Electron Beam Will Be a Disruptive Technology in the Environmental Industry – Wastewater and Drinking Water Industries

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eBeam Technology for Cleaning, Healing, Feeding, and Shaping this World and Beyond…

an International Atomic Energy Agency Collaborating Center for Electron Beam Technology

It's not a question whether eBeam technology will work in the environmental remediation industry.....

- Deer Island Wastewater Treatment Plant – 1980's
  - MIT, 400 m^3/day
- IMPELA, Ontario, Canada – 1980's
  - 50 kW, 100 mA, 10 MeV electrons, 2454 dry tons/year
- Virginia Key, Miami, Florida – 1990's
  - 75 kW, 50 mA, 1.5 MeV electrons, 4 kGy, 645 m^3/day
- 2011 – S. Korea – mobile demonstration eBeam system for wastewater disinfection (low energy /low dose)
- 2017 China – eBeam technology for reducing COD in dyeing industry wastewater (low energy/low dose)
  - (3000 m^3/day)
- 2021 China – eBeam technology for treating medical wastewater – 400 m^3/day (Dynamitron™ technology)

But why isn't it happening in a larger scale?
How do we make this technology truly disruptive?

- Many decision makers in the environmental industry do not understand this technology (at least in the US)

- When can this technology move from prototype to large scale? (> 100 million gallons/day volumes)?

Outline

- Changing views of biosolids
- Response of microbial pathogens in sludges and effluent to eBeam doses
- Enhancing methane production by eBeam technology
- Economics of eBeam technology (sludge treatment)
- What is needed in terms of technology and outreach?

Changing View of Biosolids Management

Sludge Disposal

Biosolids Beneficial Re-use

Bioenergy

Resource Recovery

1970 1993 2000 2005 2010

Contemporary View

- Municipal sewage are significant pools of energy substrates, nutrients, and water
- Wastewater Treatment Plants
- **Sustainable Resource Recovery Facilities**
  - Compelling need to exploit different technologies to extract as much of the energy, nutrients and water as possible from different waste-streams

eBeam Technology Applications for Wastewater Industry

Class A Biosolids

- EPA recognizes E-Beam as a PFRP process to generate Class A biosolids
- Effective against all types of microorganisms
- Microbe inactivation is terminal
- Microbes will not show any regrowth
- “Green technology” since no chemical is used
- Process takes only a few seconds
- Dose can be adjusted higher to achieve recalcitrant organic degradation

Bio-gas Production

- will break down organics and enhance microbial degradation in digesters
- will increase dewaterability
- will reduce viscosity thereby increasing digester efficiency
- Could potentially reduce digester residence time
- Digester product will be Class A and stabilized
- Significantly lower costs than commercial processes in the market

Effluent Treatment

- Significant disinfection capability
- Chemical-free “green technology”
- E-Beam will destroy estrogenic compounds in effluent at appropriate doses
- E-Beam can replace multiple technologies in effluent treatment
- Same equipment can be used to treat sewage sludge and effluent provided appropriate product handling system is in place
- Ozone produced during e-beam generation can be used in conjunction with e-beam as an advanced oxidation treatment process

Microbial levels in biosolids

	Total Solids	Fecal coliforms (MPN/4 g)	E.coli (MPN/4g)	*Salmonella* spp (MPN/4g)	Aerobic spores (CFU/4 g)	*Clostridium* sp., (CFU/4 g)	Enterococci (MPN/4 g)
College Station							
Sample # 1	3.7 %	28.1	28.1	Bd*	1.7×10^7	2.9×10^4	$> 2.4\times 10^4$
Sample # 2	2.8%	2.2×10^7	42.9	<0.93	2.20×10^7	1.4×10^5	$> 2.4\times 10^4$
Sample # 3	3.1%	5.2	51.8	<0.84	2.2×10^8	1.5×10^5	$> 2.4\times 10^4$
Sample # 4	3.1%	NA	52.1	0.94	4.7×10^7	Bd**	$> 2.4\times 10^4$
Sample # 5	2.8%	8.4	47.7	2.93	2.9×10^7	2.1×10^4	$> 2.4\times 10^4$
TAMU							
Sample # 1	2.4%	$>1.8\times 10^3$	2.7×10^3	1.2	4.8×10^7	2.9×10^4	$> 2.4\times 10^4$
Sample # 2	3.4%	1.9×10^3	1.1×10^3	1.69	1.0×10^8	1.3×10^7	$> 2.4\times 10^4$
Sample # 3	3.4%	1.9×10^3	1.9×10^3	0.84	5.6×10^8	7.4×10^6	$> 2.4\times 10^4$
Sample # 4	3.6%	$>1.6\times 10^3$	$> 1.6\times 10^3$	5.52	2.5×10^7	7.7×10^4	$> 2.4\times 10^4$
Sample # 5	3.5%	$>1.6\times 10^3$	$> 1.6\ X\ 10^3$	7.95	5.5×10^7	3.6×10^5	$> 2.4\times 10^4$

Detection limit 0.84 MPN/4g for Salmonella spp., and 1 CFU/4 g for Clostridium spp.

Target Virus levels in biosolids

	Total Solids	Somatic Coliphages (PFU/4 g)	Culturable Viruses (PFU/4g)
Texas location # 1			
Sample # 1	3.7 %	bd*	Bd*
Sample # 2	2.8%	3.3	Bd
Sample # 3	3.1%	5.9	Bd
Sample # 4	3.1%	bd*	Bd
Sample # 5	2.8%	bd*	Bd
Texas location # 2			
Sample # 1	2.4%	1.9×10^2	Bd
Sample # 2	3.4%	1.8×10^2	Bd
Sample # 3	3.4%	1.4×10^2	Bd
Sample #4	3.6%	1.5×10^2	Bd
Sample # 5	3.5%	2.0×10^2	Bd

**Detection limit = 1 PFU/4g*

eBeam-based Inactivation of Pathogens in Biosolids

Target Organism	Biosolid Matrix	D_{10} value (range) kGy	If 10 kGy is delivered
E.coli	Aerobic digester sample	0.26 – 0.41	24-log reduction
E.coli	Anaerobic digester sample	0.25 -0.35	28 log reduction
Spiked Salmonella sp.	Aerobic digester sample	0.18 -0.35	28 log reduction
Spiked Salmonella sp.	Anaerobic digester sample	0.23 -0.33	30 log reduction
Aerobic spores	Aerobic digester sample	2.43-4.81	2-log reduction
Aerobic spores	Anaerobic digester sample	2.68 – 3.08	3-log reduction
Anaerobic spores*	Aerobic digester sample	3.34-5.13	2-log reduction
Anaerobic spores*	Anaerobic digester sample	3.12	3-log reduction
Spiked Poliovirus	Anaerobic digester sample	2.6	~3.8 log reduction
Spiked Rotavirus	Anaerobic digester sample	1.5	7 log reduction

Enhancing Hydrolysis

- Thermal Hydrolysis Process (THP)
  - Cambi™ process
- Biological Hydrolysis
  - Acid phase digestion
- Mechanical Hydrolysis
- Chemical Hydrolysis

Cambi® Process (Thermal Hydrolysis)

- Process
  - High temperature: 150°C – 170°C
  - High pressure: 6-9 bars
  - Reaction time: 20-30 min
  - Dewatered sludge: 14% -17%

- Result
  - Decreased viscosity
    - Allows sludge mixing at higher concentration
    - Decrease digestion volume
  - Sterilized sludge
  - Improved anaerobic digestion
    - Increased volatile solids reduction
    - Improved biogas production
    - Reduced mass for further processing

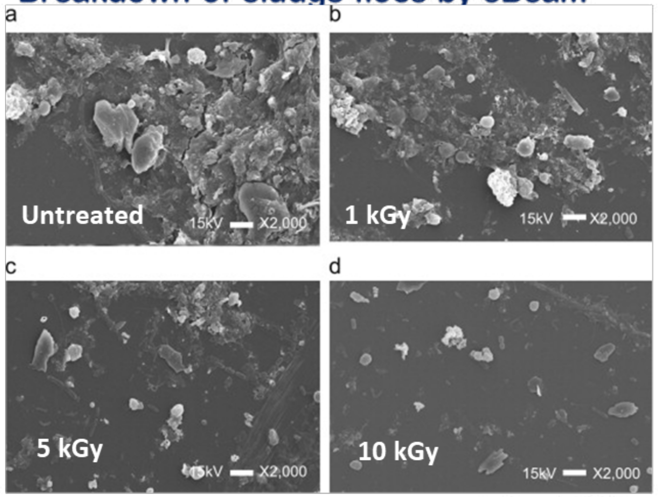
eBeam Technology for Energy Recovery from Municipal Sewage Sludge

- **Physico-chemical changes to sludge**

	Waste Activated Sludge			Thickened sludge		
Parameter	Control	3 kGy	6 kGy	Control	3 kGy	6 kGy
pH	6.41	6.28	6.17	6.28	6.20	6.06
COD_{sol} (mg/L)	52	828	1254	442	1560	1970
Soluble protein (mg/L)	14.4	306	397.3	62.4	383.8	559.0

Shin and Kang, 2003

Breakdown of sludge flocs by eBeam



Park et al., 2009

eBeam for Enhancing Methane Generation from Sewage Sludges

ANAEROBIC DIGESTER A CONTROL – NO eBeam TREATMENT	20 days	15 days	10 days
OLR (g COD_{sol} / [L.d])	50.3	62.0	87.0
Influent VS (%)	1.92	2.15	1.81
VS Removal (%)	36.7	32.5	22.3
Biogas (L/ [m3.d])	82	95	65

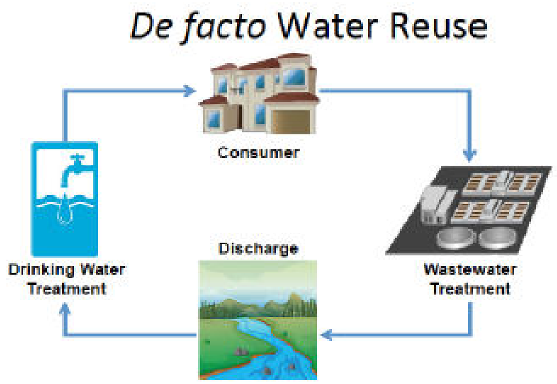
ANAEROBIC DIGESTER B eBEAM Treatment – Dose 1 kGy	20 days	15 days	10 days
OLR (g COD_{sol} / [L.d])	87.9	110.9	143.6
Influent VS (%)	1.91	1.96	1.83
VS Removal (%)	51.4	42.0	30.2
Biogas (L/ [m3.d])	155	180	175

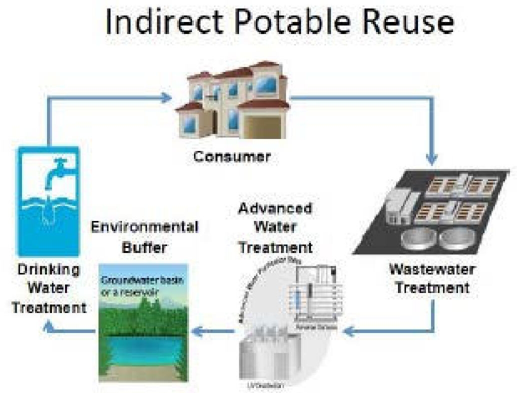
ANAEROBIC DIGESTER C eBEAM Treatment – Dose 3 kGy	20 days	15 days	10 days
OLR (g COD_{sol} / [L.d])	102.5	149.8	198.5
Influent VS (%)	1.88	1.91	1.85
VS Removal (%)	56.7	48.1	32.3
Biogas (L/ [m3.d])	230	260	235

ANAEROBIC DIGESTER D eBEAM Treatment – Dose 6 kGy	20 days	15 days	10 days
OLR (g COD_{sol} / [L.d])	114.5	163.7	224.1
Influent VS (%)	1.90	1.89	1.85
VS Removal (%)	60.3	50.4	38.2
Biogas (L/ [m3.d])	236	290	231

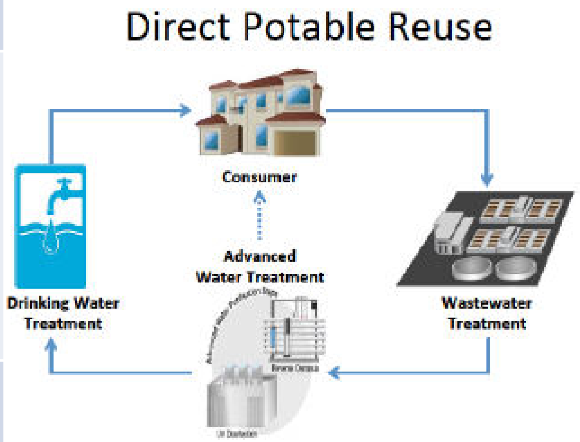
Shin and Kang, 2003

Water Reuse Challenges



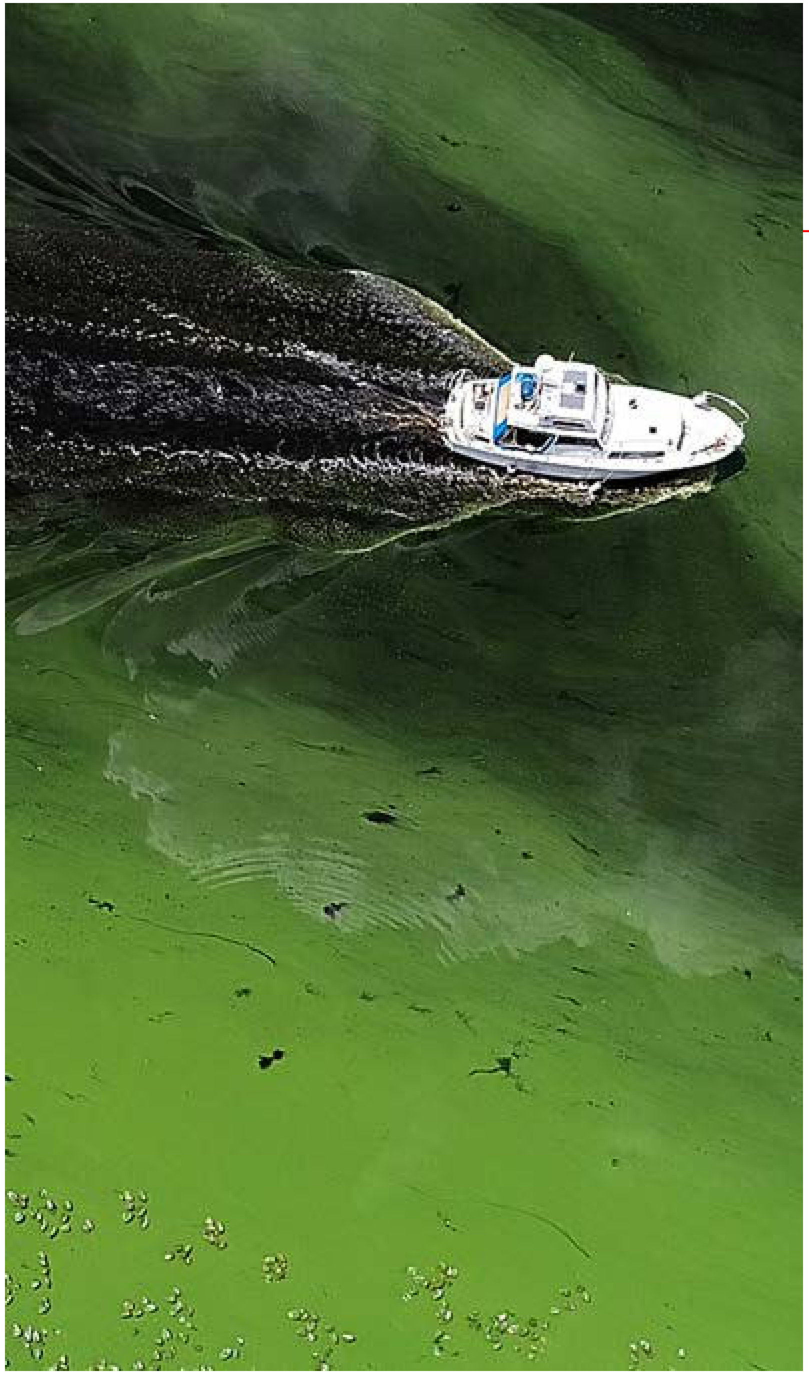


Chemical Contaminants	Microbial Contaminants
Disinfection byproducts (bromoform, bromate, chloroform, trihalomethanes)	Enteric viruses (rotavirus, noroviruses, hepatitis A virus)
Household products and industrial waste streams (Bisphenol A, perfluorooctanoic acid –PFOA and perfluorooctane sulfonic acid –PFOS)	Enteric bacterial pathogens (*Salmonella* spp., toxigenic *E.coli*, *Listeria spp.*
Household waste streams (antibiotic residues, estrogenic compounds, β-estradiol)	Pathogens during epidemics and pandemics (coronaviruses, *V. cholerae*)
	Protozoan parasites (*Cryptosporidium* sp., *Giardia* sp.



eBeam Pathogen Inactivation in Wastewater Effluent

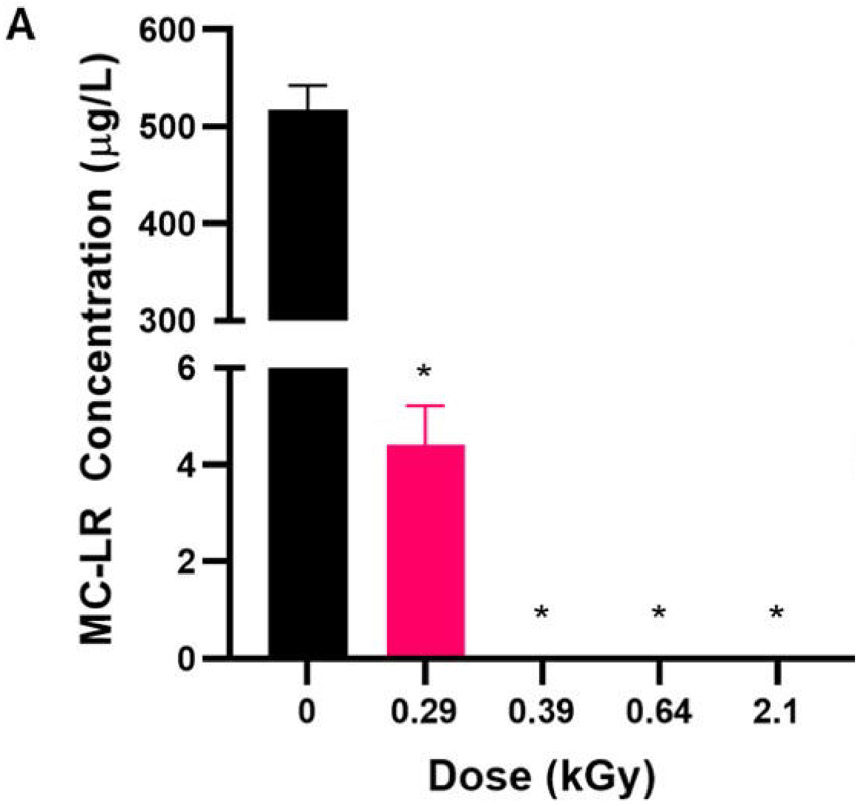
	Mean D_{10} Value (kGy)	Log_{10} Reduction Levels		
Pathogen		1 kGy	5 kGy	10 kGy
Bacterial cocktails				
Salmonella	0.156 ± 0.03^{A}	5.92	29.62	59.25
Shigella	0.097 ± 0.02^{B}	10.02	50.10	100.20
Aeromonas	0.066 ± 0.01^{C}	15.09	75.45	150.92
Viruses				
Hepatitis A Virus	4.386 ± 0.34^{D}	0.23	1.14	2.28
Murine norovirus	3.769 ± 0.19^{E}	0.27	1.33	2.65
Rotavirus	1.449 ± 0.15^{F}	0.69	3.45	6.90
Protozoa				
C. parvum	0.032 ± 0.002^{G}	30.96	154.80	309.60



nrdc.org; miamiherald.com

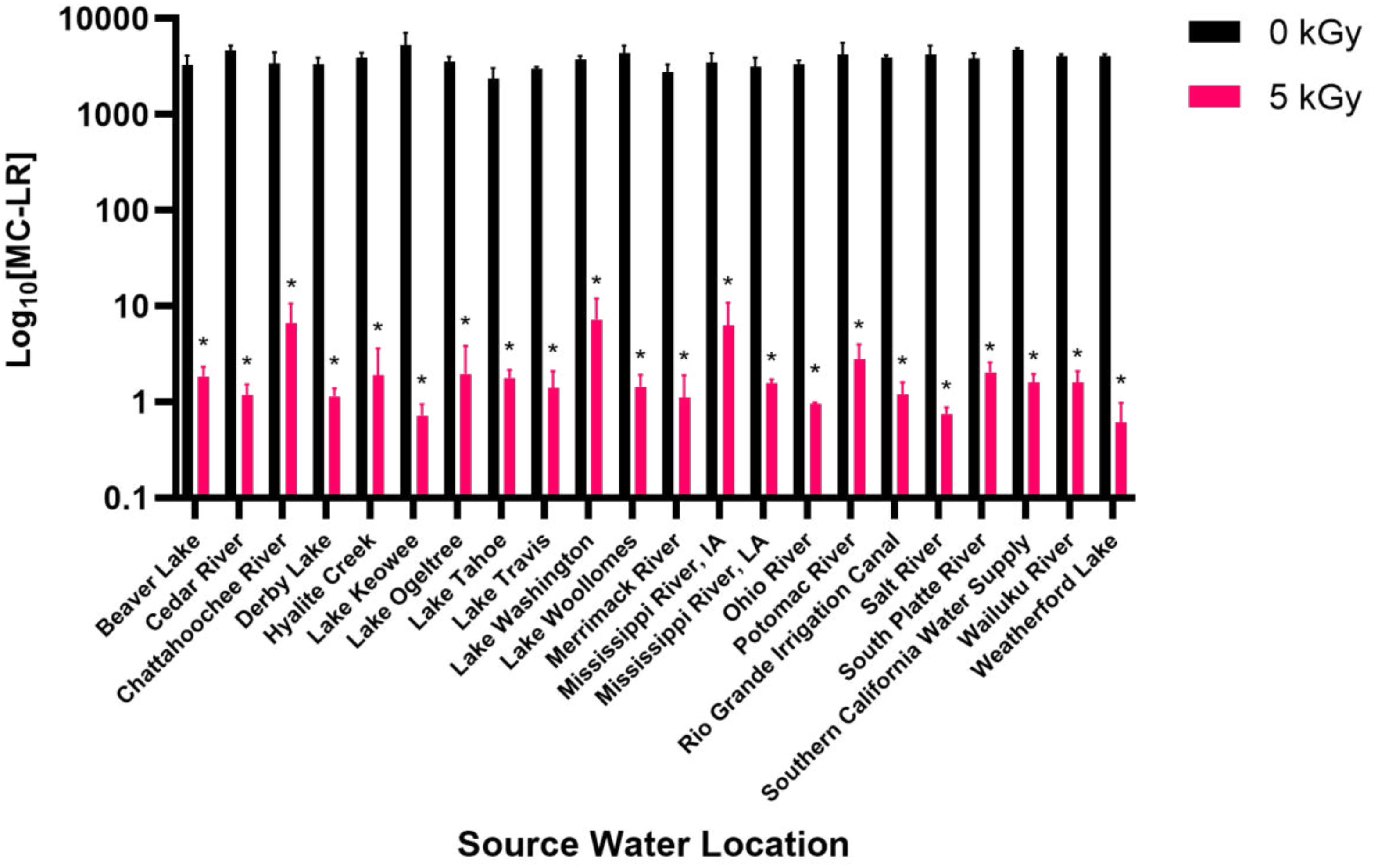
MC-LR is Degraded at Low eBeam Doses

- Initial MC-LR degradation via LC-MS/MS
  - Pure water
  - Doses >0.3 kGy <LOD
  - 0.3 kGy ~85% reduction in MC-LR



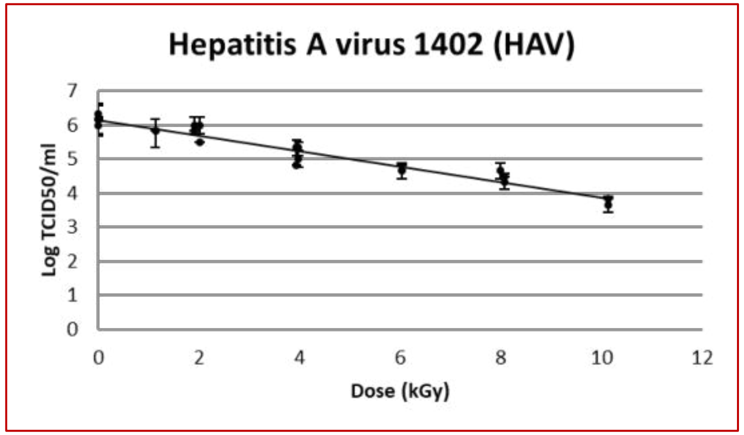
Folcik, et al. (2021) *Rad. Phys. Chem.*

eBeam Degrades MC-LR in Surface Water

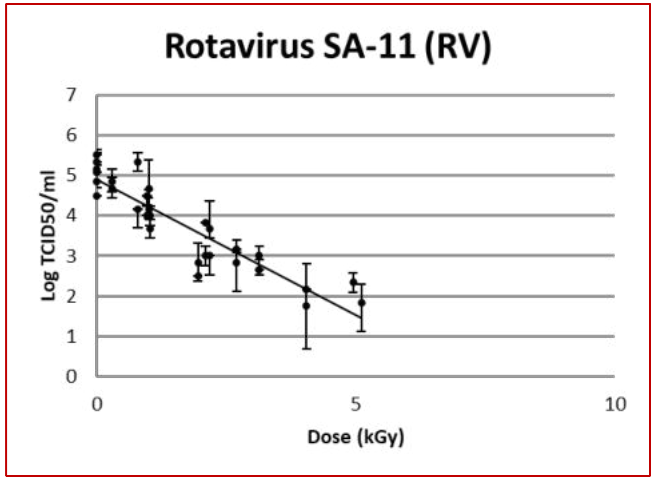


- MC-LR degradation exceeded 99% in all samples
- No trends observed between water quality and degradation

eBeam for Water Reuse by Destroying Pollutants



Pillai and Reimers WERF Report 2009



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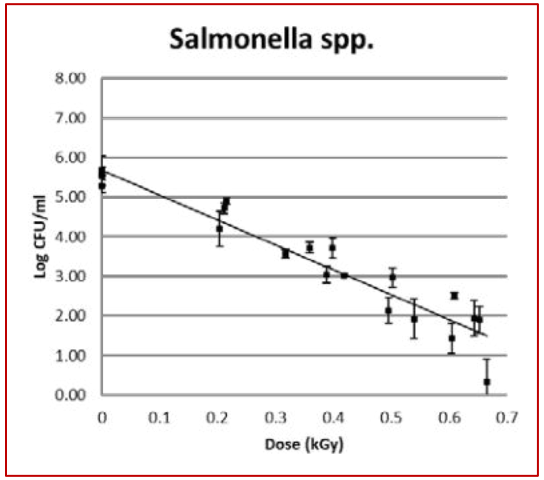

Pillai and Reimers WERF Report 2009

Pathogen	Water Reuse Target	eBeam dose that can achieve Water ReuseTarget
Viruses	8-log reduction	15 kGy
Cryptosporidium oocysts	5.5 log reduction	2 kGy
Giardia cysts	6 log reduction	2 kGy
Coliform bacteria	9 log reduction	2 kGy

Comparison of e-Beam to Thermal Hydrolysis to Mesophilic Anaerobic Digestion (MAD) in US $ per dry ton

Process Scheme	10 MGD	10-100 MGD	100 MGD
E-Beam (100 kW) with Iron Stabilization	$ 440	$ 171	$ 132
E-Beam (100 kW) MAD Pre-treatment	$ 600	$ 331	$ 293
Alkaline Stabilization (open system)	$ 886	$ 808	$ 730
Alkaline Stabilization (closed system)	$ 665	$ 606	$ 548
Thermal Hydrolysis MAD Pre-treatment	N. A.	$ 662	$ 502
Thermal Hydrolysis MAD Post-treatment	N.A.	N.A.	$ 735
Anaerobic Digestion Class A	$ 810	$ 747	$ 590
Heat Drying utilized at Houston	$ 1,165	$ 809	$ 619
Neutralizer ™ Process	$ 518	N.A.	N.A.
Aerobic Digestion Class A	$ 780	N.A.	N.A.

Economic Analysis

Table 4: eBeam processing costs for biosolids of varying treatment plant throughputs

System	Capacity	Dry Tons/day	Capital Costs	Annual Amortization	Annual O&M	Total $/dt
eBeam	10 MGD /100kW	7dtpd	$3,323,350	$388,832	$366,168	$ 311
eBeam	50 MGD /100kW	35dtpd	$3,323,350	$388,832	$366,168	$ 62
eBeam	50 MGD /400kW	35dtpd	$7,635,053	$893,301	$581,753	$ 143
eBeam	100 MGD /400kW	70dtpd	$7,635,053	$893,301	$581,753	$ 72

Economic Justification for Disruption

Table E1: E-*beam process coupled with stabilization (dollars/dry ton)*

Capacity (mgd)	E-beam process	Dewatering	Thickening	Cost of Total Process
10	$ 311	$ 90	$ 39	$ 440
50	$ 63	$ 80	$ 28	$ 171
100	$ 32	$ 78	$ 23	$ 133

Table E3 *Comparison of the e-beam process costs if used for replacing the Cambi™ process prior to MAD (dollars/dry ton)*

Plant Capacity (mgd)	**Cambi™**	E-beam
50	$ 499	$ 251
100	$ 386	$ 215

Reimers, Pillai et al.,

Technology Gaps/Future Work

- High Energy, High power (> 1000 kW) eBeam equipment non-existent
- Process trains for handling high volume sludges, biosolids, effluent are still in their infancy
- The practitioners in the water and wastewater industry have limited information on the technology
  - Metcalf & Eddy – Disinfection section has NOTHING about Ionizing Technology
- Need more facilities around the world as proof that the technology does indeed work

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http://ebeam-tamu.org