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Water and Sediment Quality in Drinking Water Tanks Located Near the BELCO Generating Station, Bermuda

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Executive Summary

- This report provides an analysis of data from a survey of household water tanks in Bermuda, conducted in August-September 2020. The objective of the survey was to investigate the possible impact of BELCO emissions on water quality in houses close to the generating plant.

- Ten locations were chosen: eight in close proximity to the BELCO plant and two control sites some distance from the plant. Water samples were collected at all 10 locations. Sediment was collected from the two control sites and five of the locations close to BELCO.

- All sample collection was performed independently by BIOS personnel, and witnessed by representatives from BELCO, IEPC, and DENR. Personnel from Renew Ltd. assisted with water pumping and sediment removal.

- All chemical analyses were performed by a certified commercial laboratory (ISO/IEC 17025:2005 compliant). Microbiological analysis of water samples was undertaken by the Bermuda Department of Health.

- A suite of chemical parameters were analysed in water and sediment samples, with parameter selection guided by advice from DENR and the Bermuda Department of Health. Water samples were analysed for a standard suite of water quality indicators, including coliform bacteria, and for heavy metals, pesticides, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and polychlorinated dibenzodioxins and furans (PCDD/Fs – aka “dioxins”). Sediment samples were analysed for metals, PAHs and PCDD/Fs.

- No pesticides, VOCs, PAHs or PCDD/Fs were detected in any water samples, indicating that consumption of tank water at the locations studies does not pose a significant human health risk from these contaminants.

- The chemical water quality at all locations was "good". None of the chemical parameters exceeded any of the applicable Bermuda or U.S. primary or secondary Drinking Water Standard values, suggesting no human health risk is present from chemicals in water from the locations tested.

- The microbiological water quality at 90% of the locations was "poor", with the drinking water standards for Total Coliform Bacteria and/or *E. coli* bacteria being exceeded.

- Metals, PAHs and PCDD/Fs were detected in all tank sediment samples. The low level of detection of these same chemicals in the overlying water suggests that tank sediment is not a source of contaminants in tank water.

- The concentrations and ranges of most contaminants in sediment was similar to those observed in an island-wide survey of water tanks conducted in 2005. This previous study concluded that the profile of most metals in Bermuda tank sediment reflected that of local soils, indicating that local soil is a major source of tank sediment. The current findings thus suggest that BELCO emissions are not significantly contributing to contaminants in tank sediment.

- An exception to this was for the metals nickel (Ni) and vanadium (V) which were present in tank sediment at locations close to BELCO at levels elevated with respect to other locations in Bermuda which were measured in the 2005 study. This may indicate that BELCO might be a source for these chemicals in sediment. However, no human health risk arising from the presence of Ni and V is indicated.

- There is potential for ingestion of tank sediment and associated contaminants in drinking water if the tank sediment is disturbed and becomes suspended in the overlying water. A basic risk assessment was performed to assess critical levels of suspended sediment in tank water. This showed that a threshold of 25 mg/L of suspended sediment would result in a Primary Drinking Water Standard for benzo [a]pyrene being exceeded, and should be considered as a minimum value to protect human health. It should further be noted that this concentration of suspended sediment would likely result in visibly turbid water.

- The findings and conclusions for water tank sediment quality apply equally to water tanks across Bermuda, regardless of proximity to BELCO.

- **Recommendations:**

  1) Houses in Bermuda should be equipped with methods to reduce the introduction and accumulation of sediment in water tanks.

  2) All homeowners in Bermuda should ensure that they follow government guidance on maintaining water tanks to ensure a safe water supply.

  3) A better understanding of the potential impacts of contaminants in water tanks in Bermuda would be gained by systematically studying a small number of water tanks over an extended period of time to assess the cycling of sediment and the behaviour of contaminants during typical water use and recharge conditions.

- **List of Abbreviations used:**

BELCO	Bermuda Electric Light Company Limited	mg	milligram (10^{-3} g)
BIOS	Bermuda Institute of Ocean Sciences	mL	millilitre (10^{-3} L)
CDD	Chlorinated dibenzo-dioxin	na	not available or not applicable
CDF	Chlorinated dibenzo-furan	ND	not detected
cfu	Colony-forming units	NTU	Nephelometric Turbidity Units
DENR	Department of Environment and Natural Resources	OC Pesticides	Organochlorine Pesticides
DL	Detection Limit	PAH	Polycyclic Aromatic Hydrocarbon
DoH	Department of Health	PCB	Polychlorinated biphenyl
DW	Drinking Water	PCDD/F	Polychlorinated dibenzo-dioxins and - furans
DWS	Drinking Water Standard	PE	Polyethylene
EFSA	European Food Safety Authority	pg	picogram (10^{-12} g)
EPA	Environmental Protection Agency	PMCL	Primary Maximum Contaminant Level
g	gram	QA/QC	Quality Assurance/Quality Control
HDPE	High-density Polyethylene	RfD	Reference Dose
IEC	International Electrotechnical Commission	SMCL	Secondary Maximum Contaminant Level
IEPC	iEPC Engineering Services	TDI	Tolerable Daily Intake
IRIS	Integrated Risk Information System	TEF	Toxicity Equivalency Factor
ISO	International Organization for Standardization	TEQ	Toxic Equivalency
kg	kilogram (1000 g)	VOC	Volatile organic compound
L	Litre (1000 mL)	WHO	World Health Organisation
MAL	Maximum Acceptable Levels	µg	microgram (10^{-6} g)

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Owing to concerns about the quality of rainwater-harvested drinking water that is collected and stored in cisterns ("tanks") at properties in proximity to the BELCO power generating station, water and sediment from water tanks were sampled in August and September 2020 for chemical analysis.

1 - Sampling

A total of 10 locations were used for water samples (Table 1), and seven of these were also used for sediment samples. Sample locations were determined by input from DENR in response to reports from occupants of soot fallout, and by selection of control locations to provide an indication of "background" conditions. Eight of the locations are in close proximity to the BELCO station, and comprise of a former school now used as a community centre, one current school, and six private residences. The final two locations (numbers 9 and 10) are more distantly located and were selected as control sites. The water tanks at all locations had not been recently cleaned by BELCO in response to customer alerts, and thus could be expected to provide an accurate representation of rainwater harvested water (i.e. no auxiliary water supplies from groundwater or produced water) and also to provide sufficient sediment accumulation to enable sediment sampling to occur. On closer inspection during the sampling work, three of the locations (numbers 3, 4 and 5) were found to have insufficient sediment accumulation, and at least one of these tanks had recently been independently cleaned.

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Site id no.	Location	Date of water sampling	Date of sediment sampling
Test sites:			
1	Old Berkeley school	27/08/2020	03/09/2020
2	New Berkeley school	27/08/2020	03/09/2020
3	Berkeley Road	27/08/2020	n/a
4	Ocean Lane	27/08/2020	n/a
5	Ocean Lane	27/08/2020	n/a
6	Whitney Avenue	27/08/2020	16/09/2020
7	Langton Hill	27/08/2020	16/09/2020
8	Underhill Crescent	27/08/2020	16/09/2020
Control sites:			
9	Paget Post Office	27/08/2020	04/09/2020
10	Shorelands, Flatts	27/08/2020	04/09/2020

Table 1: Sampling locations and dates

Sampling was conducted independently by BIOS personnel, witnessed by representatives from BELCO, IEPC, and DENR. Personnel from Renew Ltd. conducted water pumping and sediment removal. All sampling methods were approved by DENR. The sampling methodology (details below) was based on methods previously used by BIOS scientists for tank water sampling efforts in Bermuda, and matched those performed in 2005 for an island-wide survey of tank water and tank sediment quality conducted at 112 and 36 private households, respectively.

Water tanks at all properties were accessed via an inspection hatch. Water was collected in pre-cleaned bottles supplied by the analytical laboratory (see Table 2). Bottles were either dipped by hand while wearing new nitrile gloves to avoid sample contamination, or by attachment to an aluminum pole, depending on the distance of the surface of the water from the access point. Sample containers with preservative were filled by manually decanting water from a corresponding clean container. Samples were also collected for analysis of the microbiological

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quality of water, using sample bottles provided by the Bermuda Department of Health (DoH), who also conducted the analysis of microbiological quality.

Water tanks used for sediment sampling were first inspected to assess the level of sediment accumulation to ensure that a representative sample could be collected. Tank sediment loading can be expected to be dependent on prior roof and tank maintenance. However limited information on roof and water tank maintenance was available. Residents at three locations (#'s 3, 4 and 8) reported roof cleaning and painting taking place in the three months prior to sampling, and at one location (# 7) in 2017. Three of the locations (#'s 3, 4, and 8) also had undertaken tank cleaning each in 2017, 2018 and 2020, respectively.

Sediment was collected from water tanks by lowering the water level sufficiently to allow a person to stand on the tank base to manually deploy a suction pool cleaner to remove sediment from the layer deposited on the bottom of the tank, producing a slurry. The pool cleaner effluent was directed into barrels or IBC totes which were then covered and the water-sediment slurry was allowed to settle for a number of days. Following settling of the sediment, the overlying water was removed by pumping and the accumulated sediment was manually sub-sampled into pre-cleaned containers supplied by the analytical laboratory (see Table 2) using pre-cleaned metal (for organics) or HDPE (for metals) utensils. All manipulations of sediment were conducted wearing new nitrile gloves to avoid sample contamination.

After filling, all sample containers were immediately labelled then double-bagged in PE "zip-lock" bags and stored in coolers with frozen freezer blocks. Samples for chemical analysis were transported to the BIOS laboratory where they were stored in refrigerators at 4°C. Samples for microbiological analysis were delivered to the DoH laboratories in person on the day of sampling (27 August 2020).

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For chemical analyses, the samples were shipped to the analytical laboratory in two batches: water samples on 31 August 2020 and sediment samples on 30 September 2020. Sample containers were packed in insulated cooler boxes with bubble wrap and freezer blocks that had been frozen at -80°C. Chain of custody forms were completed by BIOS personnel to record all sample information and these were dispatched with the samples. The containers were shipped using FedEx Priority Alert service to ensure that they would be kept refrigerated in the event of any delay during shipping.

The parameters for chemical analysis were determined by DENR in consultation with DoH. All chemical analyses were performed by Bureau Veritas Laboratories, Bedford, Nova Scotia, Canada. BV Labs are accredited by the Standards Council of Canada and conform with the requirements of ISO/IEC 17025:2005. All analytical results from BV Labs were sent in duplicate to BIOS, IEPC, BELCO and DENR. The full results for all analyses, including QA/QC and blank assessments, are provided in Appendix 1.

Analysis	Size	Type	Preservative	No. per site
Water:				
PCDD/Fs	1 L	Amber glass bottle	none	4
Mercury	100 mL	Clear glass bottle	HCl	4
Metals	120 mL	Plastic bottle	HNO_3	2
PAHs	250 mL	Clear glass bottle	none	4
PCBs/OC Pesticides	500 mL	Amber glass bottle	none	4
General Chemistry	250 mL	Plastic bottle	none	2
VOCs	40 mL	Clear glass vial	$NaHSO_3$	4
Sediment:				
PCDD/Fs	120 mL	Clear glass jar	none	1
Metals & PAHs	250 mL	Clear glass jar	none	1
Moisture	60 mL	Clear glass jar	none	1

Table 2: Analysis and sample container details

2 - Results

2.1 Water Quality

All measurements of PAHs (21 compounds), PCDD/Fs (16 compounds), PCBs and organochlorine pesticides (35 components), and VOCs (8 components) were below detection limits, meaning that these chemicals were not observed to be present in tank water.

In addition to these parameters, eleven metal elements were analysed in the water samples, along with the parameters hardness ($CaCO_3$), nitrate (NO_3^-), nitrite (NO_2^-), chloride (Cl^-), and pH. The results for these are shown in Table 3. For values below the detection limit (indicated by "ND"), a value of half of the detection limit has been used to calculate the mean value. This provides a conservative estimate of the average concentration for metals with low detection rates. Where applicable, maximum and minimum values of detected analytes are also provided. Of the 11 metals analysed, 5 (Sb, As, Fe, Pb and Hg) were below the analytical detection limit in all samples and the minimum values have been reported as half the detection limit (i.e. DL x 0.5).

Table 3 also shows the drinking water standards as defined by the Government of Bermuda's Ministry of Health and by the U.S. Environmental Protection Agency (EPA) under the U.S. Safe Drinking Water Act (US EPA, 2021a). Both of these schemes include primary and secondary drinking water standards. In Bermuda, Maximum Acceptable Levels (MAL) are not routinely monitored or legally enforced. In the U.S. level, the Primary Standards (PMCLs) are legally enforceable federal standards that apply to all public water systems in the USA and define the maximum legal limit for a contaminant in drinking water (individual U.S. states can enforce their own more stringent standards). The standards reflect the level that: a) protects human health; and b) water supply systems can achieve using the best available technology. The Bermuda Aesthetic Quality standards and the U.S. Secondary Standards (SMCLs) are guidelines for aesthetic considerations of drinking water, such as taste, color, and odor; these contaminants are not considered to present a risk to human health at the limits designated.

The Bermuda and U.S. standards are very similar, with the following exceptions:
1) inclusion of a secondary standard for hardness ($CaCO_3$) in the Bermuda standards;
2) inclusion of primary standards for nitrite, antimony (Sb) and copper (Cu) in the U.S. standards;
3) the assessment of coliform bacteria is different in the Bermuda and the U.S. EPA methods.

None of the chemical parameters measured exceeded any of the applicable Bermuda or U.S. drinking water standard values, suggesting that these chemicals do not pose a human health risk from consuming water from these sources.

However, the microbiological quality at nearly all locations was poor, with the Bermuda MAL for Total Coliform Bacteria being exceed at 90% of locations, and the *E. coli* bacteria MAL being exceeded at 80 % of locations. Notably, location #2, the New Berkeley School, did not exceed either of the microbiological MAL values. Guidance from the DoH indicates that the water tanks at the 9 failing locations should be chlorinated to eliminate bacterial contamination.
These findings are consistent with previous studies that have found a high incidence of microbiological contamination of water tanks in Bermuda (Lévesque et al., 2008; Government of Bermuda, 2017), and further highlight the need for homeowners to follow government guidance and regulations governing water tank maintenance and cleanliness (https://www.gov.bm/sites/default/files/Safe%20Water%20-%202017.pdf).

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Location	Hardness (CaCO3)	Nitrate (N)	Dissolved Chloride (Cl-)	Nitrate + Nitrite (N)	Nitrite (N)	pH	Total Antimony (Sb)	Total Arsenic (As)	Total Cadmium (Cd)	Total Calcium (Ca)	Total Copper (Cu)	Total Iron (Fe)	Total Lead (Pb)	Total Magnesium (Mg)	Total Nickel (Ni)	Total Vanadium (V)	Total Mercury (Hg)	Total Coliform Bacteria	*E. coli* Bacteria
	mg/L	mg/L	mg/L	mg/L	mg/L	pH	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	cfu/100ml	cfu/100ml
Test sites:																			
#1	16	0.21	7.0	0.21	ND	7.39	ND	ND	0.01	5600	1.10	ND	ND	490	2.70	4.60	ND	>>4	>>1
#2	14	0.18	5.4	0.18	ND	7.33	ND	ND	ND	4900	ND	ND	ND	330	ND	3.00	ND	<1	<1
#3	20	0.18	3.5	0.18	ND	7.93	ND	ND	ND	7300	ND	ND	ND	330	ND	2.10	ND	>>4	2
#4	15	0.19	2.9	0.19	ND	7.19	ND	ND	ND	5500	ND	ND	ND	230	ND	3.10	ND	>>4	52
#5	24	0.25	15.0	0.25	ND	7.67	ND	ND	0.03	8800	0.63	ND	ND	620	ND	2.90	ND	>>4	2
#6	27	0.17	6.1	0.17	ND	7.84	ND	ND	ND	9800	0.92	ND	ND	540	ND	2.30	ND	>>4	46
#7	39	0.13	6.5	0.13	ND	7.73	ND	ND	ND	14000	ND	ND	ND	770	ND	4.10	ND	>>4	>>1
#8	17	0.22	3.8	0.22	ND	7.35	ND	ND	ND	6100	ND	ND	ND	340	ND	4.20	ND	10	<1
Control sites:																			
#9	36	0.29	9.4	0.29	ND	7.56	ND	ND	ND	13000	ND	ND	ND	740	ND	ND	ND	>>4	10
#10	25	0.24	4.2	0.24	ND	7.62	ND	ND	ND	9200	ND	ND	ND	440	ND	ND	ND	42	1
Mean	23	0.21	6.4	0.21	0.005	7.56	0.5	0.5	0.01	8420	0.44	25	0.25	483	1.2	2.8	0.007		
Min	14	0.13	2.9	0.13	na	7.19	na	na	0.01	4900	0.25	na	na	230	1.0	1.0	na		
Max	39	0.29	15.0	0.29	na	7.93	na	na	0.03	14000	1.10	na	na	770	2.7	4.6	na		
Bda DWS MAL		10						10	5.0				15				2.0	4	0
Bda Aesthetic	300		300			6.5-8.5					1000	300							
U.S. EPA PMCL		10			1.0		6.0	10	5.0		1300		15				2.0	5% [A]	
U.S. EPA SMCL			250			6.5-8.5					1000	300							

Table 3: Results of analysis of water samples.
ND = not detected; na = not applicable; Bda DWS MAL = Bermuda Drinking Water Standards – Maximum Acceptable Limit; Bda Aesthetic = Bermuda Drinking Water Standards – Aesthetic Quality limit; U.S. EPA PMCL = Primary Maximum Contaminant Level; U.S. EPA SMCL = Secondary Maximum Contaminant Level; mg/L = milligrams per litre; µg/L = micrograms per litre; cfu/100mL = number of colony-forming units in 100 mL of water; A: No more than 5.0% samples total coliform-positive in a month, and for water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month. See text for further details. Note different units.

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2.1.1 Comparison of Water Quality Results with Previous Results

Table 4 shows the mean, minimum and maximum water concentrations from the current study and the corresponding values for the same parameters determined in the 2005 island-wide survey of water tank quality in Bermuda (BIOS, 2006). It can be seen that the current values are very similar to those determined in 2005, and that the average 2020 values fall on the lower ends of the ranges determined in 2005. This suggests that the water sampled from tanks in this study can be considered to be representative of water from other tanks across Bermuda.

		2020			**2005**		
	Units	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Inorganics							
Hardness (CaCO3)	mg/L	23	14	39	na	na	na
Nitrate (N)	mg/L	0.21	0.13	0.29	1.6	<0.5	150
Dissolved Chloride (Cl-)	mg/L	6.4	2.9	15	15	0.69	920
Nitrate + Nitrite (N)	mg/L	0.21	0.13	0.29	na	na	na
Nitrite (N)	mg/L	*0.005*	ND	ND	na	na	na
pH	pH	7.56	7.19	7.93	7.81	6.93	9.53
Metals							
Antimony (Sb)	µg/L	*0.50*	ND	ND	0.82	0.4	2.9
Arsenic (As)	µg/L	*0.50*	ND	ND	<0.4	<0.4	1.8
Cadmium (Cd)	µg/L	0.01	0.005	0.034	<0.2	<0.2	0.4
Calcium (Ca)	µg/L	8420	4900	14000	13000	5400	120000
Copper (Cu)	µg/L	0.44	0.25	1.1	<1	<1	74
Iron (Fe)	µg/L	*25*	ND	ND	7.8	<5	330
Lead (Pb)	µg/L	*0.25*	ND	ND	0.15	<0.1	17
Magnesium (Mg)	µg/L	483	230	770	1000	300	47000
Nickel (Ni)	µg/L	1.2	1	2.7	<0.2	<0.2	2
Vanadium (V)	µg/L	2.8	1	4.6	2	<0.2	13
Mercury (Hg)	µg/L	*0.007*	ND	ND	<0.2	<0.2	0.5

Table 4: Comparison of 2020 mean tank water concentrations from Table 3 (N = 10 locations) with data from the 2005 island-wide survey of tank water quality (N = 112 locations). Italic = mean determined as DL x 0.5; ND = not detected; na = not available ($CaCO_3$ and nitrite were not determined in the 2005 study); mg/L = milligram (0.001 g) per litre; µg/L = microgram (0.000,001 g) per litre.

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2.2. Contaminants in Sediment

Sediment from the water tanks was analysed for the following suite of chemicals: metals, PAHs, and PCDD/Fs. Summarized results are shown in Tables 5 to 7 (the full results are presented in Appendix 1). For values below the detection limit (indicated by "ND"), a value of half of the detection limit has been used to calculate the overall mean value. This provides a conservative estimate of the average concentration for metals with low detection rates. Where applicable, maximum and minimum values of detected analytes are also provided.

	Acid Extractable Antimony (Sb)	Acid Extractable Arsenic (As)	Acid Extractable Cadmium (Cd)	Acid Extractable Copper (Cu)	Acid Extractable Iron (Fe)	Acid Extractable Lead (Pb)	Acid Extractable Mercury (Hg)	Acid Extractable Nickel (Ni)	Acid Extractable Vanadium (V)
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Test sites:									
#1	6.2	3.3	7.3	500	42000	1100	13.0	440	240
#2	3.1	7.5	1.1	340	24000	75	0.4	190	140
#6	3.5	7.1	2.0	220	14000	110	1.0	120	79
#7	ND	ND	0.8	130	8100	220	0.3	140	75
#8	4.2	9.1	1.1	280	18000	94	0.4	150	93
Control sites:									
#9	5.4	6.4	2.1	200	18000	160	1.2	22	25
#10	5.0	2.8	1.8	110	10000	92	1.3	95	55
Mean	4.1	5.3	2.3	254	19157	264	2.5	165	101
Min	1.0	1.0	0.8	110	8100	75	0.3	22	25
Max	6.2	9.1	7.3	500	42000	1100	13.0	440	240

Table 5: Results of analysis of metals in tank sediment. ND = not detected.

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	1-Methylnaphthalene	2-Methylnaphthalene	Acenaphthene	Acenaphthylene	Anthracene	Benzo(a)anthracene	Benzo(a)pyrene	Benzo(b)fluoranthene	Benzo(b/j)fluoranthene	Benzo(g,h,i)perylene	Benzo(j)fluoranthene	Benzo(k)fluoranthene	Chrysene	Dibenzo(a,h)anthracene	Fluoranthene	Fluorene	Indeno(1,2,3-cd)pyrene	Naphthalene	Perylene	Phenanthrene	Pyrene
	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Test sites:																					
#1	ND	ND	ND	ND	ND	0.40	0.49	0.71	1.00	0.53	0.32	0.32	0.81	ND	1.20	ND	0.35	ND	0.11	0.36	1.00
#2	ND	0.05	ND	ND	0.05	0.64	0.59	0.77	1.10	0.49	0.36	0.35	0.96	0.08	1.70	ND	0.34	ND	0.18	0.43	1.30
#6	ND	ND	ND	ND	ND	0.29	0.37	0.54	0.78	0.44	0.24	0.23	0.65	ND	0.89	ND	0.27	ND	ND	0.25	0.74
#7	ND	ND	ND	ND	0.04	0.25	0.22	0.28	0.41	0.21	0.13	0.13	0.36	ND	0.77	ND	0.14	ND	0.05	0.30	0.58
#8	ND	ND	ND	ND	0.04	0.28	0.34	0.54	0.78	0.40	0.24	0.22	0.62	0.05	0.95	ND	0.21	ND	0.08	0.31	0.75
Control sites:																					
#9	ND	ND	ND	ND	ND	0.30	0.32	0.58	0.81	0.47	0.23	0.21	0.68	ND	0.90	ND	0.20	ND	ND	0.34	0.81
#10	ND	ND	ND	ND	ND	ND	0.07	0.09	0.09	0.17	ND	ND	0.11	ND	0.16	ND	ND	ND	0.08	0.19	0.15
Mean	0.01	0.01	0.01	0.01	0.02	0.31	0.34	0.50	0.71	0.39	0.22	0.21	0.60	0.02	0.94	0.01	0.22	0.01	0.07	0.31	0.76
Min	na	na	na	na	0.01	0.01	0.07	0.09	0.09	0.17	0.01	0.01	0.11	0.01	0.16	na	0.01	na	0.01	0.19	0.15
Max	na	na	na	na	0.05	0.64	0.59	0.77	1.10	0.53	0.36	0.35	0.96	0.08	1.70	na	0.35	na	0.18	0.43	1.30

Table 6: Results of analysis of PAHs in tank sediment.
ND = not detected; na = not applicable.

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	2378-TCDD	Total Hexa-CDDs	TEQ
	pg/g	pg/g	pg/g
Test sites:			
#1	2.92	356	40.1
#2	0.67	259	31.7
#6	0.91	386	42.8
#7	0.26	55	6.1
#8	0.41	309	35.2
Control sites:			
#9	ND	310	32.7
#10	0.36	73	7.1
Mean	0.92	250	28.0
Min	0.26	55	6.1
Max	2.92	386	42.8

Table 7: Summary of results of analysis of PCDDs in tank sediment. These three categories are the PCDD/F metrics most often considered for human health assessment. ND = not detected; TEQ = Toxic equivalency factor; pg/g = picogram (0.000,000,000,001 g) per gram of sediment.

Note on PCDD/Fs and TEQ - Of the total possible 210 congeners of PCDDs and PCDFs, only the 17 congeners with chlorine substitutions in the 2, 3, 7, and 8 positions are considered to exhibit mammalian toxicity. Accordingly, the concept of a toxic equivalence (TEQ) was introduced to estimate total dioxin-like toxicity in a particular sample or system. This method is based on summing the relative toxicity of the 17 active dioxins and furans factored to the toxicity of 2,3,7,8- tetrachloro-dibenzodioxin, the most toxic dioxin chemical.

A TEQ is derived by multiplying the concentration of each active congener by a toxic equivalence factor (TEF) and has the same units as the concentration units (e.g. pg/g):

$TEQ = \Sigma_{n1}[PCDD_i \times TEF_i] + \Sigma_{n2}[PCDF_i \times TEF_i] + \ldots$

where: TEQ = toxic equivalence (e.g. in pg/g);
TEF_i = unitless toxic equivalence factor of PCDD/F congener I;
$PCDD_i/PCDF_i$ = concentration of PCDD/F congener i (e.g. in pg/g).

2.2.1 Comparison of Sediment Quality Results with Previous Results

A comparison of sediment quality data are shown in Table 8 for the same parameters determined in the 2005 island-wide survey of water tank quality in Bermuda (BIOS, 2006). As was observed for the water quality data, the 2020 values are very similar to the results from the 2005 study, and tank sediment sampled for this study can be considered to be representative of sediment from other tanks across Bermuda, with two exceptions: the mean values for Ni and V in the current samples exceeded the maximum values previously observed in Bermuda water tank sediment. This might be an indication that the BELCO emissions could be a source of these two metals: they are prominent in the BELCO exhaust emissions profile (BELCO, unpublished data), and it can be seen in Table 5 that Ni and V are present at higher concentrations in sediment from the five test locations closer to BELCO than the control sites, located some distance from the plant.

		2020			**2005**		
	Units	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**
Antimony (Sb)	mg/kg	4.1	1.0	6.2	0.38	<0.1	7.6
Arsenic (As)	mg/kg	5.3	1.0	9.1	3.9	1.3	21
Cadmium (Cd)	mg/kg	2.3	0.77	7.3	2.8	0.7	15
Copper (Cu)	mg/kg	254	110	500	110	34	720
Iron (Fe)	mg/kg	19157	8100	42000	14000	6800	190000
Lead (Pb)	mg/kg	264	75	1100	160	33	1100
Mercury (Hg)	mg/kg	2.5	0.28	13	0.98	0.09	30
Nickel (Ni)	mg/kg	165	22	440	49	13	130
Vanadium (V)	mg/kg	101	25	240	29	12	74
B[a]pyrene	mg/kg	0.34	0.07	0.59	0.04	<0.01	1.0
2378-TCDD	pg/g	0.92	0.26	2.92	0.62	0.05	39
Hexa-CDD	pg/g	250	55	386	310	25	8300
TEQ	pg/g	28	6.1	43	39	4.2	1300

Table 8: Comparison of 2020 mean tank sediment concentrations from Table 3 (N = 7 locations) with data from the 2005 island-wide survey of tank water quality (N = 36 locations). mg/kg = milligram per kilogram of sediment; pg/g = picogram (0.000,000,000,001 g) per gram of sediment.

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2.2.2 Assessment of Health Risk from Water Tank Sediment in Bermuda

There are no legislative limits in effect for the chemical quality of sediment in drinking water tanks in Bermuda or the USA. However, a simple health risk assessment was undertaken by considering how much sediment would need to be entrained in tank water to elevate the contaminants to a concentration that exceeds a Drinking Water Standard - i.e. what is the amount of suspended sediment in 1 litre of water that would result in a standard being exceeded? The results are shown in Table 9.

Contaminant	DWS	DWS Source	Average sediment concentration, (test sites only)	Suspended sediment threshold
	mg contam./L		mg/kg	mg sediment/L
Metals:				
Sb	0.005	UK DW Regulations	4.3	1163
As	0.01	US EPA and Bda Primary DWS	6.8	1471
Cd	0.003	WHO DW Guidelines	2.5	1200
Cu	1.0	US EPA and Bda Secondary DWS	294	3401
Fe	0.20	UK DW Regulations	21220	9
Pb	0.01	WHO DW Guidelines	320	31
Hg	0.002	US EPA and Bda Primary DWS	3.0	667
Ni	0.02	UK DW Regulations	208	96
V	NA		125	NA
Organics:				
B[a]P	1.0E-05	UK DW Regulations	0.40	25
2378-TCDD	3.0E-08	US EPA Primary DWS	1.0E-06	29126

Table 9: Suspended sediment thresholds for contaminants in water tank sediment. See UK (2021) and WHO (2021) for respective DWS values. NA = not available – no DWS for vanadium established. Note only sites # 1, 2, 6, 7 and 8 used (control sites # 9 and 10 not included).

For this assessment, the average concentration of contaminants in the test sites only were used (data from the control sites #9 and #10 were excluded). In each case, the most stringent DWS in effect has been used. For Fe, Ni and B[a]P, the UK Water Supply Regulations 2016 was used (UK Government, 2021), and for Pb the WHO Guidelines for Drinking-water Quality was used (WHO, 2017). For all others, the legal limits in the Bermuda or Federal U.S. drinking water legislation were used.

The results show that Primary Drinking Water Standards for benzo[a]pyrene, a toxic PAH compound, and the heavy metal lead (Pb), would be exceeded at suspended sediment concentrations of 25 and 31 mg per litre of water, respectively. A concentration of suspended sediment of 9 mg per litre of water would be sufficient to exceed a Secondary DWS for iron (Fe), leading to poor taste and discolouration of drinking water.

Turbidity is the measure of the degree to which the water loses its transparency owing to the presence of suspended particulates - the more total suspended sediment in water, the murkier it seems and the higher the turbidity. Turbidity is derived using a nephelometer instrument and is measured in Nephelometric Turbidity Units (NTU). There is no simple conversion between NTU and mg/L as it is dependent on a range of factors such as sediment particle size range, particle shape, colour, and mineralogy. Data for turbidity or suspended sediment concentrations in water tanks in Bermuda are not available. However, as a rough estimate 1 mg/L = 1 to 3 NTU; therefore, 9 mg/L suspended sediment is going to have a turbidity of around 9 - 27 NTU, which would be visibly turbid.

The US EPA Drinking Water Standards state: "Turbidity: For systems that use conventional or direct filtration, at no time can turbidity (cloudiness of water) go higher than 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least

95 percent of the samples in any month. Systems that use filtration other than the conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTUs."

Thus, tank water exceeding 9mg/L of suspended sediment would likely exceed the US EPA turbidity limits of 0.3 and 1.0 NTU, and furthermore, would be visibly turbid and likely rejected as drinking water. For reference, raw sewage has typical suspended sediment concentrations in the range 400-600 mg/L and septic tank outlets in the range of ~150 mg/L. It is essential to note that none of the tanks sampled for this study had discoloured or turbid water. Furthermore, none of these chemicals were detected in any of the water samples at levels above the applicable drinking water standard. Additional data on suspended sediment levels (turbidity) and behavior in drinking water tanks in Bermuda would contribute to a better risk assessment being made.

Given that ingestion is the most likely exposure pathway of tank sediment arising for people consuming tank water in Bermuda, it is also of use to compare the burden of concentrations of metals in tank sediment with the U.S. EPA's Reference Dose (RfD), the EPA's principal approach to and rationale for assessing risk for health effects (US EPA, 2021b), and the Tolerable Daily Intake (TDI) used by the European Food Safety Authority to assess human exposure via consumption of contaminants (EFSA, 2019). Both of these parameters are estimates of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a person's lifetime.

The results of this analysis are shown in Tables 10 and 11 below. The RfD and the TDI (column A) are in units of milligrams (mg) of contaminant per kilogram (kg) of body weight, and corresponding daily limits have been calculated for a representative 70 kg adult and 10 kg child (columns B and C). These daily limits represent the maximum daily limit of a contaminant which can be considered safe to ingest and assuming a life-time exposure (i.e. intake for every day of a person's life). The mean concentration of the contaminants detected in sediment at the test sites in this study (column D) is then applied to calculate a hypothetical maximum allowable amount of sediment by ingestion per person per day (columns E and F). *Note* – The body weights used are consistent with recommended current US EPA human health risk assessment procedures.

These results suggest that consumption of suspended tank sediment in water may present a human health risk from ingesting excess iron (Fe) for children if more than 0.38 g per day of sediment is ingested, and for adults if more than 2.6 g per day of sediment is ingested.

These results of tank sediment loadings in Bermuda are similar to previous findings from more than 100 private water tanks across Bermuda (BIOS, 2006), and highlight the need for home owners to follow government guidance on maintaining water tanks to ensure a safe water supply (Government of Bermuda, 2017): "Clean your tank as often as necessary to prevent sediment accumulation (by law every 6 years)".

Furthermore, and in common with the previous study, these latest results suggest that:
1) all rainwater harvested supplies of potable water in Bermuda should be equipped with measures to reduce suspended sediment (regardless of the proximity to BELCO), for example by considering the use of a range of techniques such as first-flush diverters and leaf guards, or through point-of-use or point-of-entry filtration systems;
2) further research is required to study suspended sediment in Bermuda water tanks - to establish the range and frequency of occurrence of any incidences of elevated loads and to examine the particle size ranges and chemical composition of suspended sediment.

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	A	B	C	D	E	F
	RfD EPA IRIS			**Avg sediment concentration (test sites only)**	**Max allowable sediment consumption:**	
	mg/kg-day	**70 kg adult mg/day**	**10 kg child mg/day**	**mg/kg**	**70 kg adult g/day**	**10 kg child g/day**
Metals:						
Sb	0.0004	0.028	0.004	4.3	6.5	0.93
As	0.0003	0.021	0.003	6.8	3.1	0.44
Cd	0.0005	0.035	0.005	2.5	14	2.0
Cu	na	na	na	294	na	na
Fe	na	na	na	21220	na	na
Pb	na	na	na	320	na	na
Hg	na	na	na	3.0	na	na
Ni	na	na	na	208	na	na
V	na	na	na	125	na	na
Organics:						
B[a]P	0.0003	0.021	0.003	0.40	53	7.5
2378-TCDD	7.0E-10	4.9E-08	7.0E-09	1.0E-06	47.6	6.80

	A	B	C	D	E	F
	EFSA TDI			**Avg sediment concentration (test sites only)**	**Max allowable sediment consumption:**	
	mg/kg-day	**70 kg adult mg/day**	**10 kg child mg/day**	**mg/kg**	**70 kg adult g/day**	**10 kg child g/day**
Metals:						
Sb	0.006	0.42	0.06	4.3	98	14.0
As	0.0003	0.021	0.003	6.8	3.1	0.44
Cd	3.6E-04	0.025	3.6E-03	2.5	10	1.4
Cu	na	na	na	294	na	na
Fe	0.8	56	8	21220	2.6	0.38
Pb	na	na	na	320	na	na
Hg	na	na	na	3.0	na	na
Ni	0.012	0.84	0.12	208	4.0	0.58
V	na	na	na	125	na	na
Organics:						
B[a]P	na	na	na	0.40	na	na
2378-TCDD	na	na	na	1.0E-06	na	na

Tables 10 and 11: Estimation of exposure risk via ingestion of water tank sediment in Bermuda using: i) Top - the US EPA reference dose values (RfD) from the US EPA Integrated Risk Information System (IRIS, 2020); and ii) Bottom - the European Food Safety Authority (EFSA) Tolerable Daily Intake (TDI) values (EFSA, 2019). Note only sites # 1, 2, 6, 7 and 8 used (control sites # 9 and 10 not included). na = not applicable – no RfD/TDI has been established for this chemical.

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3 – Dioxins in Water Tanks and in BELCO Soot and Stack Exhaust

PCDD/Fs are relatively chemically stable and they are found in the environment as complex mixtures of congeners. Variations in the profiles of PCDD/F congeners are a result of differences in: source emissions; physicochemical properties between congeners (e.g. aqueous solubility, volatility); and susceptibility to biotic and abiotic degradation. As a result, environmental mixtures of PCDD/Fs can exhibit spatial and temporal patterns which may be very different from the mixture released by any particular source. This makes difficult the unequivocal identification of sources of PCDD/Fs in the environment; however, the profile of congeners present can be considered a "fingerprint" to provide an indication of their likely source.

In addition to the water tank samples, a sample of soot from a composite sample from the exhaust systems of the BELCO North Power Station generating plant was also submitted for analysis of PCDD/F content. Figure 1 shows the PCDD/F congener profile for the sediment samples in this current study, as a proportion of the total PCDD/F content. It can be seen that the profile of PCDD/Fs in tank sediment is dominated by octa-CDD, with minor amounts of 1,2,3,4,6,7,8-heptaCDD and octa-CDF, whereas the BELCO soot profile has a very different profile, being dominated by 1,2,3,4,6,7,8-heptaCDD and octa-CDF, with minor amounts of other congeners.

Similarly, the profile of PCDD/Fs in tank sediments is different from the profile in BELCO stack exhausts. Data for generators E-4 and D-14 were obtained by isokinetic stack testing by a third party contractor in 2008, and the congener profiles are also shown in Figure 1 below. The PCDD/F congener profile from water tank sediment more closely resembles the emissions profile from vehicle exhaust, as shown in Figure 2 and also indicated in a previous study of tank sediment in Bermuda (BIOS, 2006).

These observations suggest that BELCO emissions are not a source of the PCDD/Fs in water tank sediment.

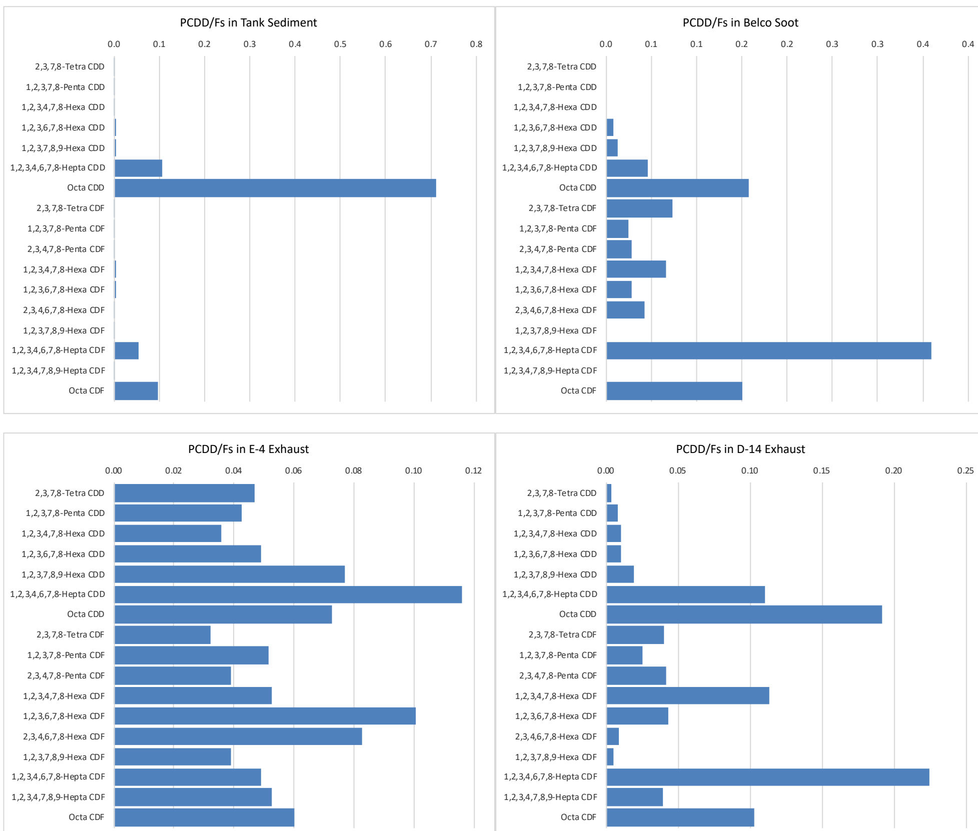

Figure 1: PCDD/F congener profiles for tank sediment (top left), BELCO soot (top right), and emissions exhaust from generators E-4 (bottom left) and D-14 (bottom right).

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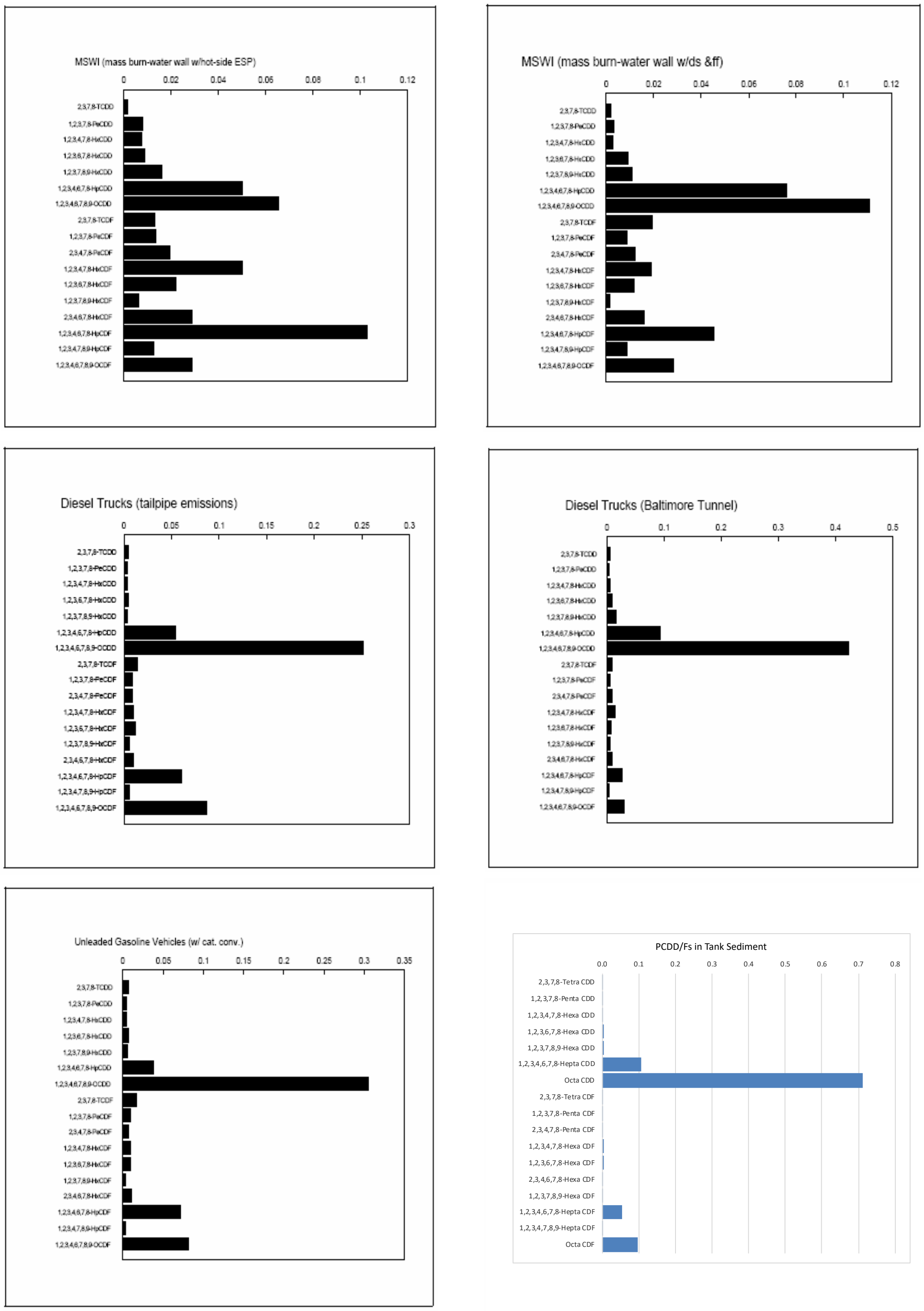

Figure 2: PCDD/F congener profiles for particular sources (from Cleverley *et al.*, 1997) and Bermuda tank sediment (this study - bottom right). ESP = electro-static precipitators; ds = dry scrubbers; ff = fabric filters.

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