and Japan, industrial scale accelerators have been employed for sewage processing, but these systems were mostly at pilot plant demonstration scale and operated for just 2 – 4 years before being abandoned (Wang and Wang 2007). By the late 1990s, more powerful accelerators were introduced on the market, but the reliability for stable, long-term application was not established. Pilot reactors at this scale, suffered from accelerator malfunction, which led to crippling downtimes. Thus, redundant systems were required, but electron beams are complex equipment to maintain, and redundancy is not as simple as a standby unit and a hydraulic bypass when large numbers of units are required.

In the current market, substantial improvements in reliability and operational stability have reduced these concerns, and industrial scale electron beam facilities have been in continuous operation at wastewater treatment facilities in China and Poland for over 5 years with 1 MeV, 400 kW accelerators (Personal Communication with Han 2017). Additionally, to achieve acceptable reliability standards, technical support and spare parts for electron beam equipment

must be readily available in the US and worldwide to be able to repair equipment rapidly. Finally, sufficient safeguards must be in place to guarantee reliable line power and electrical power service from the provider, stability from the grid, resiliency for natural disasters and extreme weather events, and backup generator power capacity.

During this cost analysis, it became obvious that redundancy and reliability of operation are important considerations for any new technology adoption. A key requirement of electron beams for environmental applications is the need to operate continuously, particularly for wastewater treatment. If the downtime is 10%, for example, this would represent a major problem for a wastewater treatment facility, which must operate without interruption. For a biosolids treatment application, the system could operate a batch process as suggested in the previous section (16 hr/day, 20 days/month), such that if adequate on-site storage exists, minor downtime would be manageable.

Aging of equipment and fouling is another maintenance issue that could increase downtimes, particularly since wastewater and biosolids operations will expose the equipment to pH, alkalinity, hardness (iron, manganese, calcium), high temperature, solids, salts, and corrosive conditions. The flow distributor or weir is particularly vulnerable to plugging or clogging, and any disruption to that system will decrease efficiency of treatment performance and lead to instrument downtime. Thermal stress and material fatigue will cause challenges for the structural elements and working mechanisms in the radiation field. The window is most vulnerable in this case. Choosing an ageing/fouling factor of 0.5 – 0.9 will allow the unit to account for less beam power applied to the target. However, this means the unit is oversized and draws more power, which inevitably increases the operational costs. According to Kurucz et al. (1995), the other common system failures included vacuum leaks, failure of logic boards, wave form generators, ramp boards, cooling water interlocks, power supply diodes, exhaust fans, and pumps. More research is needed from demonstration testing to determine an expected mean time between failures (MTBF) value for design purposes.

Another important question is where in the treatment plant flow path diagram does an electron beam process fit best, and will its use impact upstream and/or downstream processing of wastewater and biosolids? For example, at a wastewater treatment plant, the process train is dictated by the ultimate disposal water quality requirements of the receiving water in the permit, which is site-specific. Federal regulations require secondary treatment, which means at a minimum biological treatment (eg. activated sludge) then disinfection. In some instances, this is preceded by primary treatment (bar screens, grit removal, sedimentation) as well. Electron beams applied upstream of secondary treatment have the advantage of breaking down the recalcitrant organics to more readily biodegradable forms and reducing toxic metals species that inhibit biological growth (Amro et al. 2008; Gehringer et al. 2008; Han et al. 2008; Capodaglio 2017). Therefore, electron beams have no documented ill effects when employed as a pre-treatment step to secondary treatment. Other literature has reported the efficacy of electron beam treatment as a disinfection step after secondary treatment with no issues noted (Kurucz et al. 1995; Kimura et al. 2007). Thus, the main focus should be on managing the levels of free radical scavenging compounds such as O_2, HCO_3^-, Cl^-, NO_2^-, NO_3^- (Campodaglio 2017) and DOC, including

humic acids, phenolic compounds, lignin sulfonates, copper, iron, and other compounds that tend to absorb radiation and decrease treatment efficiency (Jesky et al. 2001). Some of these can be controlled via primary sedimentation followed by ion exchange, but the economic impact of adding more treatment unit processes must be investigated. Another aspect that must be explored is if the electron beam is employed for wastewater treatment, will the associated benefits be translated to the waste sludge without an additional accelerator just for biosolids processing. But note that all these process costs are in addition to the accelerator costs noted previously. In such cases an analysis would need to be performed to determine which, if any, processes could be removed to cut costs.

The most efficient electron beam utilization will employ a single pass, thin sheet of flow presented to the electron beam in either a falling film or upflow configuration (horizontal beam) or a drum-type or conveyor configuration (vertical beam). The desired film thickness/beam width must be determined. Film thickness is a function of the radiation penetration depth. Some commercial systems operate with thin sheet of flow on the order of 1 – 10 mm up to 2 – 3 cm thick. The beam width is governed by the geometry of the scan horn. Research is needed for engineers to properly design the dimensions to ensure that high energy electrons are reaching the target without losing strength before reaching the target. Another key parameter will be the velocity of the inlet nozzle injector or inlet device to insure sufficient radiation exposure. Plugging, clumping, or other mechanism that obstructs the distribution of the flow to the electrons will adversely impact treatment performance. Thus, individual flow meters, temperature sensors, and control valves will be required for fine adjustment.

Shielding for backscatter, personnel protection, and safeguarding electronics is required. Thick concrete vaults or lead lining can be used. More design guidance is required for assisting engineers in determining the minimum shielding requirements, which will help reduce costs. Realtime monitoring will allow close control of energy output and treatment performance as well as rapid notification of malfunction. Alarms for run time, sensor calibration, low dose, low power, matrix transmittance changes, high/low flow or velocity, film thickness/width changes, system failure, high temperature, etc. would be desired. Low cost sensors for measuring real-time radiation intensity at the target (temperature increase ΔT), power output, effects of system ageing, fouling, matrix transmittance, etc. will help to reduce costs. Critical control systems are just as important as monitoring equipment. Automatic adaptive control that switches operation to the hot start backup unit after a set amount of hours or a sensor signal will allow the operators to switch to a backup unit for no loss in treatment efficiency. Analogous to UV radiation banks, if electron beam systems could be configured with multiple electron guns per unit, then redundancy can become more cost effective. Finally, some type of modular design would be useful for wastewater applications to be able to reduce the number of accelerators needed to perform the treatment.

The cost analysis allowed for determination of opportunities for innovation to help increase efficiency of operation. The key components of an electron beam facility include the high voltage terminal, electron gun, beam tube, scan magnet, horn, scan window (metal foil), inlet thin film distributor and conveyor system. If the wall power or beam power efficiency can be increased

from 48% to 81% or higher, this will lower the cost by $1.60/kgal for wastewater and $90/DT for biosolids. The aim would be to provide MW-range high energy electrons at low electrical requirements, while maintaining high beam quality with beam loss less than 1 W/m. These goals could be achieved with more efficient vacuum environments and more resilient materials for the scan window. Easily swapped out transmission windows can be an alternative for reducing the fouling effect. Additives for fouling control can be explored as well as pre-treatment to remove fouling agents prior to electron beam processing. Improvements in the inlet distributor design to reliably maintain the desired velocity profile and film thickness at the target will also increase process efficiency and reduce downtime.

For biosolids, a better understanding of the beneficial impacts of electron beam treatment are needed with respect to viscosity reduction to reduce pumping costs, improved methane yield to provide renewable energy, improved sludge conditioning to reduce polymer demand and increase the final solids content to reduce costs associated with hauling water, odor abatement to reduce odor control costs, and finally ways to improve the penetration of radiation into the sludge matrix will improve efficiency and reduce costs, specifically for biosolids applications. If these opportunity costs can be quantified and included in the analysis, the cost will come down and become more competitive with conventional processing.

6.7 Summary and Conclusions

The preliminary cost analysis conducted here indicates that the capital and O&M costs are nearly cost-competitive with existing conventional technologies, although the cost estimates are slightly above the industry standard using conservative assumptions. Key opportunities for innovation to reduce costs and improve efficiency were identified for reliability/redundancy, aging/fouling control, pre- and post-treatment requirements, hydraulics/flow configurations, and shielding/monitoring. The lack of US technology vendors and skilled personnel to repair and service the installations, as well as the lack of engineering design guidance will continue to be a hurdle for utilities to consider adoption of electron beam processing options.

Utilities are responsible on a continuous basis for meeting strict regulatory effluent standards that directly affect public health. The introduction of new or innovative technologies to this industry has notoriously been slow, as utilities do not want to be the first to install unproven treatment systems that may put their customers at risk, which is why successfully penetrating this market is difficult. Therefore, there has been no real attempt to conduct long-term reliability testing, develop economic analyses, prepare engineering design guidance, or train operators in electron beam technology. Bridging this gap between the innovation of the accelerator industry and its inability to penetrate the environmental applications market involving water, wastewater, and biosolids treatment will require a joint venture of stakeholders including universities, accelerator manufacturers, water/wastewater utilities, government laboratories, and regulatory agencies to conduct the needed full scale demonstration testing and the education, outreach, and training guidance follow-up to establish buy-in for adoption.

CHAPTER 7

POTENTIAL DEMONSTRATION PROJECTS

During the 2018 Workshop, several breakout groups were charged with brainstorming the most high-impact demonstration projects. The participants follow-up survey further ranked these projects in order of importance:

1. Biosolids conditioning before anaerobic digestion
2. Reclaimed water for potable reuse
3. Military site remediation
4. Leachate treatment for solid waste management

At the time of publication, there authors were not aware of any pilot-scale or full-scale electron beam systems in operation in the world at a wastewater treatment facility. Therefore, the participants agreed that a near full scale demonstration project is necessary to evaluate the effectiveness of the electron beam technology in practice. Three of the top four potential demonstration projects are summarized in detail in the following sections.

7.1 Biosolids Conditioning Before Anaerobic Digestion

Solids treatment of waste activated sludge was described in Chapter 3.3. The main processes involved include thickening, conditioning, stabilization, and disinfection. An electron beam could potentially be used a conditioning step to replace chemical polymers for enhanced thickening, more complete stabilization, better dewatering characteristics, and disinfection (Meeroff et al. 2004). According to previous work (Kurucz et al. 1991; Cooper et al. 1992), a 4 MeV electron beam exposure to thickened waste activated sludge is expected to enhance the rate-limiting hydrolysis step in downstream anaerobic digestion applications by bringing about more complete decomposition of complex organic material. This effect is manifest by enhanced levels of volatile fatty acids (VFAs) in the early stages of the digestion process, signaling a more rapid onset of acidogenesis. Therefore, total digester gas generation as well as methane production is expected to increase. Pilot testing (Meeroff et al. 2004) using 4, 10, and 20 kGy doses from a 4 MeV unit showed that digester gas generation rates increased with higher volatile solids loading but did not correlate with VSS or COD destruction. Although bench scale biogas generation rates were an order of magnitude lower than those reported at full scale, biogas yields increased with time and dose. At doses lower than 20 kGy, digester gas production was inhibited compared to controls, for substrate that was prior to and also after thickening. Biogas composition analysis showed higher methane levels for exposed samples, suggesting that electron beam exposure accelerated the decomposition of recalcitrant polysaccharides into more bioavailable short-chained fatty acids. This observation is supported by organic acid composition analysis in which four common VFAs (formate, acetate, propionate, and butyrate) were monitored as indicators of

decomposition and process instability. Accumulation of acetate, propionate, and butyrate was observed after electron beam treatment, which suggested that greater destruction of complex organic material was achieved. For the 4 kGy dose, exposure stimulated total VFA levels high enough to approach inhibition of digestion under low loading conditions, and elevated concentrations of acetate after stabilization indicated that insufficient numbers of acetate-metabolizing microorganisms were present. VFA levels are expected to increase to a maximum after approximately 6-7 days under anaerobic conditions and then decrease gradually with the onset of methanogenesis (Stronach *et al*. 1986). Temporal profiles of these parameters suggest that inadequate acclimation times were allowed since acetate was found to accumulate faster than it was being consumed, delaying the onset of methanogenesis by about 6-8 days longer than expected (Kazumi et al. 2000; Meeroff 2001). One possible explanation is that accelerated degradation nearly offset cellular disruption, since the exposed sample and the control exhibited nearly equal biogas generation rates. Over the stabilization period, total digester gas and methane production was lower than expected for non-exposed control samples, indicating a large proportion of crude fibrous material and more likely insufficient seeding/acclimation. Regardless of pilot conditions, no biogas stimulation was observed, and it was not clear from these studies which factor governed the biogas generation rate.

As retention time was extended, volatile solids destruction was improved at SRT = 21 days by 22% compared to unexposed controls. In terms of design, a decrease in retention time from 21 days to 14 days would result in 40% less digester volume required to treat the same quantity of waste. However, since the full scale facility was operating on a retention time of 12 – 22 days (similar to the pilot plant), electron beam treatment did not decrease the required detention time for stabilization in bench scale tests. Based on critical solids retention times (CSRTs), electron beam treated samples had 5% lower CSRTs than controls. The effect on volume reduction and increased loading rates was minimal in this pilot scale study with unacclimated seed, but may be a significant factor for large treatment plants. Longer acclimation time was related to the nature of the pilot tests, which were operated in batch mode using existing seed from a full scale facility instead of acclimated laboratory seed. In addition, the effective reactor volume and seed volumes may have been too small in relation to full-scale reactors. Another effect of longer acclimation time was pH inhibition, in which initial pH conditions were depressed due to insufficient buffer capacity in the pilot reactor to resist the characteristic pH drop induced by electron beam exposure. These issues are unique to the design of a batch pilot unit and would likely not occur in field applications at full-scale under flow-through conditions, which is why full-scale demonstration projects are needed. It is recommended to conduct multiple laboratory tests using acclimated seed microorganisms using the ultimate sludge digestibility protocol, as outlined by Sethi (2018) to document the dose-dependent benefits. Finally Meeroff et al. (2004) conducted laboratory tests to determine the dewaterability characteristics of raw and thickened sludge upon exposure to electron beam treatment with promising results. It is recommended to conduct larger scale tests to see if polymer usage can be reduced or eliminated altogether. This would represent a substantial savings that could potentially offset the annual operating costs of the electron beam process. For example, the Metropolitan Water Reclamation District of Greater Chicago uses a dose of 450 lb of polymer per dry ton at a cost of $0.08/lb (personal

communication with Albert Cox). If 404 DTPD of solids is processed, then the chemical cost is nearly $5.4 million annually.

The research questions that would be addressed in this proposed biosolids demonstration project would be as follows:

- Can electron beam treatment take the place of thickening or does pre-thickening enhance electron beam processing?
- Can electron beam treatment take the place of polymer conditioning or does it substantially reduce the chemical addition requirements?
- Can electron beam treatment reduce the solids retention time in anaerobic digestion, and does it improve volatile solids destruction, biogas generation, methane content, and/or final product stability?
- Can electron beam treatment improve dewaterability of the sludge?
- Can electron beam treatment take the place of biosolids disinfection or does it substantially reduce the disinfection requirements for final disposal?

7.2 Reclaimed Water for Potable Reuse

Liquid treatment requirements for recycling of treated wastewater for indirect or direct potable reuse were described in Chapter 3.2.3 – 3.2.5. Electron beam processing for recycling treated wastewater and perhaps dealing with troublesome internal recycle flows would seek to address reduction of suspended solids/colloids, nutrient reduction, destruction of emerging contaminants, and enhanced disinfection.

A potable reuse demonstration project could follow the template used in Bloetscher et al. (2011) for the City of Pembroke Pines, FL. The experiment should evaluate an indirect/direct potable reuse program that would either inject highly treated reclaimed water into an aquifer for retrieval downstream in their wells as an alternative water supply solution, or as a source water for water treatment facility. Of importance would be to monitor ongoing water quality and the removal of nutrients (nitrogen and phosphorous) and emerging substances of concern (ESOCs).

It is anticipated that the gold standard for direct potable reuse would be a combined treatment train comprised of microfiltration, reverse osmosis membranes and ultraviolet light/advanced oxidation (UV/AOP). It is proposed to replace UV/AOP with an electron beam unit. A comprehensive analysis of substances found in the wastewater treatment plant should be performed in triplicate, with the purpose of evaluating the facility's readiness to manage micro-pollutants present in feedwater. The water quality characteristics of the wastewater are an important factor to consider when determining the efficiency of a membrane system. Parameters should include organics, inorganics, trace metals, salts, radionuclides, pathogen indicators, nutrients, and ESOCs such as acetaminophen, carbamazepine, ibuprofen, antibiotics, triclosan,

steroids/hormones, estrone, nitrosomines, and n-dimethylnitrosamine (NDMA) (see Nickelson et al. 2005 and Bloetscher et al. 2011 for a complete list). Water quality characteristics for specific conductivity, pH, ORP, temperature and dissolved oxygen should be collected as well.

A major issue in demonstrating efficacy of proposed treatment schemes in most potable reuse applications is that the influent water quality may not contain the parameters of interest at detectable levels since ESOC concentrations are generally found in very low concentrations if at all, so spike testing is required. Spiking with endocrine disruptors and certain pathogens must be approved by the local regulatory agency in the jurisdiction prior to initiating testing, as not securing permission could lead to wasted effort. An argument could be made that treated effluent from spike testing under the demonstration protocol would be returned to the wastewater plant headworks for re-treatment to reduce the risks (see prior discussion on full treatment).

The research questions that would be addressed in this proposed demonstration project would be as follows:

- Can electron beam treatment eliminate the target compounds necessary for safe wastewater reclamation, and what is the removal efficiency for specific target compounds during spike testing scenarios?
- At what stage should the electron beam be deployed to achieve water quality goals, while reducing treatment costs? How does the treatment efficiency of electron beam processing change when using filtered secondary wastewater effluent vs. reverse osmosis permeate?
- Can electron beam treatment take the place of any of the unit processes in the full treatment scheme?
- Does electron beam treatment generate any byproducts that must be managed as a result of treatment?
- How does electron beam processing affect public confidence in potable reuse projects?

7.3 Leachate Processing

Landfill leachate is generated by excess rainwater percolating through the waste layers in a landfill. It also includes the moisture content of the waste as disposed and metabolic water generated during the anaerobic degradation process in the landfill. A combination of physical, chemical, and microbial processes occurs in the waste, which transfer pollutants to the percolating water (Christensen and Kjeldsen 1989). Leachate consists of many different organic and inorganic contaminants that may be either dissolved or suspended (Bila et al. 2005). General leachate parameters from various published reports and articles were reviewed and tabulated (Table 17**Table**) (Christensen et al. 2001; Meeroff and Gasnier 2008; Youngman 2013; Meeroff and Lakne, 2014; Shaha et al. 2016).

Table 17. Typical Composition of Landfill Leachate (values are in mg/L unless otherwise stated)

Parameter	Units	Range
pH	Standard units	4.5 – 9.0
Specific conductance	µS/cm	2500 – 35,000
Total solids	mg/L	2000 – 65,000
Total organic carbon	mg/L as C	30 – 29,000
Biochemical oxygen demand (BOD_5)	mg/L as O_2	20 – 57,000
Chemical oxygen demand (COD)	mg/L as O_2	140 – 152,000
BOD_5/COD ratio	Unitless	0.02 – 0.80
Organic nitrogen	mg/L as N	14 – 2500
Total phosphorus	mg/L as P	0.1 – 23
Chloride	mg/L as Cl-	150 – 4500
Sulfate	mg/L as SO_4^{2-}	8 – 7750
Bicarbonate	mg/L as $CaCO_3$	610 – 7320
Sodium	mg/L as Na	70 – 7700
Potassium	mg/L as K	50 – 3700
Ammonium	mg/L as N	50 – 2200
Calcium	mg/L as $CaCO_3$	10 – 7200
Magnesium	mg/L as Mg	30 – 15,000
Iron	mg/L as Fe	3 – 5500
Arsenic	mg/L as As	0.01 – 1
Chromium	mg/L as Cr	0.02 – 1.5
Copper	mg/L as Cu	0.005 – 10
Lead	mg/L as Pb	0.001 – 5
Mercury	mg/L as Hg	0.00005 – 0.16
Zinc	mg/L as Zn	0.03 – 1000

Leachate can be classified as stabilized (mature), intermediate, or fresh (young) based on the biodegradability (Table 18) (Robinson and Maris 1983; Amokrane et al. 1997; Meeroff and Teegavarapu 2010; Sun et al. 2010; Pilli et al. 2011). Leachate from mature landfills is typically characterized by a high ammonium (NH_4^+) content, low biodegradability (low BOD_5/COD ratio) and a high fraction of refractory and large organic molecules such as humic and fulvic acids, but leachate from young landfills contains low organic compound concentrations (Li et al. 2010; Ziyang et al. 2009; Kulikowska and Klimiuk 2008; Kjeldsen et al. 2002; Lo 1996; Meeroff and Teegavarapu 2010). Usually young landfill leachates are treated more easily than mature leachate (Koh et al. 2004).

Table 18. Leachate Classification Based on Biodegradability (BOD_5/COD) and Age of Leachate

Leachate classification	BOD_5/COD	Age, years
Stabilized (mature)	<0.1	>10
Intermediate	0.1-0.5	5-10
Fresh (young)	>0.5	<5

Current leachate management strategies include: a) onsite treatment (biological, chemical and physical methods), b) recirculation of leachate, c) hauling or discharge to a nearby wastewater treatment facility, and d) injection into deep confined rock formations using Class I industrial and municipal waste disposal wells. The performance effectiveness of leachate treatment processes is highly dependent on biodegradability of the contaminants, which becomes more recalcitrant with the age of the landfill, as demonstrated by the low BOD_5/COD ratio (refer to Table 18). Renou et al. (2008) reviewed the potential advantages and drawbacks of leachate treatment methods and found that integrated approaches involving multiple physical–chemical–biological processes (regardless of the order) provides better pollutant removal compared to individual processes. Because of the variation in leachate composition and the wide range of pollutants, it is difficult to predict a treatment technique that will be most effective for all circumstances (Atmaca 2009; Mahvi 2009). Usually a combination of physical, chemical and biological methods is used for effective treatment of landfill leachate, since it is difficult to obtain satisfactory results by using any one of those methods alone (Kurniawan et al. 2006). However, advanced oxidation processes (AOPs), such as O_3/H_2O_2, O_3/ultrasound, H_2O_2/ultrasound, Fenton (Fe^{2+}/ H_2O_2, electron beam and other photochemical processes using UV, have been shown to enhance the biodegradability of liquids containing various organic compounds that are non-biodegradable and/or toxic to most microorganisms (Chiang et al. 1995; Cortez et al. 2011). AOPs offer excellent oxidative capabilities and process removal efficiencies, making them a promising technique for purifying leachates with respect to recalcitrant organic and inorganic contaminants (Anglada et al. 2011; Kargi and Pamukoglu 2004). From a basic economical point of view, the combination of biological treatment systems with AOP treatment was more favorable than other combinations (Gao et al. 2015; Chemlal et al. 2014; Renou et al. 2008; Tizaoui et al. 2007; Wiszniowski et al. 2006; de Morais et al. 2005; Lopez et al. 2004; Geenens et al. 2001; Meeroff and Teegavarapu 2010; Meeroff et al. 2012). Treatment performance efficiencies of AOPs are well documented in published research and case studies including but not limited to COD destruction between 46-74.6%, BOD_5/COD ratio increase from 0.01 to 0.24, and TOC removal between 30.4-78.9% (Cortez et al. 2011; Qureshi et al. 2002; Meeroff et al. 2008; Pieczykolan et al. 2012; Youngman 2013; Meeroff, Lackner and Coffman 2016; Meeroff et al. 2014). Applying biological treatment as pre- or post-treatment to advanced oxidation processes-based technologies could help achieve higher removal efficiencies.

Electron beam treatment involves the formation of reactive free radicals to render organic destruction (Huang et al. 1993). These reactive species undergo complex reactions with target organic compounds, which are either completely mineralized or broken down into lower molecular weight fragments. Duarte et al. (2002) conducted experiments with a 1.5 MeV, 37 KW accelerator and reported that 20 kGy was an optimum dose to reduce 90% of organic compounds present in an industrial effluent. A 1000-L capacity tanker truck was used to transport the liquid wastes from the source to the electron beam pilot plant, and they were treated with 5-50 kGy at a flow rate of 30 L/min by varying the beam current from 1.2 to 10.6 mA. Rela et al. (2000) studied electron beam processing as a promising technology to treat sludge, groundwater, surface water, and municipal and industrial wastewater and found that a 1.5 MeV, 60 kW unit supplying a 2 kGy dose to a flow of 70 m^3/hr was cost competitive. Although electron beam

processing is effective for achieving complete mineralization of organic contaminants, it is likely more efficiently used as a pretreatment for biological processes (Yahmed et al. 2009; Lim et al. 2010). However, the application of electron beam processing in leachate management to enhance biodegradability is yet to be explored.

To evaluate the performance of electron beam technology in leachate treatment, a demonstration project could be designed with a portable unit. The candidate facility would be a large leachate generating landfill producing approximately 1 million gallons or more per month of mature leachate. This facility would likely be located in a rural setting, far from a large wastewater treatment plant, requiring both large amounts of storage and hauling. If the nearest POTW is a small plant with a capacity relative to the leachate flow rate of greater than 10:1, then it is likely that it could not accept the leachate or levies excessive surcharges on the landfill operators for disposal. The major constituents of leachate that indicate the performance of treatment are BOD_5/COD ratio, ammonia, and TOC. These constituents will be tested with dose ranges between 0-20 kGy to determine the differences between treated and untreated controls. In addition, a cost analysis is necessary based on power consumption, unit cost, operation and maintenance cost, and miscellaneous costs.

The research questions that would be addressed in this proposed demonstration project would be as follows:

- Can electron beam treatment eliminate the target compounds necessary for safe discharge to a POTW or to the environment? How is treatment efficiency different in the leachate matrix compared to wastewater or biosolids?
- Can electron beam treatment handle the large variability in flow and concentration of leachate contaminants?
- Does electron beam processing generate any byproducts that must be managed as a result of treatment?
- Does electron beam treatment successfully penetrate the matrix or is there a need to remove background color, TSS, etc. prior to electron beam treatment?
- Is a pre-treatment or post-treatment polishing step required to meet the discharge goals?

7.4 Potential Demonstration Sites – Utilities

As part of the participants' follow-up survey, respondents indicated if they would be willing to serve as host facilities for demonstration projects. Several utilities expressed interest including some of those who were invited as speakers in the 2018 Workshop.

7.4.1 Metropolitan Water Reclamation District (MWRD) of Greater Chicago

MWRD is an independent government and taxing body that manages wastewater treatment, reuse, and disposal from 125 municipalities including the city of Chicago, serving 5.25 million

people. The local municipalities manage the wastewater collection, and Cook County manages the stormwater collection systems. The District manages a tunnel system for pollution and flood control. MWRD has multiple treatment plants from 2.3 to 1200 MGD. Currently, one of the District's high priority areas is biosolids management. The District's goal is 100% beneficial reuse of biosolids through land application, such as fertilizer on farmland in nearby counties and as soil amendment for turf and other applications in the Chicago metro area. MWRD has 400 acres, which is used for biosolids processing, including lagoons where the biosolids are aged for about 18 months and paved cells for biosolids drying, both of which contribute reduction of pathogen content before used in the Chicago metro area. A new component of the MWRD biosolids management program is composting of biosolids, which involves 1 part biosolids to 3 parts wood chips with 23-day active composting followed by 16 weeks curing. Regulatory drivers for MWRD operation goals include requirements of**:**

- Disinfection of effluent: 200 CFU/mL monthly mean
- Biosolids processing to achieve USEPA Class A standard:
  - <1000 MPN/g, fecal coliform
  - Helminth, OVA < 1/4g
  - Enteric virus < 1 PFU/4g
- Nutrients to meet effluent permit limits:
  - 1 mg/L total P
  - Future goal: 0.5 mg/L total P

At present, disinfection is accomplished with either chlorine or UV. For example, the Calumet plant located in southern Chicago is a 350 MGD plant (Figure 38) with a cost of $12/MGD disinfection with chlorine. The O'Brien plant, located Skokie, has 333 MGD capacity and uses UV for disinfection (Figure 39). Electrical demand is 40 kWh/MG with a cost of $3/MG (MWRD 2018). In addition, 900 bulbs need replacement every 3 years at a cost of $1.5 million. Operations goals include decreasing energy consumption, and increasing renewable energy production. This can be accomplished through increases in biogas production and utilization.

Figure 38. Calumet wastewater treatment plant aerial photograph. (MWRD 5/11/2018 presentation at Fermilab)

Figure 39. O'Brien wastewater treatment plant UV disinfection units. (MWRD 5/11/2018 presentation at Fermilab)

Pubic concerns involve emerging contaminants, pharmaceuticals and personal care products (PPCPs), endocrine disrupting compounds (EDCs), and odor emissions. MWRD performed an evaluation to compare treatment performance on these emerging contaminants using the following technologies:

- Ozone (O_3)
- Advanced oxidation processes (AOPs)

- Membranes (e.g. RO, NF)
- Activated carbon

They determined that advanced treatment can provide complete to near complete removal of most emerging contaminants. These treatment process performance evaluations were conducted at both the Calumet and O'Brien facilities, with summaries of specific contaminants presented in Table 19 and Table 20, respectively.

Table 19. GG Calumet WRP: Pharmaceuticals Pre- and Post-Hypochlorite Disinfection (MWRA 2018)

Parameter	Samples Detected	Pre-Disinfection Concentration (ng/L)	Post-Disinfection Concentration (ng/L)	Percent Removal
Estrone (E1)	1	9 ± 1	8 ± 1	11%
Estradiol (E2)	0	Below Detection	Below Detection	n/a
Bupropion	16	90 ± 100	60 ± 40	33%
Cabemazepine	16	160 ± 50	150 ± 50	6%
Citalopram	16	82 ± 70	29 ± 20	65%
Duloxetine	16	3 ± 3	2 ± 2	33%
Fluoxetine	16	320 ± 550	130 ± 140	59%
Norfluoxetine	10	63 ± 68	18 ± 31	71%
Norsertraline	16	270 ± 240	220 ± 180	19%
Paroxetine	4	3 ± 1	2 ± 1	33%
Sertraline	16	39 ± 65	13 ± 6	67%
Venlafaxine	16	100 ± 40	67 ± 28	33%

Table 20. O'Brien WRP: Pharmaceuticals Pre- and Post-UV Disinfection Data (MWRA 2018)

Parameter	Samples Detected	Pre-Disinfection Concentration (ng/L)	Post-Disinfection Concentration (ng/L)	Percent Removal
Estrone (E1)	1	9 ± 2	9 ± 2	--
Estradiol (E2)	1	2 ± 3	Below Detection	n/a
Bupropion	15	120 ± 50	100 ± 40	17%
Cabemazepine	15	230 ± 150	170 ± 70	26%
Citalopram	15	130 ± 40	120 ± 40	8%
Duloxetine	10	12 ± 15	4 ± 3	67%
Fluoxetine	15	13 ± 17	20 ± 35	--
Norfluoxetine	7	3 ± 4	4 ± 6	--
Norsertraline	15	210 ± 140	180 ± 150	6%
Paroxetine	4	8 ± 1	2 ± 2	75%
Sertraline	16	60 ± 90	24 ± 16	60%
Venlafaxine	16	240 ± 440	160 ± 60	33%

Ultimately the utility is seeking solutions for biosolids and wastewater treatment to recover resources and reduce pollution in the Mississippi River basin.

7.5.2 Milwaukee Metropolitan Sewerage District (MMSD)

MMSD serves 1.1 million customers in 28 municipalities over an area of 411 square miles. The system has 2 water reclamation facilities and a 521 MG tunnel system to prevent wet weather overflows. With respect to sludge, MMSD created Milorganite® in 1926 from sludge, and in the 1970's, USEPA deemed the product safe for produce growth. MMSD receives over $6.73 million of annual cost recovery from sales of nearly 43,500 tons of Milorganite®.

The system has many concerns, among them are the growing issues related to non-regulated contaminants, such as pharmaceuticals, in effluent and biosolids. Pharmaceuticals have been detected in the wastewater effluent. Electron beam processing may be an option to ensure the absence of these types of contaminants in both Milorganite® and the effluent discharges.

CHAPTER 8

RECOMMENDATIONS

8.1 Outcomes from the Barriers to Implementation

The 2018 Workshop participants identified 6 areas of need to develop a pathway forward for the accelerator technology in the wastewater field, as outlined in Chapter 5. These included education, building a mobile demonstration unit, demonstration projects, dose requirements (efficacy studies), costs, and funding for research or demonstration projects, as follows:

1. **Education**. How do we better educate the public, policy makers, engineers and operator about the benefits of electron beam technology?
2. **Mobile demonstration unit**. What would an electron beam installation look like – from an engineering and operations perspective? How long would it take to build a unit that is plug and play? What are the components, critical spare parts, performance limitations and can we evaluate the reliability, need for redundancy and operations for a working installation?
3. **Demonstration projects**. Where should be the highest impact project sites to pilot test the mobile demonstration unit to collect the data needed to establish efficacy and reliability of the technology?
4. **Dose requirements**. Can we define the effective dose for wastewater and biosolids, so that the 40 CFR part 503 regulation value can be revisited? How does the dose requirement change for 10 MeV vs 1 MeV vs 0.4 MeV? What is the uncertainly of dose measurements? How does the electron beam dose relate to a CT value for disinfection? If so, how efficiently are key emerging contaminants (viruses, PCB, PCP, odorants, explosives, nutrients, cyanobacteria, oocysts, pharmaceuticals, PAHs, etc.) removed or destroyed?
5. **Cost of implementation**. What is the true cost of operating a utility-scale electron beam facility? Does it depend on treatment goals?
6. **Funding**. Is NSF the appropriate funding source for such projects? Is there another source?

Based on the questions asked, the answers to the questions create a pathway of next steps, which are as follows:

1. Create a short video of the history of electron beam technology

2. Write an article in the Water Environment Federation journal and/or the Journal of the American Water Works Association that introduces the environmental engineering community to the electron beam technology
3. Write a chapter for the next edition of the Metcalf & Eddy textbook authored by Dr. George Tchobanglous et al.
4. Secure funding for one or more of the full scale demonstration projects mentioned in Chapter 7. MWRA is a potential demonstration site for biosolids treatment, as they are investigating future solutions now.
5. Create a fundable demonstration project for potable reuse treatment. Several facilities are investigating this in Florida and California. Miami-Dade County and Metropolitan Water District of Southern California were represented at the 2018 Workshop and both indicated a willingness to participate as they are investigating future potable reuse options for the future. To capitalize on this strategic moment, a demonstration project must be implemented to field test the technology and provide answers to the questions about disinfection and emerging contaminant removal put forth in this document. Also a demonstration project or series of demonstration projects would go a long way towards identifying engineering design considerations and operations/maintenance challenges for such a facility.
6. Further develop the cost assessment model and publish it in the engineering literature
7. NSF appears to be a logical choice to coordinate funding

8.2 The E-Beam Prize

As a result of the 2018 Workshop, it is proposed to create a funded competition ("E-Beam Prize") with a substantial cash award that would test new accelerator designs in conjunction with the FAST Water Network (Facilities Accelerating Science & Technology) test bed program (http://www.werf.org/lift/FASTWaterNetwork) targeting large (Q > 100 MGD) capacity facilities but treating <1% of the flow to establish the innovation and engineering data needed for the industry. The FAST Water Network could screen the contestants to connect technology partners with test bed facilities for demonstration testing and monitor the performance to ensure acceptance of the engineering data to generate market demand. The FAST Water Network will serve as a neutral party to establish a set of competition criteria and coordinate the demonstration work. The ideal competitor for the E-Beam Prize would be a design, build, operate (and insure) entity.

To date, there has not been a robust scientific attempt to conduct long-term reliability testing, develop cost models, prepare engineering/design guidance, or train operators in electron beam technology. Bridging this gap between the innovation of the accelerator industry and its inability to penetrate the environmental applications market involving water, wastewater, and biosolids treatment will require a joint venture of stakeholders including universities, accelerator manufacturers, water/wastewater utilities, government laboratories, and regulatory agencies to

conduct the needed full scale demonstration testing and the education, outreach, and training guidance follow-up to establish buy-in for adoption.

8.3 WEFTEC Workshop

The Water Environment Federation (WEF) was established in 1928 and is a not-for-profit technical and educational organization of 35,000 individual members from 75 affiliated Member Associations representing water quality professionals around the world. As a global water sector leader, its mission is to connect water professionals; enrich the expertise of water professionals; increase the awareness of the impact and value of water; and provide a platform for water sector innovation. WEF and its global network of members and Member Associations (MAs) provide water quality professionals around the world with the latest in water quality education, training, and business opportunities. Membership includes scientists, engineers, regulators, academics, utility managers, plant operators, and other professionals. WEF uses this collective knowledge to further a shared goal of improving water quality around the world.

The annual technical exhibition and conference of this global association is called WEFTEC. More than 20,000 water professionals and 1,000 water companies typically attend to learn about the latest developments and technologies in the water sector. Each year, a series of workshops are hosted at this event. These workshops offer the opportunity to learn about a specific topic in an in-depth, hands-on format. The WEF Program Committee selects workshops through rigorous process that ensures WEFTEC workshops are targeted, organized, and provide the most up-to-date information. In addition, WEF follows strict guidelines so that the highest level of education credits (CEUs) can be awarded for all workshops. It was suggested that 2018 Workshop organizers apply to host a WEFTEC workshop at next year's WEFTEC.

8.4 Engineering Design Textbook Chapter

The 5th edition of "Wastewater Engineering: Treatment and Resource Recovery" is the authoritative engineering design textbook on wastewater treatment and residuals processing. It is likely that nearly every environmental engineering professional or civil/environmental engineering major has a desk copy of this book. It covers the rapidly evolving field of wastewater engineering and the technological and regulatory changes that have occurred including: wastewater as a source of energy, nutrients and potable water; more stringent discharge requirements related to nutrients; enhanced understanding of the fundamental microbiology and physiology of the microorganisms responsible for nutrient removal and emerging constituents; methods to deal with separate treatment of return flows; increased emphasis on the treatment and management of biosolids; carbon footprints and greenhouse gas emissions, and an emphasis on the development of energy neutral or energy positive wastewater plants through more efficient use of chemical and heat energy in wastewater. What is missing is a chapter that covers electron beam processing.

8.5 Scholarly and Technical Publications

A series of technical papers should be developed with the water and environmental fields in mind. The first paper should be related to the cost analysis in Chapter 6 (submitted). It is suggested that additional papers be presented at WEFTEC. These will focus on additional efforts to understand applications and limitations. Dr. Slifko, a participant in the conference, and Drs. Bloetscher and Meeroff, plus Mr. Fergen, all have data that should be developed and published with respect to electron beam application in the water/wastewater and biosolids sector. Southern California and potentially Florida have interest in potable reuse options, which creates the potential for a third paper. It is duly noted that many water professionals do no read peer-reviewed publications, rather papers in trade periodicals like the Journal AWWA and Florida Water Resources Journal are many times preferred. Companion articles should be targeted to these trade publications as well.

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APPENDIX A

Pathogens.

(a) *Sewage sludge - Class A.*

(1) The requirement in § 503.32(a)(2) and the requirements in either § 503.32(a)(3), (a)(4), (a)(5), (a)(6), (a)(7), or (a)(8) shall be met for a sewage sludge to be classified Class A with respect to pathogens.

(2) The Class A pathogen requirements in § 503.32 (a)(3) through (a)(8) shall be met either prior to meeting or at the same time the vector attraction reduction requirements in § 503.33, except the vector attraction reduction requirements in § 503.33 (b)(6) through (b)(8), are met.

(3) ***Class A - Alternative 1.***

(i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella* sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f).

(ii) The temperature of the sewage sludge that is used or disposed shall be maintained at a specific value for a period of time.

(A) When the percent solids of the sewage sludge is seven percent or higher, the temperature of the sewage sludge shall be 50 degrees Celsius or higher; the time period shall be 20 minutes or longer; and the temperature and time period shall be determined using equation (2), except when small particles of sewage sludge are heated by either warmed gases or an immiscible liquid.

$$D = \frac{131,700,000}{10^{0.1400t}} \qquad Eq.\ (2)$$

Where,
D = time in days.
t = temperature in degrees Celsius.

(B) When the percent solids of the sewage sludge is seven percent or higher and small particles of sewage sludge are heated by either warmed gases or an immiscible liquid, the temperature of the sewage sludge shall be 50 degrees Celsius or higher; the time period

shall be 15 seconds or longer; and the temperature and time period shall be determined using equation (2).

(C) When the percent solids of the sewage sludge is less than seven percent and the time period is at least 15 seconds, but less than 30 minutes, the temperature and time period shall be determined using equation (2).

(D) When the percent solids of the sewage sludge is less than seven percent; the temperature of the sewage sludge is 50 degrees Celsius or higher; and the time period is 30 minutes or longer, the temperature and time period shall be determined using equation (3).

$$D = \frac{50,070,000}{10^{0.1400t}} \qquad Eq.\ (3)$$

Where,
D = time in days.
t = temperature in degrees Celsius.

(4) ***Class A - Alternative 2.***

(i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella* sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f).

(ii)

(A) The pH of the sewage sludge that is used or disposed shall be raised to above 12 and shall remain above 12 for 72 hours.

(B) The temperature of the sewage sludge shall be above 52 degrees Celsius for 12 hours or longer during the period that the pH of the sewage sludge is above 12.

(C) At the end of the 72 hour period during which the pH of the sewage sludge is above 12, the sewage sludge shall be air dried to achieve a percent solids in the sewage sludge greater than 50 percent.

(5) ***Class A - Alternative 3.***

(i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella* sp. bacteria in sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag

or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f).

(ii)

(A) The sewage sludge shall be analyzed prior to pathogen treatment to determine whether the sewage sludge contains enteric viruses.

(B) When the density of enteric viruses in the sewage sludge prior to pathogen treatment is less than one Plaque-forming Unit per four grams of total solids(dry weight basis), the sewage sludge is Class A with respect to enteric viruses until the next monitoring episode for the sewage sludge.

(C) When the density of enteric viruses in the sewage sludge prior to pathogen treatment is equal to or greater than one Plaque-forming Unit per four grams of total solids (dry weight basis), the sewage sludge is Class A with respect to enteric viruses when the density of enteric viruses in the sewage sludge after pathogen treatment is less than one Plaque-forming Unit per four grams of total solids (dry weight basis) and when the values or ranges of values for the operating parameters for the pathogen treatment process that produces the sewage sludge that meets the enteric virus density requirement are documented.

(D) After the enteric virus reduction in paragraph (a)(5)(ii)(C) of this section is demonstrated for the pathogen treatment process, the sewage sludge continues to be Class A with respect to enteric viruses when the values for the pathogen treatment process operating parameters are consistent with the values or ranges of values documented in paragraph (a)(5)(ii)(C) of this section.

(iii)

(A) The sewage sludge shall be analyzed prior to pathogen treatment to determine whether the sewage sludge contains viable helminth ova.

(B) When the density of viable helminth ova in the sewage sludge prior to pathogen treatment is less than one per four grams of total solids (dry weight basis), the sewage sludge is Class A with respect to viable helminth ova until the next monitoring episode for the sewage sludge.

(C) When the density of viable helminth ova in the sewage sludge prior to pathogen treatment is equal to or greater than one per four grams of total solids (dry weight basis), the sewage sludge is Class A with respect to viable helminth ova when the density of viable helminth ova in the sewage sludge after pathogen treatment is less than one per four grams of total solids (dry weight basis) and when the values or ranges of values for the operating parameters for the pathogen treatment process that produces the sewage sludge that meets the viable helminth ova density requirement are documented.

(D) After the viable helminth ova reduction in paragraph (a)(5)(iii)(C) of this section is demonstrated for the pathogen treatment process, the sewage sludge continues to be Class A with respect to viable helminth ova when the values for the pathogen treatment process operating parameters are consistent with the values or ranges of values documented in paragraph (a)(5)(iii)(C) of this section.

(6) ***Class A - Alternative 4.***

(i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella* sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f).

(ii) The density of enteric viruses in the sewage sludge shall be less than one Plaque-forming Unit per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in §503.10 (b), (c), (e), or (f), unless otherwise specified by the permitting authority.

(iii) The density of viable helminth ova in the sewage sludge shall be less than one per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or give away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10 (b), (c), (e), or (f), unless otherwise specified by the permitting authority.

(7) ***Class A - Alternative 5.***

(i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella,* sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or given away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10(b), (c), (e), or (f).

(ii) Sewage sludge that is used or disposed shall be treated in one of the Processes to Further Reduce Pathogens described in appendix B of this part.

(8) ***Class A - Alternative 6.***

(i) Either the density of fecal coliform in the sewage sludge shall be less than 1000 Most Probable Number per gram of total solids (dry weight basis), or the density of *Salmonella,* sp. bacteria in the sewage sludge shall be less than three Most Probable Number per four grams of total solids (dry weight basis) at the time the sewage sludge is used or disposed; at the time the sewage sludge is prepared for sale or given away in a bag or other container for application to the land; or at the time the sewage sludge or material derived from sewage sludge is prepared to meet the requirements in § 503.10(b), (c), (e), or (f).

(ii) Sewage sludge that is used or disposed shall be treated in a process that is equivalent to a Process to Further Reduce Pathogens, as determined by the permitting authority.

(b) ***Sewage sludge - Class B.*** (1)(i) The requirements in either § 503.32(b)(2), (b)(3), or (b)(4) shall be met for a sewage sludge to be classified Class B with respect to pathogens.

(ii) The site restrictions in § 503.32(b)(5) shall be met when sewage sludge that meets the Class B pathogen requirements in § 503.32(b)(2), (b)(3), or (b)(4) is applied to the land.

(2) ***Class B - Alternative 1.***

(i) Seven representative samples of the sewage sludge that is used or disposed shall be collected.

(ii) The geometric mean of the density of fecal coliform in the samples collected in paragraph (b)(2)(i) of this section shall be less than either 2,000,000 Most Probable Number per gram of total solids (dry weight basis) or 2,000,000 Colony Forming Units per gram of total solids (dry weight basis).

(3) ***Class B - Alternative 2.*** Sewage sludge that is used or disposed shall be treated in one of the Processes to Significantly Reduce Pathogens described in appendix B of this part.

(4) ***Class B - Alternative 3.*** Sewage sludge that is used or disposed shall be treated in a process that is equivalent to a Process to Significantly Reduce Pathogens, as determined by the permitting authority.

(5) ***Site restrictions.***

(i) Food crops with harvested parts that touch the sewage sludge/soil mixture and are totally above the land surface shall not be harvested for 14 months after application of sewage sludge.

(ii) Food crops with harvested parts below the surface of the land shall not be harvested for 20 months after application of sewage sludge when the sewage sludge remains on the land surface for four months or longer prior to incorporation into the soil.

(iii) Food crops with harvested parts below the surface of the land shall not be harvested for 38 months after application of sewage sludge when the sewage sludge remains on the land surface for less than four months prior to incorporation into the soil.

(iv) Food crops, feed crops, and fiber crops shall not be harvested for 30 days after application of sewage sludge.

(v) Animals shall not be grazed on the land for 30 days after application of sewage sludge.

(vi) Turf grown on land where sewage sludge is applied shall not be harvested for one year after application of the sewage sludge when the harvested turf is placed on either land with a high potential for public exposure or a lawn, unless otherwise specified by the permitting authority.

(vii) Public access to land with a high potential for public exposure shall be restricted for one year after application of sewage sludge.

(viii) Public access to land with a low potential for public exposure shall be restricted for 30 days after application of sewage sludge.

(c)

Domestic septage.

(1) The site restrictions in § 503.32(b)(5) shall be met when domestic septage is applied to agricultural land, forest, or a reclamation site; or

(2) The pH of domestic septage applied to agricultural land, forest, or a reclamation site shall be raised to 12 or higher by alkali addition and, without the addition of more alkali, shall remain at 12 or higher for 30 minutes and the site restrictions in § 503.32 (b)(5)(i) through (b)(5)(iv) shall be met. [58 FR 9387, Feb. 19, 1993, as amended at 64 FR 42571, Aug. 4, 1999].

APPENDIX B

A. Processes To Significantly Reduce Pathogens (PSRP)

1. Aerobic digestion - Sewage sludge is agitated with air or oxygen to maintain aerobic conditions for a specific mean cell residence time at a specific temperature. Values for the mean cell residence time and temperature shall be between 40 days at 20 degrees Celsius and 60 days at 15 degrees Celsius.

2. Air drying - Sewage sludge is dried on sand beds or on paved or unpaved basins. The sewage sludge dries for a minimum of three months. During two of the three months, the ambient average daily temperature is above zero degrees Celsius.

3. Anaerobic digestion - Sewage sludge is treated in the absence of air for a specific mean cell residence time at a specific temperature. Values for the mean cell residence time and temperature shall be between 15 days at 35 to 55 degrees Celsius and 60 days at 20 degrees Celsius.

4. Composting - Using either the within-vessel, static aerated pile, or windrow composting methods, the temperature of the sewage sludge is raised to 40 degrees Celsius or higher and remains at 40 degrees Celsius or higher for five days. For four hours during the five days, the temperature in the compost pile exceeds 55 degrees Celsius.

5. Lime stabilization - Sufficient lime is added to the sewage sludge to raise the pH of the sewage sludge to 12 after two hours of contact.

B. Processes to Further Reduce Pathogens (PFRP)

1. Composting - Using either the within-vessel composting method or the static aerated pile composting method, the temperature of the sewage sludge is maintained at 55 degrees Celsius or higher for three days.

Using the windrow composting method, the temperature of the sewage sludge is maintained at 55 degrees or higher for 15 days or longer. During the period when the compost is maintained at 55 degrees or higher, there shall be a minimum of five turnings of the windrow.

2. Heat drying - Sewage sludge is dried by direct or indirect contact with hot gases to reduce the moisture content of the sewage sludge to 10 percent or lower. Either the temperature of the sewage sludge particles exceeds 80 degrees Celsius or the wet bulb temperature of the gas in contact with the sewage sludge as the sewage sludge leaves the dryer exceeds 80 degrees Celsius.

3. Heat treatment - Liquid sewage sludge is heated to a temperature of 180 degrees Celsius or higher for 30 minutes.

4. Thermophilic aerobic digestion - Liquid sewage sludge is agitated with air or oxygen to maintain aerobic conditions and the mean cell residence time of the sewage sludge is 10 days at 55 to 60 degrees Celsius.

5. Beta ray irradiation - Sewage sludge is irradiated with beta rays from an accelerator at dosages of at least 1.0 megarad at room temperature (ca. 20 degrees Celsius).

6. Gamma ray irradiation - Sewage sludge is irradiated with gamma rays from certain isotopes, such as 60 Cobalt and 137 Cesium, at dosages of at least 1.0 megarad at room temperature (ca. 20 °Celsius).

7. Pasteurization - The temperature of the sewage sludge is maintained at 70 degrees Celsius or higher for 30 minutes or longer.[58 FR 9387, Feb. 19, 1993, as amended at 64 FR 42573, Aug. 4, 1999]