COVANTA
Powering Today. Protecting Tomorrow.

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January 6, 2021

New Jersey Department of Environmental Protection
Bureau of Evaluation and Planning
401 E. State Street, 2nd Floor
Mail Code 401-07H
P.O. Box 420
Trenton, NJ 08625-0420

Subject: Condition (a) of Phase II, Section B of Administrative Consent Order EA ID# 200001-07736

Dear Sir or Madam:

The Administrative Consent Order ("ACO") entered into by Covanta Essex Company ("Essex") with the Commissioner of the New Jersey Department of Environmental Protection ("Department") included condition (a) of Phase II of Section B Compliance Schedule and several sub-conditions as follows:

1. Prior to conducting and modeling or health risk assessment COVANTA ESSEX COMPANY shall provide detailed estimates of all emissions associated with the purple plumes including, but not limited to, iodine and other associated acid gases and, the methodologies used to estimate the amount and duration of the emissions within 45 calendar days of the Effective Date of this ACO.
2. Within 90 calendar days of the Effective Date of this ACO but prior to conducting and modeling or health risk assessment COVANTA ESSEX COMPANY shall submit a written protocol that is prepared by an independent third party for DEP approval to the Bureau of Evaluation and Planning that is consistent with:
   a. Technical Manual 1002 Guidance on Preparing an Air Quality Modeling Protocol
   b. Technical Manual 1003 Guidance on Preparing Risk Assessment for Air Contaminant Emissions.
3. Once reviewed and approved by the Department, an independent third party shall conduct the modeling and risk assessment consistent with the protocol approval and submit results within 45 calendar days of Department approval.
4. If upon completion of DEP's review of the modeling and risk assessment identified in Phase 2, Paragraph a.3 of this ACO, there are verified findings that the emission of the purple plumes caused a non-negligible health impact (See NJDEP Division of Air Quality Technical

Manual 1003) to the public, Covanta shall disclose the findings to the public. In doing so, Covanta is encouraged to include posting the findings on its website. Covanta will disclose the non-negligible health impact within 5 days of receiving the verified findings.

As required under sub-condition 2 listed above, Covanta Essex Company shall submit a written protocol that is prepared by an independent third party for DEP approval to the Bureau of Evaluation and Planning within 90 calendar days of the Effective Date of this ACO. The attached protocol was prepared by AECOM, the third-party consultant for Covanta Essex Company, and is being submitted as required above.

If you have any questions or need any additional information please contact Patricia Earls of my staff at 973-817-7322 or pearls@covanta.com.

Sincerely,

David Blackmore
Facility Manager

cc: Richelle Wormley, NJDEP Air Enforcement (via Email)
Jeffrey Meyer, NJDEP Air Enforcement NRO (via Email)

"I certify under penalty of law that I have personally examined and am familiar with the information submitted in this letter and all attached documents and, based on my inquiry of those individuals immediately responsible for obtaining the information, I believe that the submitted information is true, accurate, and complete. I am aware that there are significant civil and criminal penalties, including the possibility of fine or imprisonment or both, for submitting false, inaccurate, or incomplete information."

David Blackmore
Facility Manager

1/6/21
Date

AECOM Environment

Prepared for:
Covanta Essex Co.
Newark, NJ

Prepared by:
AECOM
Chelmsford, MA
December 2020

Air Quality Modeling Protocol

Iodine Emissions Assessment for Covanta Essex County

AECOM Environment

Prepared for:
Covanta Essex Co.
Newark, NJ

Prepared by:
AECOM
Chelmsford, MA
December 2020

Air Quality Modeling Protocol

Iodine Emissions Assessment for Covanta Essex County

Prepared by Amanda MacNutt

Reviewed by Brian Stormwind

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1.0 Protocol Overview

Covanta Essex Company (Covanta Essex), a wholly owned subsidiary of Covanta Energy Corporation (Covanta Energy), operates the Essex County Resource Recovery Facility (the ECRRF or the Facility), under Program Interest Number 07736. The New Jersey Department of Environmental Protection (NJDEP) has required that Covanta Essex conduct a dispersion modeling analysis to assess the potential health impacts associated with iodine emissions from the Facility's Municipal Waste Combustion (MWC) units per the Consent Order dated 10/09/2020 (NJDEP 2020a).

Covanta is submitting this protocol to establish the dispersion modeling and health impact assessment approach as requested by NJDEP. The dispersion modeling assessment will be conducted consistent with the U.S Environmental Protection Agency's (USEPA's) Guideline on Air Quality Models (USEPA 2017) and NJDEP's Technical Manual 1002 dispersion modeling guidance (NJDEP 2018). The dispersion modeling methodology will generally be the same used in the March 2019 health risk evaluation conducted in support of the facility's Operating Permit renewal (AECOM 2019) that was approved by NJDEP. Details of the proposed methodology are provided in the following sections of this protocol.

1.1 Organization of the Protocol

This protocol sets forth all requirements considered to be applicable to the air dispersion modeling impact analysis. The remaining sections of the protocol include:

Section 2 – Regulatory Review describes the basis for the health effects benchmark for iodine that will be used to evaluate the dispersion modeling results.

Section 3 – Source Description provides descriptions of site location, evaluated sources, applicable air pollution controls, stack parameters and emission rates.

Section 4 – Modeling Approach describes the proposed modeling approach and model selection.

2.0 Health Effects Criteria

NJDEP's Risk Assessment Guidance (NJDEP 2018b) includes a list of air toxics for health risk assessment evaluation in its "Risk Screening Worksheet for Long-Term Carcinogenic and Noncarcinogenic Effects and Short-Term Effects" (NJDEP 2020b). However, iodine is not included in the Worksheet or in the list of Toxicity Values for Inhalation Exposure (NJDEP 2020c). Therefore, a review was conducted to identify available health benchmarks for iodine that can be used to assess potential inhalation health-risk associated with the maximum modeled concentrations.

The United States Department of Energy (DOE) has established Protective Action Criteria (PACs) that can be used to estimate the severity of the consequence of an uncontrolled release and for emergency planning purposes. The PAC-1 for iodine is 0.1 ppm (~1000 µg/m^3) (DOE 2018). The PAC-1 value is based on Emergency Response Planning Guidelines (ERPGs) produced by the American Industrial Hygiene Association (AIHA) and represents a level which does not pose a health risk to the community, but which may be noticeable due to slight odor or mild irritation. (AIHA 2006).

The Occupational Safety and Health Administration (OSHA) has compiled a side-by-side comparison of selected occupation exposure limits in their Table Z-1 (OSHA 2020). Table Z-1 lists 0.1 ppm as a Ceiling Limit or short-term exposure limit (STEL) for iodine for each of the following:

- OSHA Permissible Exposure Limit (PEL);
- California Division of Occupational Health and Safety (Cal/OSHA) PEL;
- National Institute for Occupational Health and Safety (NIOSH) Recommended Exposure Limit (REL);
- American Conference of Governmental Industrial Hygienists (ACGIH) short-term exposure limit (STEL);

These Ceiling Limits or STELs should never be exceeded at any time during the workday and are applicable to a healthy working population rather than a potentially sensitive general population. However, Ceiling Limits and STELs can be adjusted to establish 1-hour exposure limits for the general public with application of an additional safety factor. For example, this methodology is used by The New York Department of Environmental Conservation (NYSDEC) in deriving their Short-Term Guideline Concentrations (SGCs), used to evaluate the potential health effects from air toxics[1]. The NYSDEC SGC for iodine, 100 µg/m^3, was derived from the iodine ACGIH Ceiling Limit (~1000 µg/m^3) by dividing the concentration by an additional safety factor of ten (10) (NYSDEC 2016). The NYSDEC SGC for iodine (100 µg/m^3) is proposed as an appropriate health benchmark to use in evaluating the potential health effect of iodine emissions from the Covanta Essex facility.

[1] https://www.dec.ny.gov/chemical/106667.html; https://www.dec.ny.gov/docs/air_pdf/dar1.pdf

3.0 Source Description

Covanta Essex's ECRRF is an energy-from-waste (EfW) facility with three (3) identically sized independent MWC units. The MWC units each vent out of their own flue from a single stack structure with a height of 279 feet above grade elevation. The ECRRF is a major source subject to air permitting under N.J.A.C. 7:27-22, Operating Permits, as well as a major source of HAPs.

The ECRRF produces high temperature, high-pressure steam from the combustion of solid waste. The steam is utilized to generate electricity at the facility for sale to Public Service Electric and Gas and for in-plant use. Municipal solid waste (MSW) delivery hours are twenty-four (24) hours per day, Monday through Saturday. The Facility is permitted to combust MSW twenty-four (24) hours per day, 7 days per week, up to a maximum of 985,500 tons of solid waste per year.

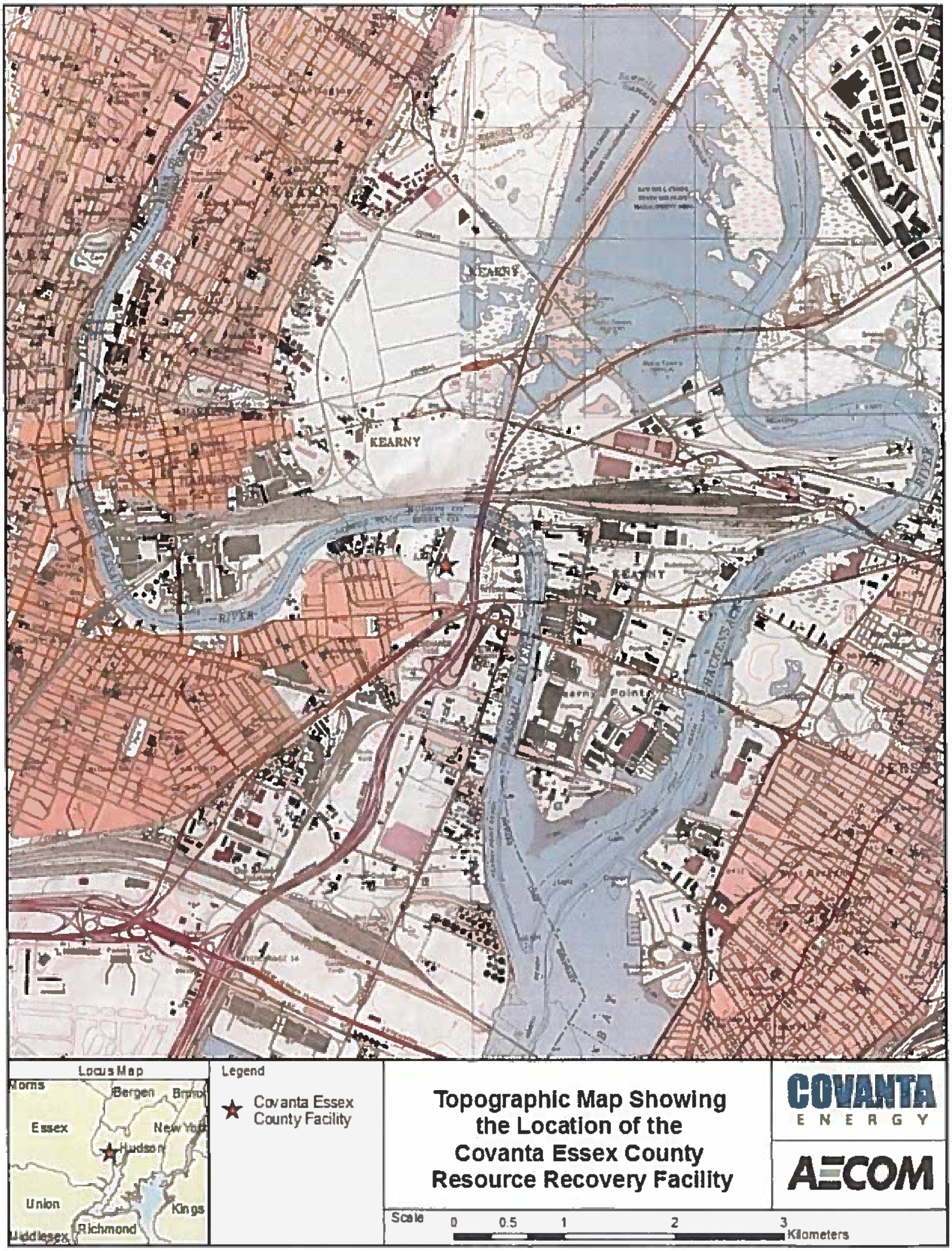
An original site plot plan of the ECRRF was provided with the 2019 risk assessment modeling report (AECOM 2019). There have been no changes to the site layout since the 2019 submittal. The various system operations are housed predominately in one main building structure consisting of: the tipping hall, the refuse storage bunker, the boiler building, the turbine- generator building, the residue processing facility, the residue bunker, and ferrous and non-ferrous metal storage areas, and the facility administrative offices. Auxiliary support buildings and equipment located separate from the main building structure include: the maintenance building, the induced draft fan control building, the air-cooled condensers, the air quality control systems, the scalehouse, the electrical switchyard, the activated carbon and lime storage silos, the aqueous ammonia storage tank, the raw water storage tank, the wastewater storage tank, the demineralized water storage tank, the condensate storage tank, and the No.2 fuel oil storage tank.

The three (3) MWC units for the combustion of waste, the generation of steam, and the handling of ash generated by the combustion process are the sources of HAPs at the facility. Each of the MWC units contains the following combustion equipment: a charging hopper which is loaded from the waste storage pit by overhead cranes, a feed chute, a ram feeder, roller grates, primary, secondary, and low NOx air systems, auxiliary fuel oil burners, and flues and ducts. Each MWC unit also includes the following steam generation equipment: economizer, main steam drum, the waterwalls (water-filled tubes that line the combustion chamber), a bank evaporator, a superheater, a spray attemperator, safety valves and blowdown tanks. The superheated steam produced at the facility is passed through two (2) turbine-generators to produce electricity. Each turbine-generator is rated at 36 megawatts ("MW"), for a total generating capacity of approximately 72 MW.

The ECRRF is located at 183 Raymond Boulevard, off of U.S. Routes 1/9 and the New Jersey Turnpike, in Newark, NJ (Essex County), as shown on **Figure 2-1**.

The subject of this modeling analysis is to conduct a health impact assessment of iodine emissions associated with plume opacity events that occurred on eleven days from January 2019 to February 2020.

Figure 3-1 Location of the Covanta Essex County Resource Recovery Facility



3.1 Iodine Emissions

Green Toxicology LLC analyzed continuous emissions monitoring system (CEMS) opacity data for fifteen (15) different plume opacity events related to iodine emissions that occurred over eleven (11) separate days (see **Table 3-1**). As documented in a technical memorandum prepared by Green Toxicology, see **Appendix A**, the iodine emission events were determined based on elevated % opacity values on a per-unit basis, and iodine emission rates were estimated from the measured opacity levels. For most of the eleven days, iodine emissions occurred from only one of the three units. However, four days included multiple events (iodine emissions from more than one unit). The Green Toxicology analysis developed 60-minute average emission rates for each event that will be used to model the events with the USEPA's AERMOD dispersion model. Further details regarding the development of the emission rates are provided in the documentation of the Green Toxicology analysis in **Appendix A**.

For each of the eleven "event days", 60-minute iodine emissions from all three units were summed to develop a total hourly emission rate from the stack for input to AERMOD. On days with more than one event (emissions occurring from more than one unit), it was conservatively assumed that any iodine emissions occurred during the same 60-minute period for all the units, even if the events were somewhat staggered and did not occur during the same hour.

Tables 3-1 and **3-2** present the hourly emission rates that will be modeled for each of the eleven event days.

3.2 MWC Stack Parameters

As noted, the ECRRF stack contains three (3) flues (each with a diameter of 7.54 feet), one for each MWC unit, that are housed in a single stack. **Table 3-1** (per unit data) and **3-2** (combined stack data) presents the stack parameters that will be modeled. The modeled diameter is based on the equivalent diameter corresponding to the number of units/flues operating during each event. The modeled stack exit velocity was calculated based on the equivalent diameter and the sum of the exhaust flow rates from each flue for the corresponding 60-minute opacity event. The modeled stack temperature was based on the flow-weighted average temperature using the average flow rate for each flue for the 60-minute event. Exhaust flow rate and temperature data for each event were obtained from the CEMS for each of the units (Covanta Essex 2020).

Note that in addition to the combined stack parameters and emissions rate to be modeled, **Table 3-2** also indicates the corresponding time period/hours of the associated meteorological data with the observed opacity events/iodine emissions. The model will be applied with the hourly emission rates and meteorological data specific to these hours, and the highest model result will be used to evaluate the impacts.

Table 3-1 Per Unit Stack Parameters and Emission Rates for Iodine Emission Event Days

DATE	1/14/2019	1/28/2019	5/2/2019	6/3/2019	6/16/2019	6/19/2019	6/24/2019	8/7/2019	9/20/2019	10/10/2019	2/5/2020
Unit 1 Flue Data											
60-min Event Start Time	**OFFLINE**	(3)	(2)	(2)	4:03	13:00	5:08	(3)	(3)	14:46	18:52
Avg Outlet Temp During Event (Deg F)	**OFFLINE**	301.9	299.4	284.7	300.0	303.3	295.3	299.2	305.8	297.5	311.6
Avg Flowrate During Event (ACFM)	**OFFLINE**	241074.3	230782.9	201627.1	201881.5	225614.9	236495.4	214730.1	237762.8	188519.7	199476.0
60-min Emission Rate (g/sec)	0	0	0	0	4.4	4.1(6)	8.6	0	0	12.4	3.7
Unit 2 Flue Data											
60-min Event Start Time	17:12	(3)	15:53	19:29	(1)	12:24	1:15	(3)	(3)	(1)	(1)
Avg Outlet Temp During Event (Deg F)	314.2	313.2	299.8	298.5	303.5	306.7	301.7	296.8	307.0	306.4	297.7
Avg Flowrate During Event (ACFM)	227413.5	259666.5	179571.7	150942.5	193995.7	204844.8	186399.9	234728.1	227034.1	240873.4	239980.9
60-min Emission Rate (g/sec)	7.2	0	4.8	11.4	0	27.0	6.4	0	0	0	0
Unit 3 Flue Data											
60-min Event Start Time	16:10	17:25	(2)	18:56	(1)	12:28	(1)	9:40	18:04	(1)	**OFFLINE**
Avg Outlet Temp During Event (Deg F)	315.9	303.2	301.2	291.5	297.8	301.8	300.6	288.5	298.0	303.1	**OFFLINE**
Avg Flowrate During Event (ACFM)	252503.6	223254.1	231412.2	200801.5	251624.4	239079.4	239766.6	231822.8	235187.8	236553.4	**OFFLINE**
60-min Emission Rate (g/sec)	8.2	15.2	0	7.2	0	23.0	0	6	6	0	0
Combined Stack Data (3 merged flues)											
Total Emissions (g/sec)	15.4	15.2	4.8	18.6	4.4	54.1	15.0	5.5	5.8	12.4	3.7
Stack Temp(4) (Flow-Weighted, F)	315.1	306.3	300.2	290.9	300.2	303.8	299.0	294.7	303.6	302.7	304.0
Total Flow (ACFM)	479917.1	723994.9	641766.8	553371.2	647501.6	669539.2	662661.9	681280.9	699984.7	665946.6	439456.9
Exit Velocity(5) (ft/sec)	89.62	90.08	79.85	68.85	80.56	83.30	82.45	84.77	87.09	82.86	82.07
Equivalent Diameter(5) (ft)	10.66	13.06	13.06	13.06	13.06	13.06	13.06	13.06	13.06	13.06	10.66

Notes:

(1) No emissions attributable to iodine occurred from this unit. However, since it was operating, the gas flow and flue gas temperatures were accounted for in the calculations of the exit velocity and stack temperature for the combined stack. Gas flow and temperature data correspond to the **Unit 1** event 60-min. period.

(2) No emissions attributable to iodine occurred from this unit. However, since it was operating, the gas flow and flue gas temperatures were accounted for in the calculations of the exit velocity and stack temperature for the combined stack. Gas flow and temperature data correspond to the **Unit 2** event 60-min. period.

(3) No emissions attributable to iodine occurred from this unit. However, since it was operating, the gas flow and flue gas temperatures were accounted for in the calculations of the exit velocity and stack temperature for the combined stack. Gas flow and temperature data correspond to the **Unit 3** event 60-min. period.

(4) Flow-weighted average temperature based on the average gas flow for each flue for the event duration.

(5) Based on an equivalent stack diameter. Equivalent diameter represents the diameter with an exit area equivalent to the sum of the area of the operating flues. The value is based on 3 units operating (3 flues) for all days except for 01/14/2019 and 2/05/2020 when only 2 units were operating, and the equivalent diameter is based on 2 flues. Each flue diameter is 7.54 feet.

(6) This event was not included in the Green Toxicology emissions report (see Appendix A) as Unit 1 did not experience an opacity excursion; however, since this was the worst-case event, it was conservatively assumed that iodine emissions from this unit were possible and emissions were estimated using the same methodology presented in Appendix A.

Table 3-2 Combined Stack Data for Input to AERMOD

Event Date	Event Start Time(1)	Meteorological Hours Modeled(2) (Hr 1, Hr 2)	Emission Rate (g/sec)	Stack Temp (K)	Exit Velocity (m/sec)
01_14_2019(3)	16:10(3)	17, 18, 19	15.4	430.4	27.3
1_28_2019	17:25	18, 19	15.2	425.6	27.5
5_2_2019	15:53	16, 17	4.8	422.1	24.3
6_3_2019	18:56	19, 20	18.6	417.0	21.0
6_16_2019	4:03	05, 06	4.4	422.2	24.6
6_19_2019	12:24	13, 14	54.1	424.2	25.4
6_24_2019	5:08	06, 07	15.0	421.5	25.1
8_7_2019	9:40	10, 11	5.5	419.1	25.8
9_20_2019	18:04	19, 20	5.8	424.0	26.5
10_10_2019	14:46	15, 16	12.4	423.6	25.3
2_5_2020	18:52	19, 20	3.7	424.3	25.0
Stack Height:	85.039 m				

Notes:

(1) 24-hour time.
(2) Meteorological hours run from 01-24 such that 0:00 = meteorological hour 01 and 23:00 = meteorological hour 24.
(3) Three hours were modeled for this day to fully capture in the model the span of events that began and 17:12 and 16:10 for Units 2 and 3, respectively.

4.0 Modeling Approach

Consistent with the 2019 health risk analysis, the USEPA's AERMOD dispersion model (version 19191) will be used to predict iodine concentrations ($\mu g/m^3$) for each of the event-days detailed in **Section 3.0.**

The suitability of an air quality dispersion model for a particular application is dependent upon several factors. For this study, four selection criteria were evaluated. The selection of AERMOD was based upon analysis of the following criteria:

- stack height relative to nearby structures;
- dispersion environment;
- local terrain; and
- representative meteorological data.

4.1 Good Engineering Practice (GEP) Stack Height Analysis

Good engineering practice (GEP) stack height is defined as the stack height necessary to ensure that emissions from the stack do not result in excessive concentrations of any air pollutant as a result of atmospheric downwash, wakes or eddy effects created by the source, nearby structures or terrain features. A GEP stack height analysis was conducted in 2018 with the USEPA's Building Profile Input Processor (BPIP) in accordance with USEPA's guidelines (USEPA, 1985). The location of the stack and buildings layout are shown in **Figure 4-1**. The GEP height for the modeled stack, H_{GEP}, was determined from the dimensions of all buildings which are within the region of influence:

$$H_{GEP} = H + 1.5L$$

where:

H = height of the structure within 5L of the stack which maximizes Hg, and

L = lesser dimension (height or projected width) of the structure.

For a squat structure, i.e., height less than projected width, the formula reduces to:

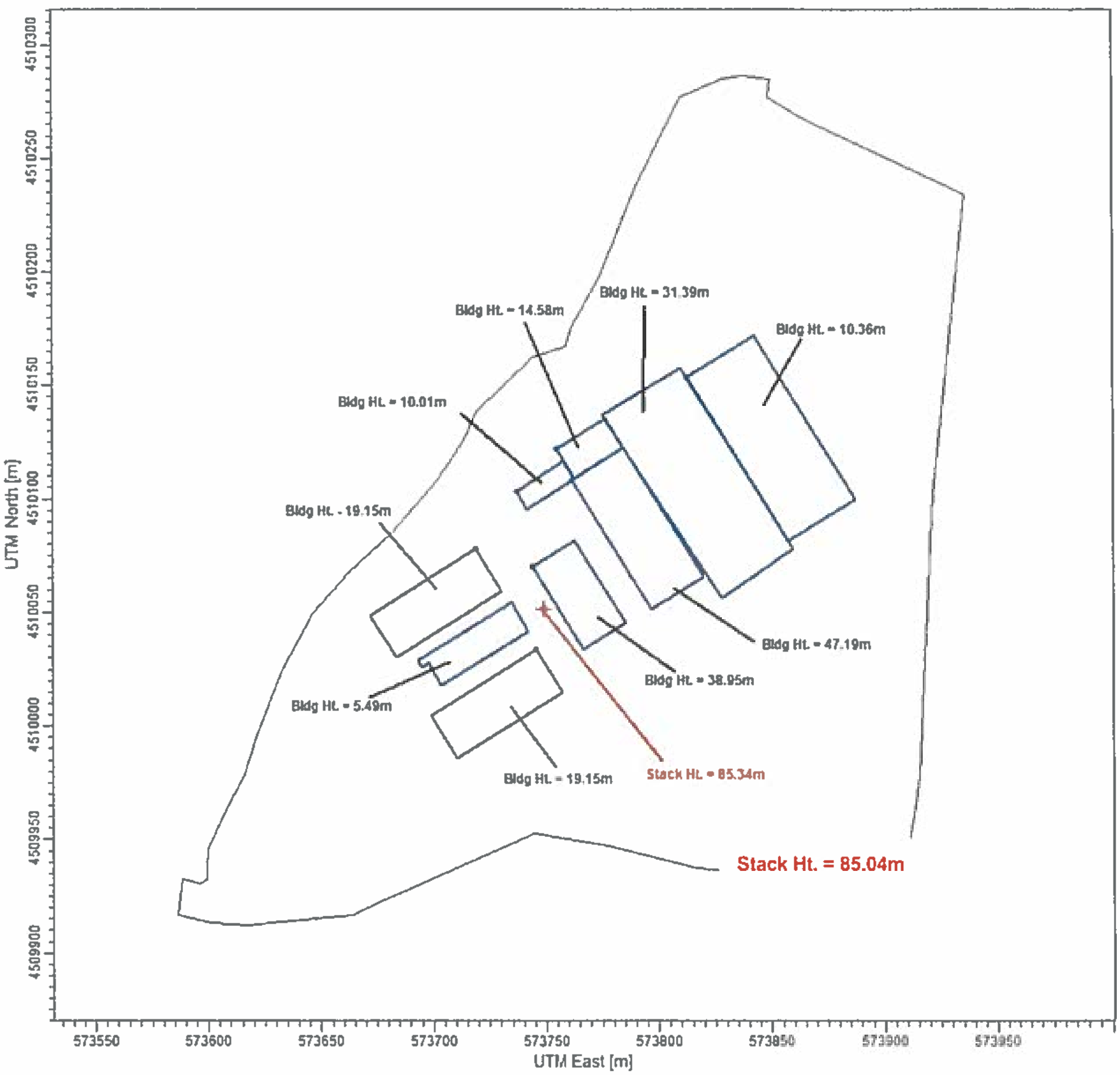
$$H_{GEP} = 2.5H$$

As required by AERMOD, the PRIME version of the BPIP program was employed. The direction-specific building dimensions generated by BPIP-PRIME for the2018 risk analysis will be used to model the iodine emission events in AERMOD. **Table 4-1** details the overall GEP summary.

Table 4-1 GEP Summary

Stack	Stack Height (m)	Building Height (m)	Maximum Projected Building Width (m)	Distance from Stack (m)	5L Distance (m)	Calculated Formula GEP Stack Height (m)
Combined 3 MWC Units	85.34	47.1 (Boiler Building)	66.48	41.0	235.5	118.02

Figure 4-1 GEP Figure



4.2 Dispersion Environment and Local Topography

The application of the AERMOD model requires characterization of the local (within 3 kilometers) dispersion environment as either urban or rural based on prevalent land use. According to USEPA modeling guidelines, if more than 50 percent of an area within a 3 kilometer radius of the proposed project is classified as rural, then rural dispersion coefficients are to be used in the dispersion modeling analysis.

Based on land-use information provided on United States Geological Survey (USGS) topographic maps and recent aerial photography, the area within 3 kilometers of the ECRRF is considered urban. Therefore, the urban option will be used in the application of AERMOD. Note that the urban option was also used in the air toxics modeling conducted in the 2019 (AECOM 2019). The population value to be used in AERMOD will be the 2019 population for Newark, NJ of 282,011 (U.S. Census Bureau 2020)

4.3 Meteorological Data

While the NJDEP typically provides applicants with AERMOD-ready meteorological data for use in dispersion modeling analyses, they have not yet processed a dataset that covers the 2019-2020 event periods. Therefore, the data will be processed specifically for this modeling analysis to prepare the meteorological data concurrent with the plume opacity/iodine emission events that will be modeled. Surface data from the National Weather Service (NWS) at Newark International Airport, NJ, and concurrent mixing heights from Brookhaven, NY will be processed with AERMET (version 19191) using methods and model options consistent with NJDEP processing. AERMET input files will be developed based on those used in the most recent NJDEP processing of Newark/Brookhaven data (NJDEP 2020d). Furthermore, AERMET will be run with surface characteristics obtained from the NJDEP-produced AERSURFACE output file for Newark.

The intent of the analysis is to model the hourly emission rate using meteorological data concurrent with the 60-minute event. However, because AERMOD can only estimate hourly concentrations for 60-minute periods beginning and ending at the top of the hour, the two consecutive "meteorological hours" that encompass each 60-minute iodine emission event will be modeled to determine the worst-case 1-hour modeled concentration. **Table 3-2** lists the two hours that will be modeled.

4.4 AERMOD Receptors

The same Cartesian receptor grid used in the 2018 health risk analysis will also be used to model the iodine emissions events. The grid consists of the following receptor spacing:

- Along the property boundary with 20 meters spacing;
- From the property boundary to 1 km with 70 meters spacing;
- From 1 km to 2 km with 100 meters spacing;
- From 2 km to 3 km with 250 meters spacing;
- From 3 km to 5 km with 500 meters spacing;
- From 5 km to 10 km with 1,000 meters spacing; and
- From 10 km to 20 km with 2,000 meters spacing.

Receptor height scales at each receptor location were developed for the 2018 analysis using AERMAP (version 18081), the terrain preprocessor for AERMOD. The receptor coordinates are referenced to North American Datum (NAD) 1983. The receptor grid is shown in **Figures 4-2** and **4-3**.

Figure 4-2 Near-Field Receptor Grid

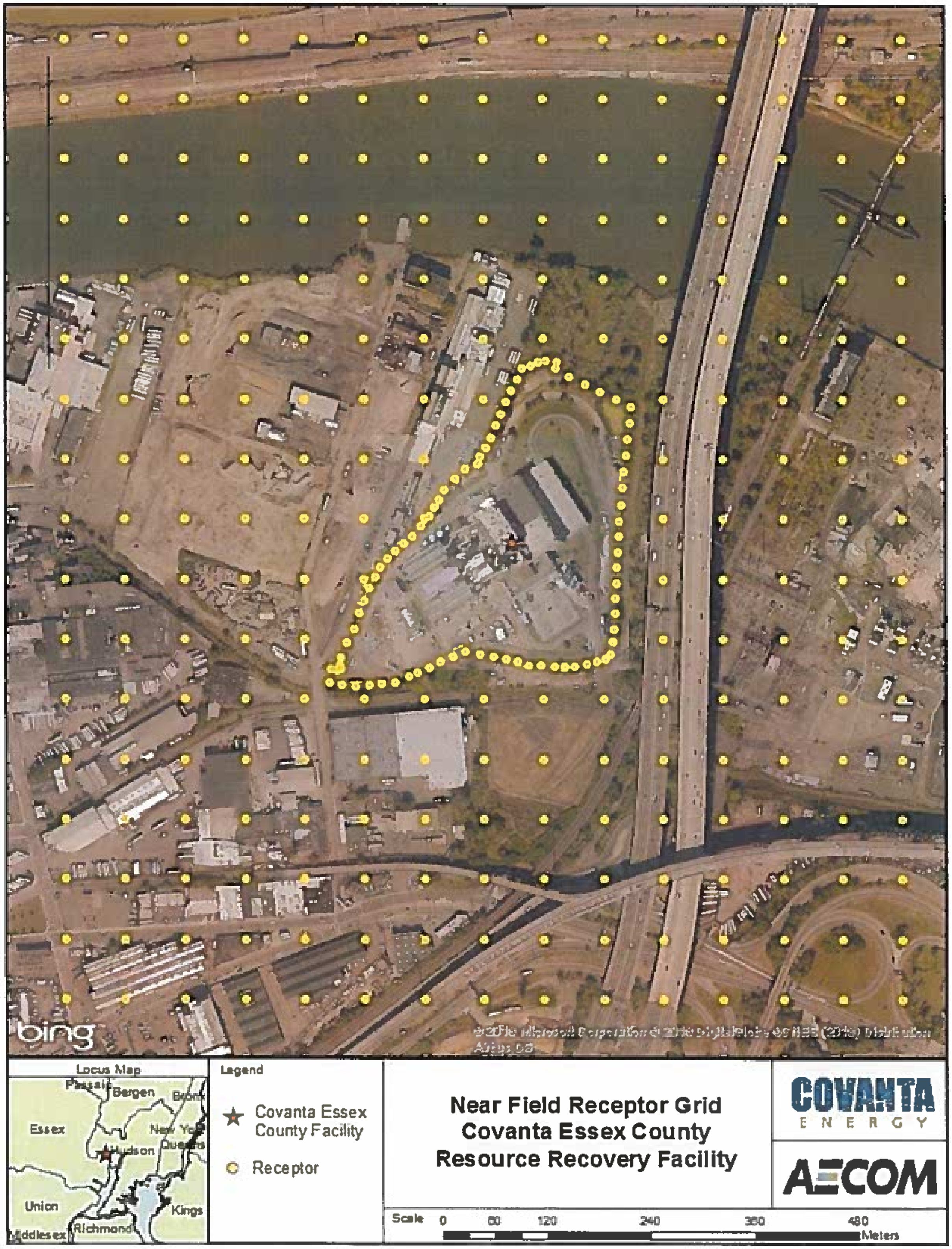
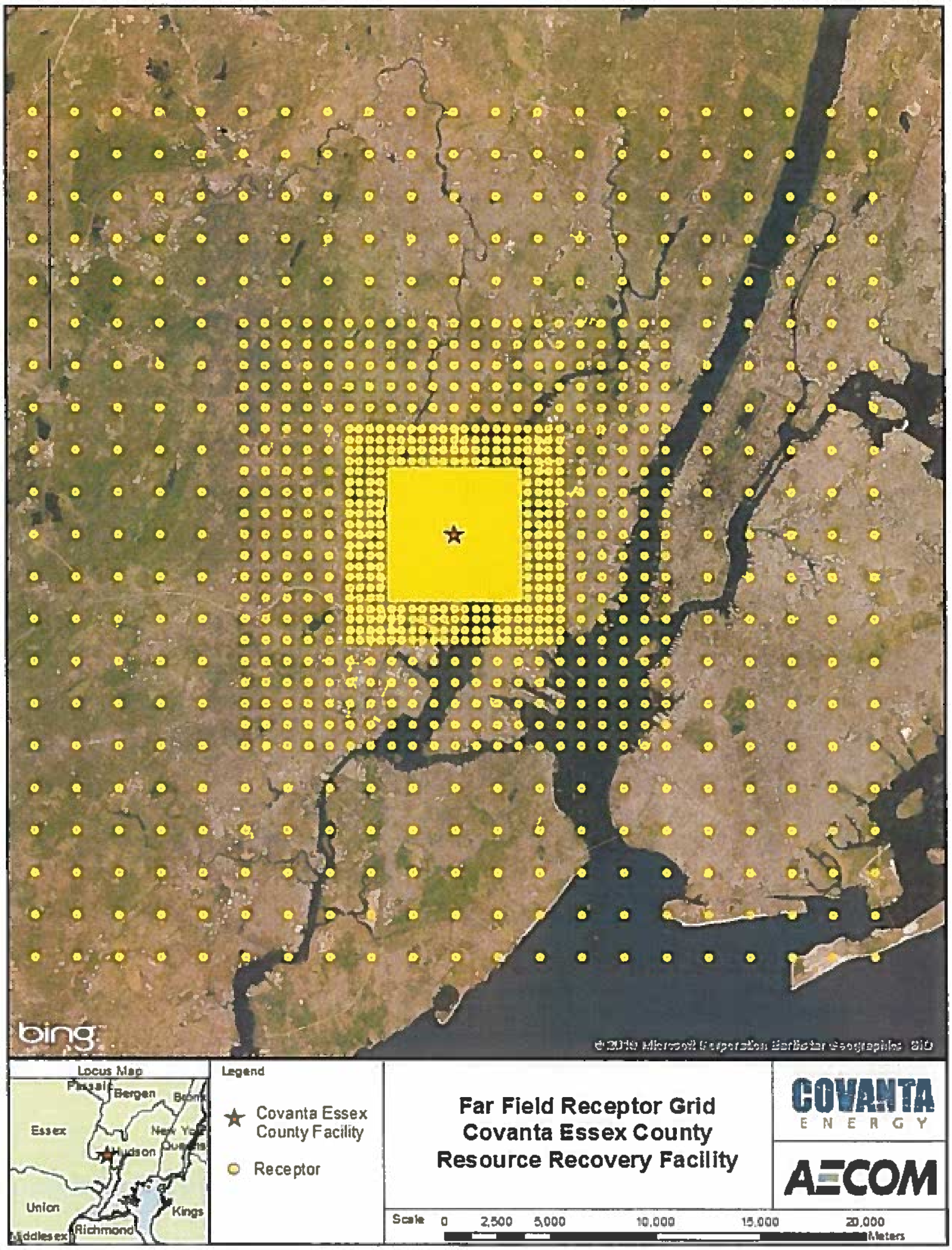


Figure 4-3 Far-Field Receptor Grid



4.5 Modeling Results

AERMOD will be applied for each event day/meteorological period with the corresponding source parameters and emission rates listed in Table 3-2. The maximum iodine concentrations modeled at offsite receptors associated with each event will be evaluated relative to the NYSDEC SGC for iodine of 100 μg/m^3.

5.0 References

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Appendix A

Green Toxicology Report

Memorandum

To: Brian Bahor and Gary Pierce, Covanta
From: Edmund A.C. Crouch, Ph.D.
Date: June 25, 2020
Subject: Iodine emissions to ambient air from the Covanta Essex Resource Recovery Facility

Introduction

The Covanta Essex resource recovery facility has experienced multiple episodes of atmospheric releases of iodine in sufficient quantities to cause purple colored plumes, with corresponding opacities measured at up to 50% over brief time-intervals. I have evaluated the levels of iodine emissions required to cause the measured increases in opacity, based on measurements of iodine optical-absorption cross-section and characteristics of the opacity monitors, combined with minute-by-minute continuous emission monitor readings of stack gas characteristics (opacity, temperature, and flow rate).

Estimation of iodine emissions based on stack gas characteristics

Methodology

Emissions of iodine are estimated by realizing that iodine vapor absorbs light in the wavelength range monitored by the opacity-measuring continuous emission monitor (CEM). Literature studies on the absorption of light by iodine vapor are used to construct a relationship between light extinction and the concentration of iodine in stack-gas as a function of light wavelength and temperature. This relationship in turn is used in conjunction with the specific light characteristics of the opacity CEM to derive a relationship between CEM opacity measurement, temperature, and the concentration of iodine in stack gas. This relationship is then used to infer stack-gas concentrations of iodine from recorded CEM measurements of opacity and temperature. Subsequent multiplication of the concentrations by flowrates results in estimates of mass emission rates.

Extinction coefficient for iodine vapor

The wavelength dependence of the extinction coefficient (equivalently, the absorption cross-section) for iodine vapor at room temperature (295 K) and in air at atmospheric pressure has been accurately measured by Saiz-Lopez et al. (2004) at high resolution in the relevant wavelength interval (Figure 1). These measurements clearly resolve the band structure, and agree[1] reasonably well on average with earlier lower-resolution measurements at room temperature (extrapolated to zero pressure) by Tellinghuisen (1973; see Figure 1), and with earlier work. Sulzer and Wieland (1952) also provide lower resolution measurements at temperatures of 423 K, 873 K, and 1323 K, together with a theoretical analysis of the major contributing component to the extinction coefficient in the relevant wavelength range. This theoretical analysis omits various smaller contributions (e.g. providing the band structure) but allows extrapolation between temperatures and provides a smooth interpolation across the band structure — see the curves shown as "Theory" in Figure 1. The Sulzer and Wieland (1952) curve shape for the extinction (absorption) coefficient ε as a function of wavelength λ and temperature T is given by:[2]

$$\varepsilon(T,\lambda) = \varepsilon_o \left(\frac{\lambda_0}{\lambda}\right)^2 \sqrt{\tanh\left(\frac{\theta}{2T}\right)} \exp\left\{-\tanh\left(\frac{\theta}{2T}\right)\left(\frac{1/\lambda - 1/\lambda_0}{1/\Delta\lambda}\right)^2\right\}$$

where λ is the wavelength and T is the absolute temperature. Fitting the Saiz-Lopez et al. (2004) data (minimizing the sum of squared differences for all points measured between 450 and 630 nm) gives the constants:

	ε_o	= 278.54 m^2 $mole^{-1}$
	λ_0	= 529.67 nm
	$\Delta\lambda$	= 8654.6 nm
with	θ	= 308.62 K based on Sulzer and Wieland (1952).[3]

Opacity meter response

The wavelength-dependence of the opacity meter responses in Units 1, 2, and 3 are provided at the 10 nm intervals measured as part of the standard quality control procedures for these instruments (all units use Lighthawk 560 Continuous Monitoring Systems, Teledyne Monitor Labs, 2006a, b, c). The measurements were performed on representative samples from the manufacturing production runs, not on the installed instruments themselves; the same sample was used for the Unit 1 and 2 instruments, with a different (later) sample for Unit 3. The LED

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[1] The agreement shown in Figure 1 is not as good as that indicated by Saiz-Lopez et al. (2004) in their paper, but I have not been able to locate the discrepancy. This agreement requires assuming that all earlier workers reported extinction coefficients with units based on moles of atomic iodine, rather than the moles of iodine vapor shown in Figure 1.

[2] This curve is a Gaussian on a frequency scale. It is written here on the wavelength scale of Figure 1.

[3] θ has a theoretical interpretation, but changes in its value simply change the estimated values for the other constants without affecting the curve fit.

light source should provide a smooth spectrum (with no narrow band structure or peaks), so interpolation of these measurements (shown on Figure 1) should be accurate. Six point Lagrange interpolation to 0.5 nm intervals was used for the Unit 1 and 2 response, and four point for the Unit 3 response.[4] Figure 1 shows that the opacity CEM response matches the absorption characteristics of iodine vapor well, so CEM measurements should be sensitive to sufficiently high iodine concentrations.

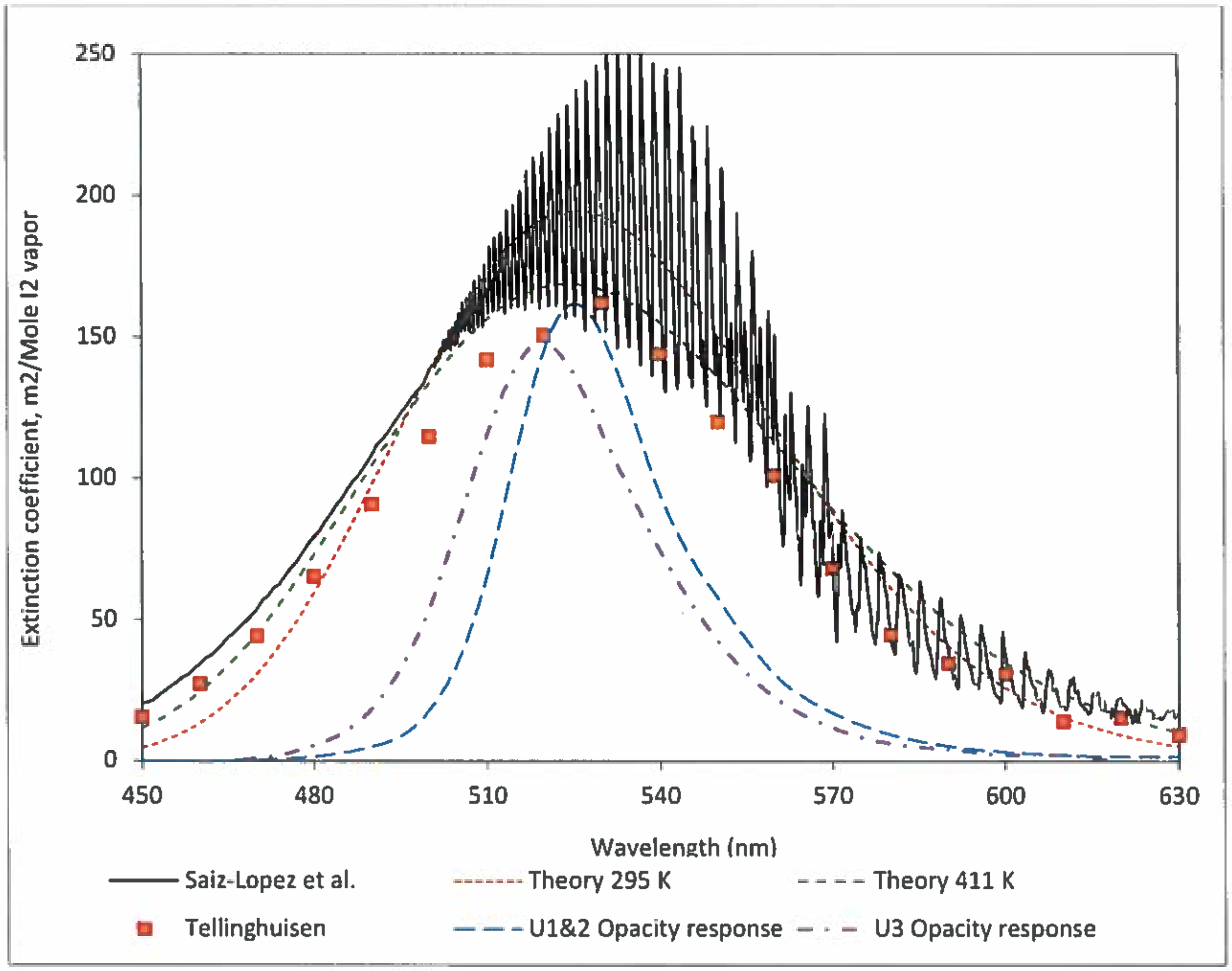

Figure 1 Extinction coefficient for I_2 vapor at 295 K, theoretical curve (see text) at 295 K and 411 K, and the opacity meter responses in Units 1, 2, and 3 (arbitrary units, but with equal areas under the curves).

[4] The overall response was given at 10 nm intervals from 360 to 750 nm for units 1 and 2, although the response was less than 1% of the maximum outside the range 480 to 630 nm. For unit 3, the overall response was given as zero outside the range 470 to 610 nm. The different interpolation orders were chosen to give smooth transitions at the end-points of the useful ranges, and variations in interpolation order have negligible effect on the result.

Overall opacity sensitivities to iodine vapor

The sensitivities of the opacity meter to iodine vapor were obtained by convolving the opacity meter responses with the extinction coefficient for iodine at the temperature of the stack gas. With the opacity meter responses shown, the band structure in the extinction coefficient will be averaged, and suitably accurate estimates may be obtained by using the smooth approximate theoretical curves of Sulzer and Wieland (1952). These theoretical curves match the average extinction coefficient over the wavelength range of the opacity meter response with reasonable accuracy at 295 K, and have the advantage of allowing extrapolating to higher temperatures (where the height and width of the curve and the band structure are all modified). Performing these convolutions[5] for stack temperatures in the range of 250 °F to 350 °F gives the wavelength integrated extinction coefficients (absorptivities) shown in Figure 2. The curves are quadratic fits to values calculated at 5 °F intervals, which values deviate negligibly from these curves.

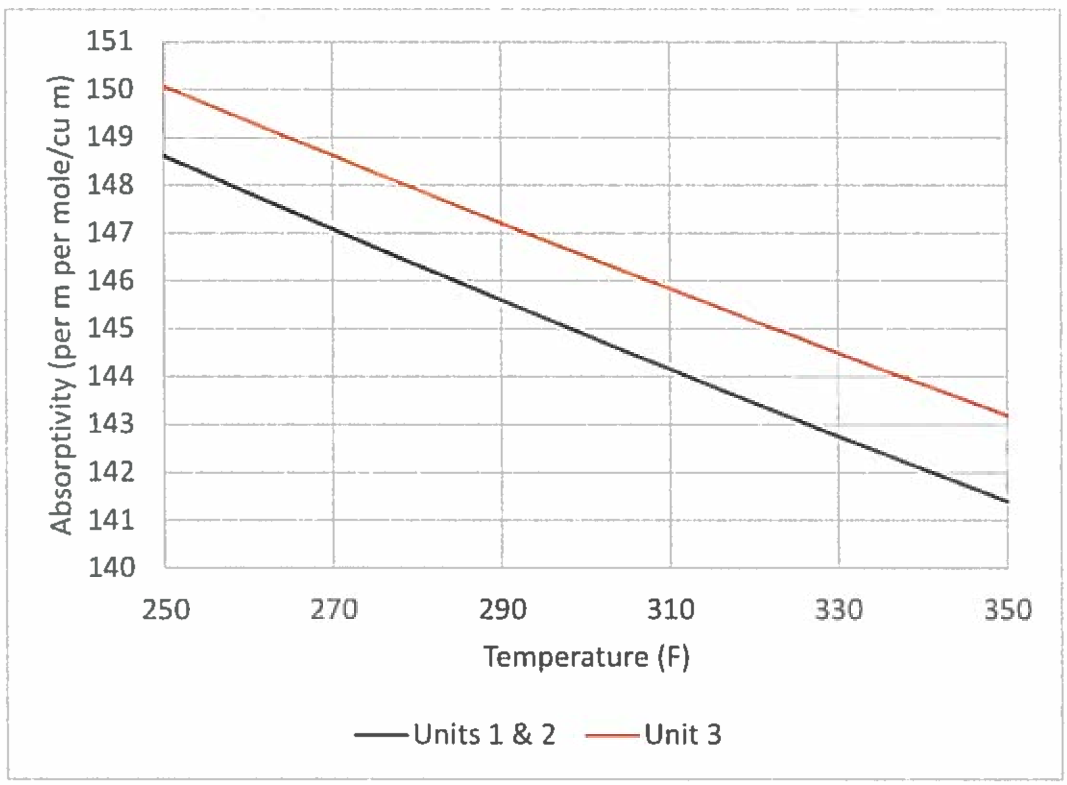

Figure 2 Wavelength integrated extinction coefficients (absorptivities) for Units 1, 2, and 3.

[5] Numerical convolution at 0.5 nm wavelength intervals using the trapezoidal rule.

Calculation of iodine emission rates

Iodine emission rates E (grams/second) were estimated from the stack gas opacity K (%), wavelength integrated extinction coefficient $H(T)$ (m^2/mole from Figure 2) at the stack temperature T (°F), and the stack flow rate (actual) V (m^3/sec), using

$$E = \frac{-\ln(1-(K-C)/100)}{LH(T)} VM$$

where C (%) is a cut-off opacity to account for drift of the opacity meter and background opacity from other materials, L (m) is the opacity meter optical path length through the stack gas (2.337 m for Units 1 and 2, 2.318 m for Unit 3), and M is the molar weight of diatomic iodine vapor (253.81 g/mole). All opacity-values above the cut-off C were assumed to be due to iodine.

Results

Total emissions and maximum emission rates

A total of 15 emission events were modeled, each one consisting of one or more peaks of opacity over periods extending up to several hours, with summary results shown in Table 1 for total mass of iodine emitted during the day, and maximum emission rates averaged over 1 minute, 15 minutes, and 1 hour, and the initial minute for the given maximum.[6] The cut-off opacity selected for each event was estimated empirically by selecting a value that just suppressed any estimate of emissions outside the event in an approximately 24-hour period containing the event. The selections were made by visual observation of graphs of opacity and emission estimates (see appendix). The various estimates are probably uncertain to at least 10% due to the limited precision of the opacity meters, which report opacity to 0.1%, and the potential drift of these meters such that positive opacity may be reported as 0% (see, for example, the lack of a longer tail to the opacity and emission curve for the event in Unit 2 on 05-02-19). In addition, there is an uncertainty of unknown size in the theoretical analysis above, in that it has not been tested empirically; such uncertainty could be evaluated by injection of iodine in known quantities into the stack gas after the baghouse and measuring the resulting opacity.

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[6] Note that the U2 01-14-19 times look a little odd compared with the rest, but examination of the figure for that case makes the reason clear — the initial spike in concentration gives the highest 1 and 15 minute averages, but the more sustained but lower later peaks give the highest 1 hour average.

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Unit & date	Total emissions (kg)	Maximum emission rate averages (grams/second)			Time of initial minute for given maximum			Cutoff (%)
		1 min	15 min	60 min	1 min	15 min	60 min	
U1 02-05-20	34.8	7.9	6.4	3.7	19:04	18:56	18:52	1.6
U1 06-16-19	34.2	9.7	7.9	4.4	04:13	04:11	04:03	0.5
U1 06-24-19	32.6	53.2	26.4	8.6	05:20	05:15	05:08	0.9
U1 10-10-19	45.8	35.8	25.3	12.4	14:52	14:49	14:46	0.0
U2 01-14-19	49.3	16.5	12.8	7.2	16:24	16:18	17:12	0.0
U2 05-02-19	17.5	9.7	8.2	4.8	16:08	16:06	15:53	0.0
U2 06-03-19	82.0	33.3	21.6	11.4	20:57	19:38	19:29	0.0
U2 06-19-19	157.9	61.8	46.6	27.0	12:48	12:45	12:24	0.0
U2 06-24-19	38.9	10.8	9.3	6.4	01:35	01:25	01:15	0.0
U3 01-14-19	30.7	24.9	19.8	8.2	16:24	16:19	16:10	0.7
U3 01-28-19	75.1	28.0	23.4	15.2	18:16	18:12	17:25	0.4
U3 06-03-19	35.1	19.1	13.1	7.2	19:07	18:59	18:56	1.2
U3 06-19-19	139.6	56.8	37.3	23.0	12:58	12:55	12:28	0.9
U3 08-07-19	21.0	8.8	8.0	5.5	10:00	09:54	09:40	2.2
U3 09-20-19	31.1	13.4	9.3	5.8	18:15	18:12	18:04	0.0

Table 1 Summary results of emission modeling for 15 iodine emission events

I understand that these emission rates will be translated via air dispersion modeling into estimated impacts to ambient air, and hence to estimated risks to public health.

Graphs of opacity and emission rate estimates versus time for these events are included in the appendix.

Conversion of opacity reading to iodine volume mixing ratio

Using the methodology described allows a calculation of the iodine volume mixing ratio (measured in ppm) in the stack gas based on the opacity reading, as follows.

Let

K = opacity reading (%)

C = background or drift of opacity meter (%)

T = baghouse outlet temperature (°F)

P = iodine ppm in stack gas

For high accuracy (<1% of ppm estimate as calculated by the methodology):

$$P = 103.5 \times (-\ln(1-(K-C)/100)) \times \left(1+0.0018 \times (T-300)\right)$$

For medium accuracy (<5% of ppm estimate up to 60% opacity)

$$P = 1.0 \times (K - C) \times \big(1 + 0.009 \times (K - C)\big) \times \big(1 + 0.0018 \times (T - 300)\big)$$

For an easy to calculate estimate with less accuracy (<10% of ppm estimate as calculated by the methodology)

$$P = 1.07 \times (K - C) \quad \text{for} \quad (K - C) \le 10.5\%$$
$$P = -2.71 + 1.32 \times (K - C) \quad \text{for} \quad 10.6\% \le (K - C) \le 35.5\%$$
$$P = -25.9 + 1.98 \times (K - C) \quad \text{for} \quad 35.6\% \le (K - C) \le 60\%$$

These apply within the stated accuracy for all three units for 250<*T*<350 °F (the slight difference in LED light sources is almost exactly cancelled by the slight difference in light path length).

References

Saiz-Lopez A, Saunders RW, Joseph DM, Ashworth SH, Plane JMC. 2004. Absolute absorption cross-section and photolysis rate of I_2. Atmos Chem Phys 4(5):1443–1450.

Sulzer von P, Wieland K. 1952. Intensitätsverteilung eines kontinuierlichen Absorptions-spektrums in Abhängigkeit von Temperatur und Wellenzahl. Helv Phys Acta 25(6):653–676. [In German].

Teledyne Monitor Labs Inc. 2006a. Manufacturer's certificate of conformance with design specifications per 40CFR60, Appendix B, Performance Specification 1, Published August 2000. LightHawk 560 Continuous Monitoring System (COMS). For Covanta Energy, Unit 1, Serial Number: 5602654. August 2014.

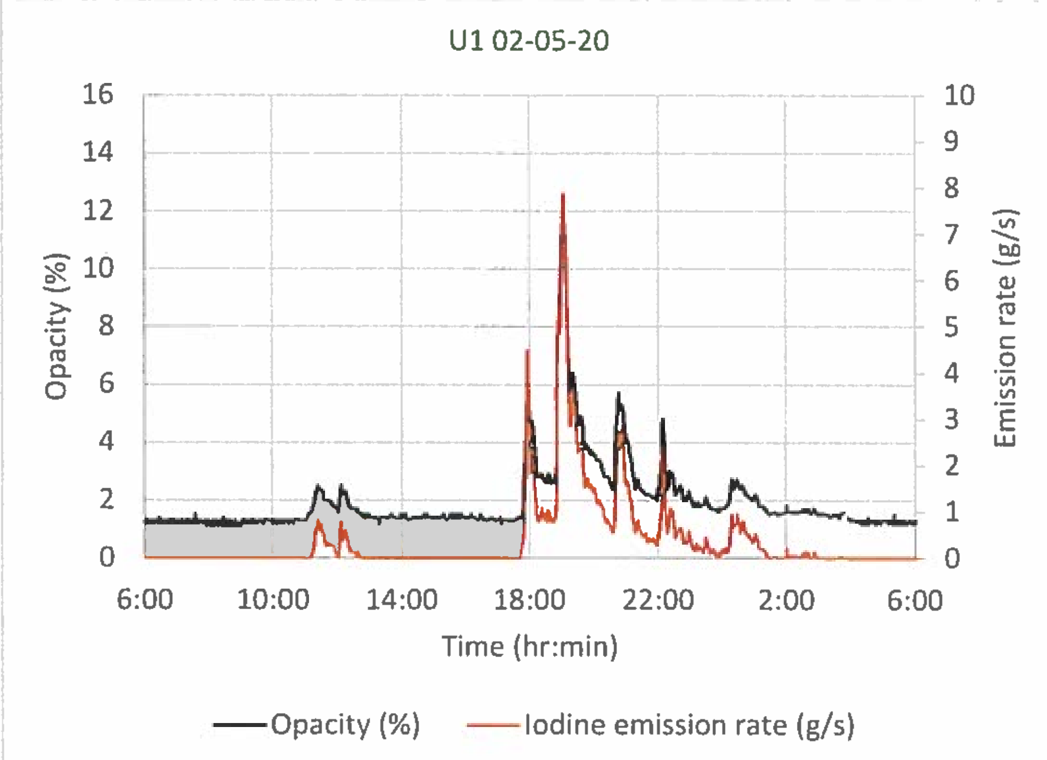
Teledyne Monitor Labs Inc. 2006b. Manufacturer's certificate of conformance with design specifications per 40CFR60, Appendix B, Performance Specification 1, Published August 2000. LightHawk 560 Continuous Monitoring System (COMS). For Covanta Energy, Unit 2, Serial Number: 5602655. August 2014.

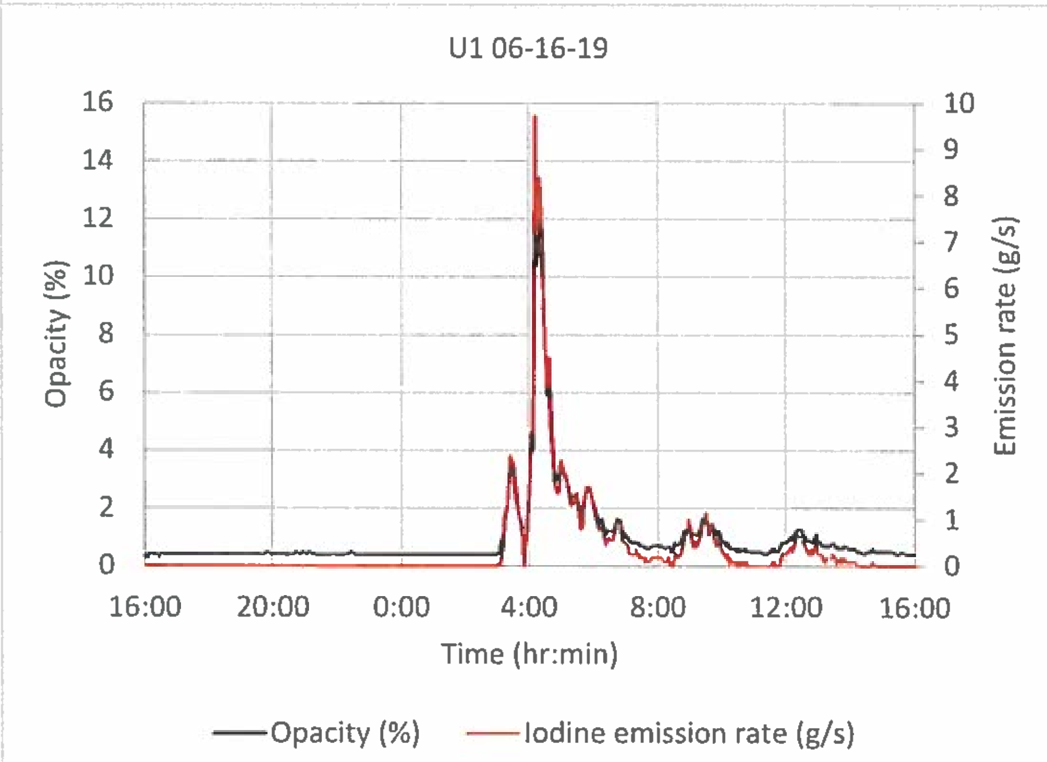
Teledyne Monitor Labs Inc. 2006c. Manufacturer's certificate of conformance with design specifications per 40CFR60, Appendix B, Performance Specification 1, Published August 2000. LightHawk 560 Continuous Monitoring System (COMS). For Covanta Essex Company, Unit 4, Serial Number: 5602790. August 2015. [Note: this instrument is installed in Unit 3; it was given the designation "Unit 4" due to a misunderstanding.]

Tellinghuisen J. 1973. Resolution of the visible-infrared absorption spectrum of I_2 into three contributing transitions. J Chem Phys 58(7):2821–2834.

APPENDIX

Graphs of opacity and estimated emission rate for each atmospheric iodine-release event





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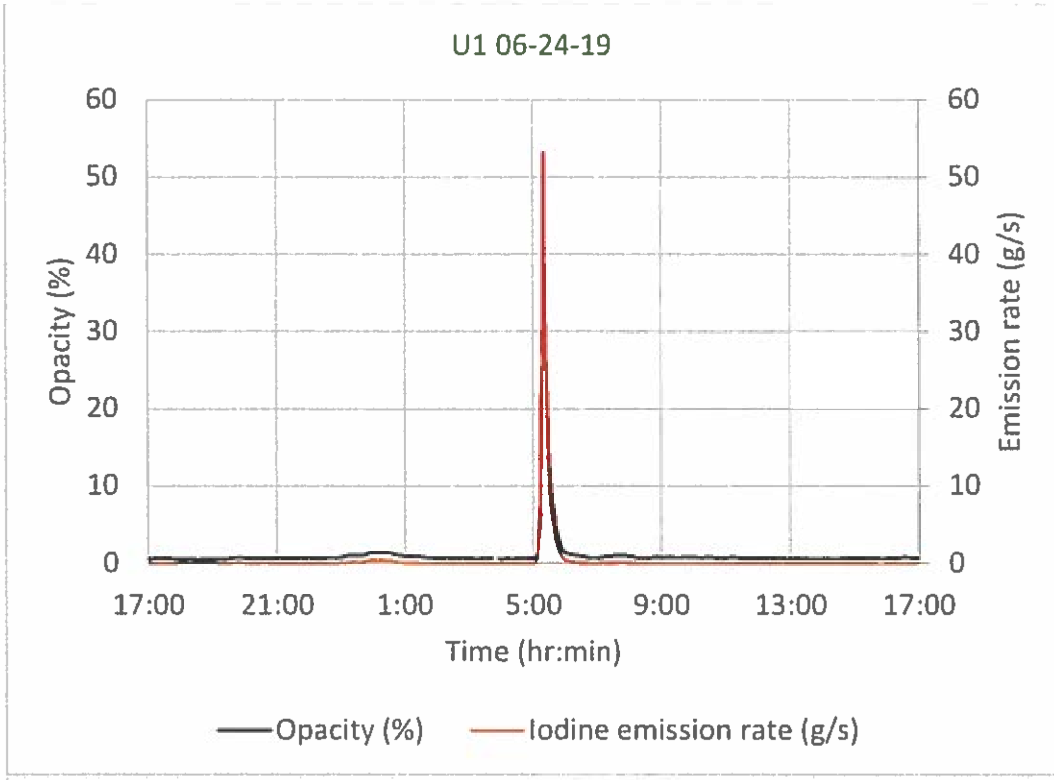

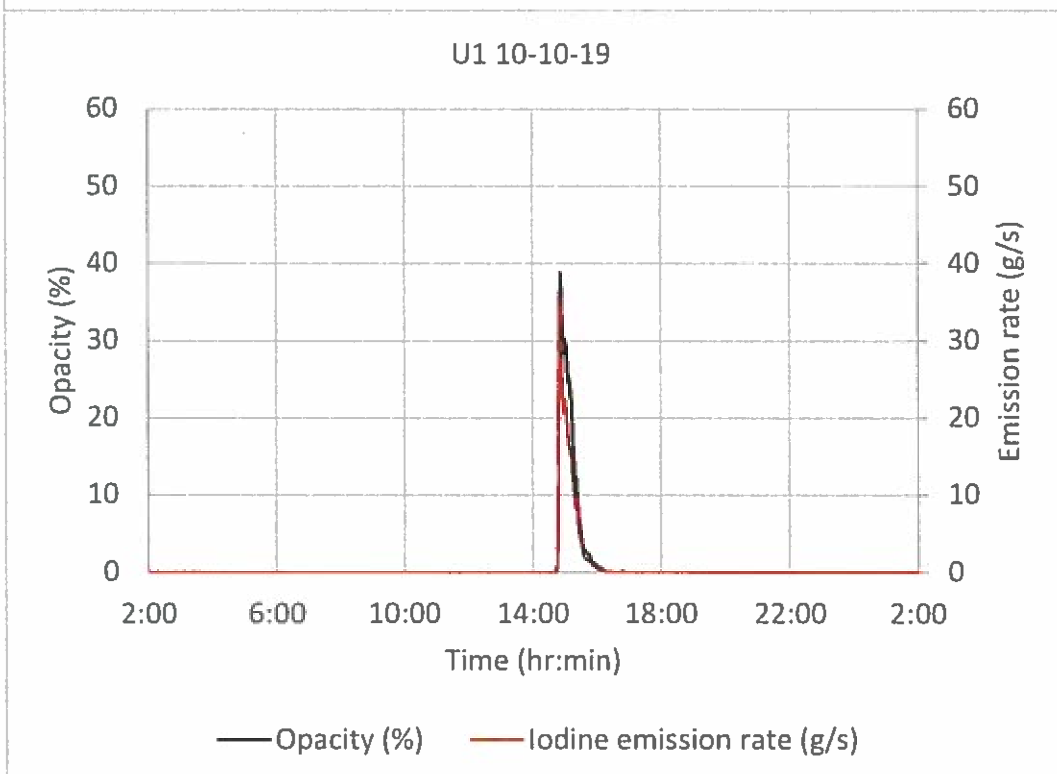

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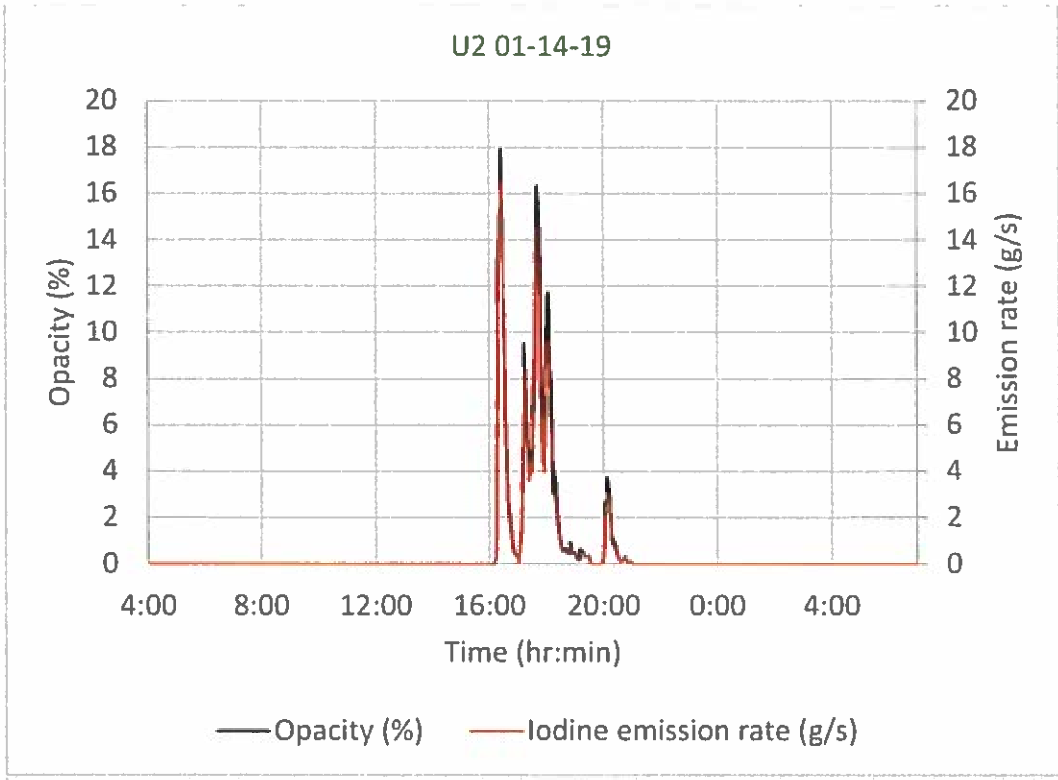
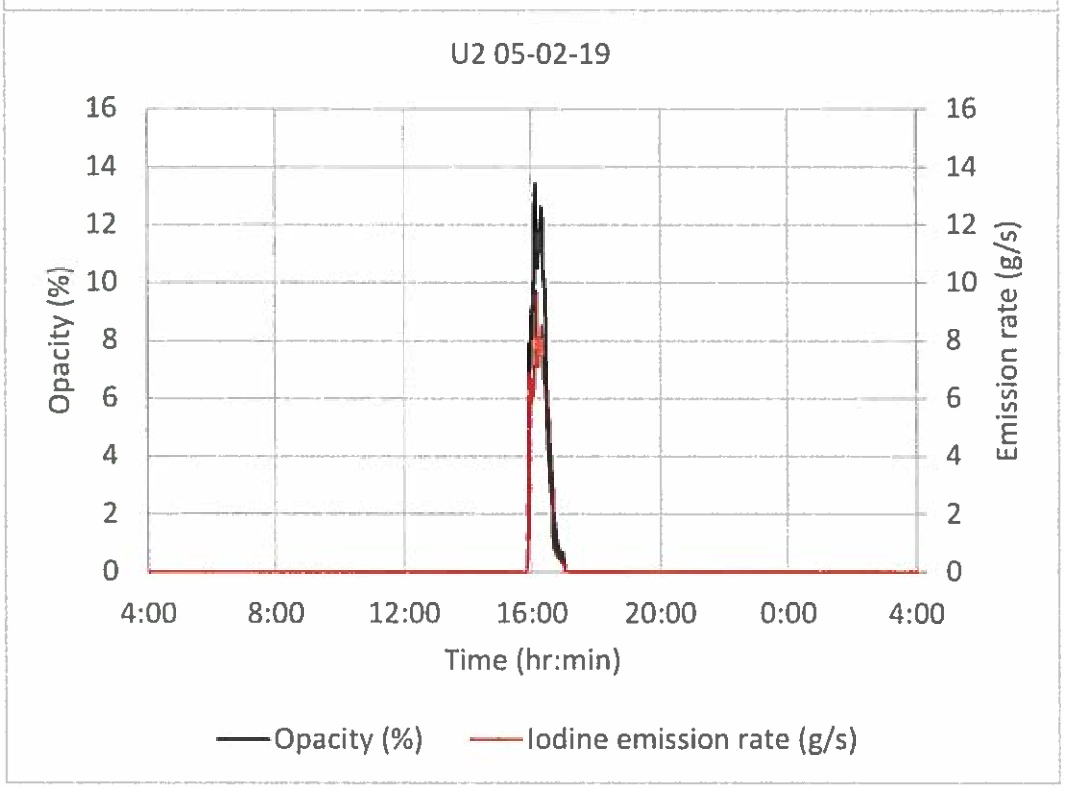
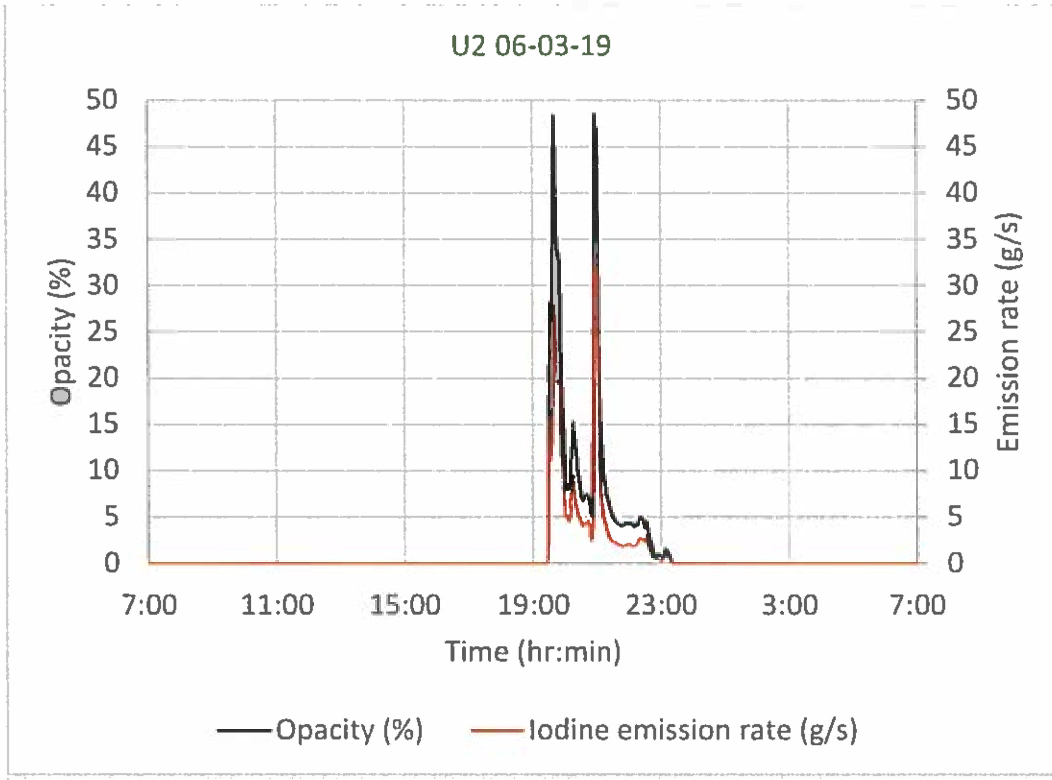
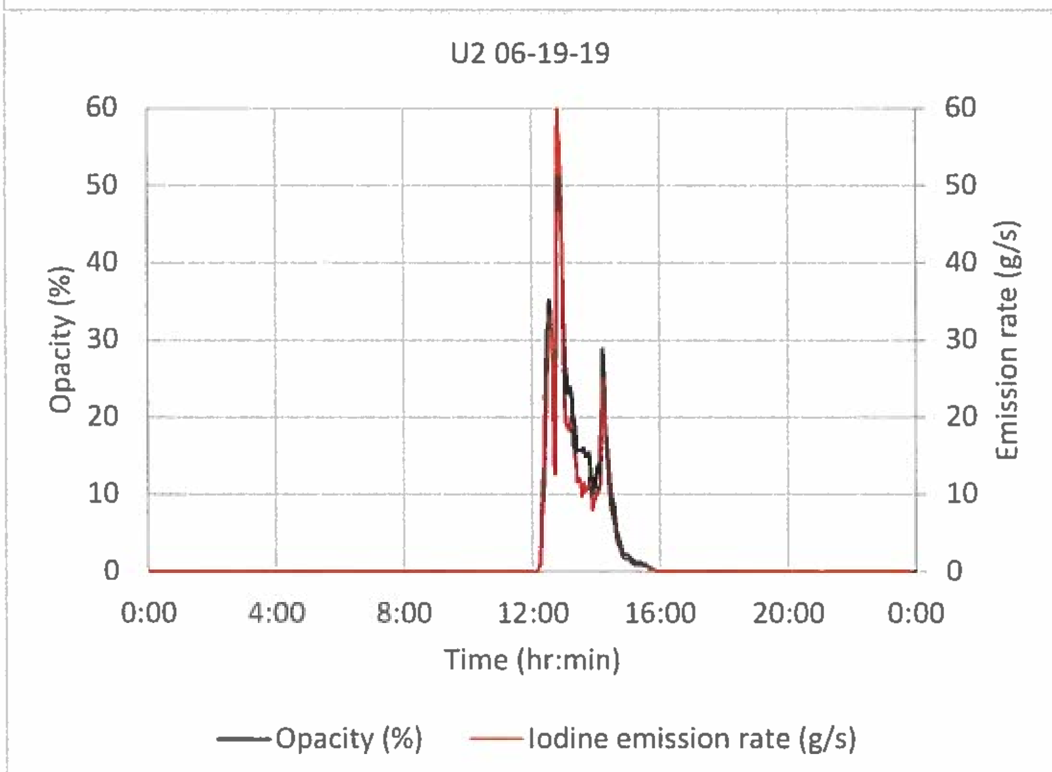
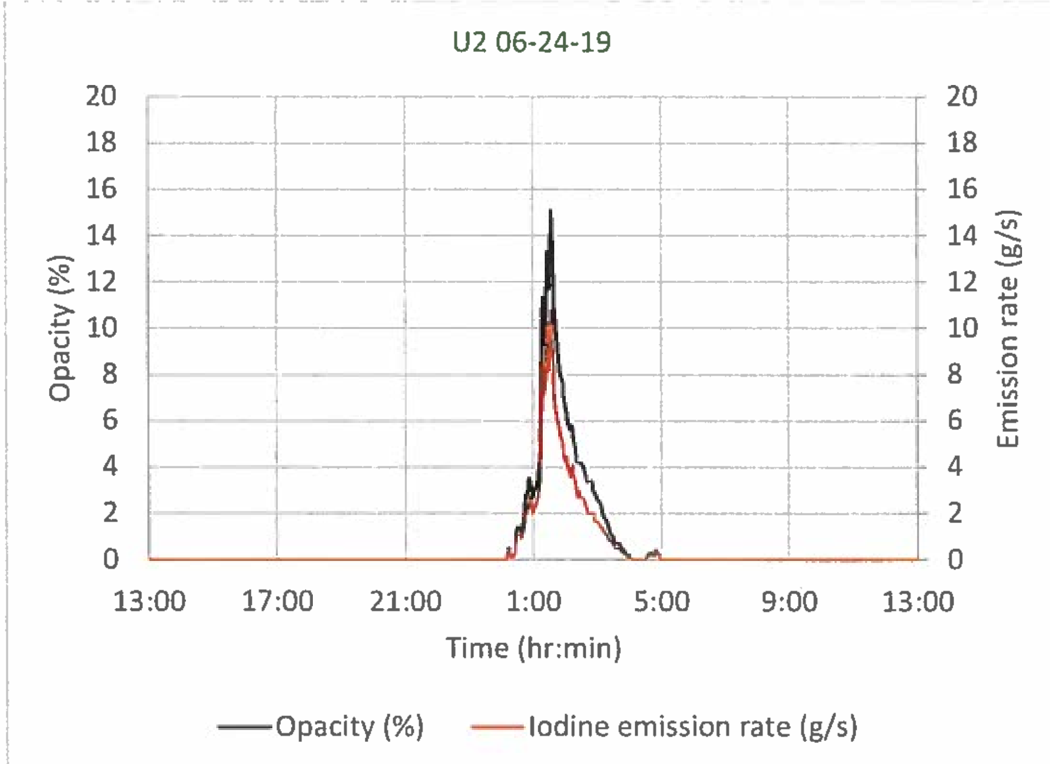
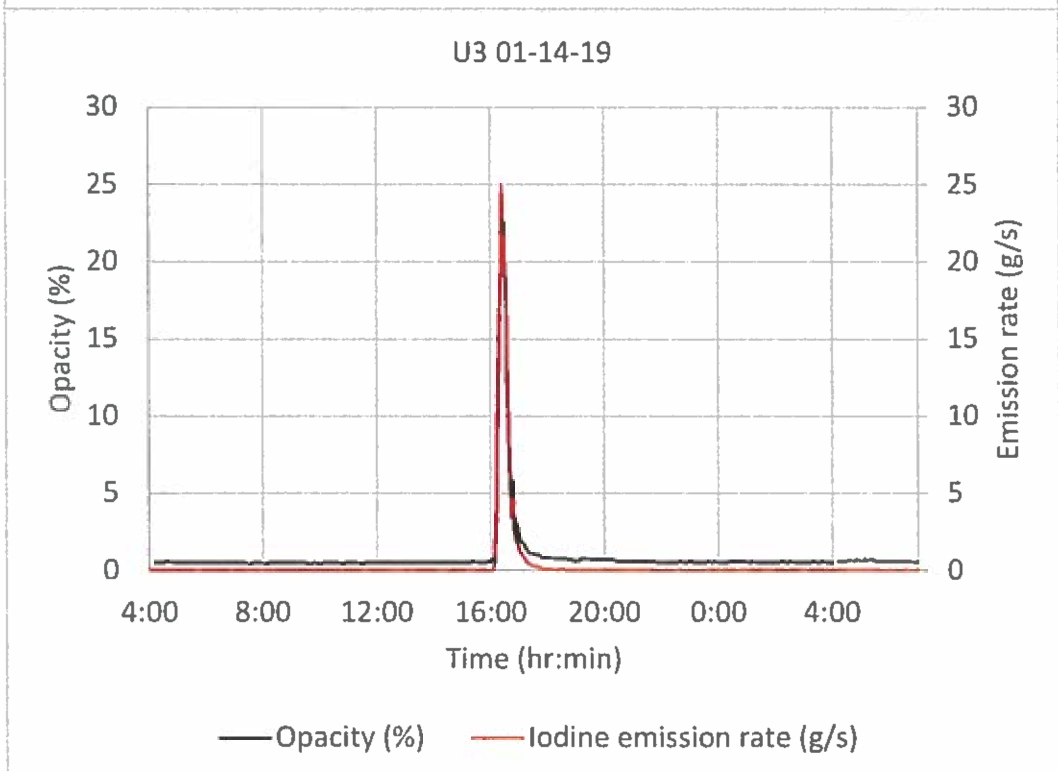

U2 01-14-19
Opacity (%)
Emission rate (g/s)
20
18
16
14
12
10
8
6
4
2
0
4:00
8:00
12:00
16:00
20:00
0:00
4:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)

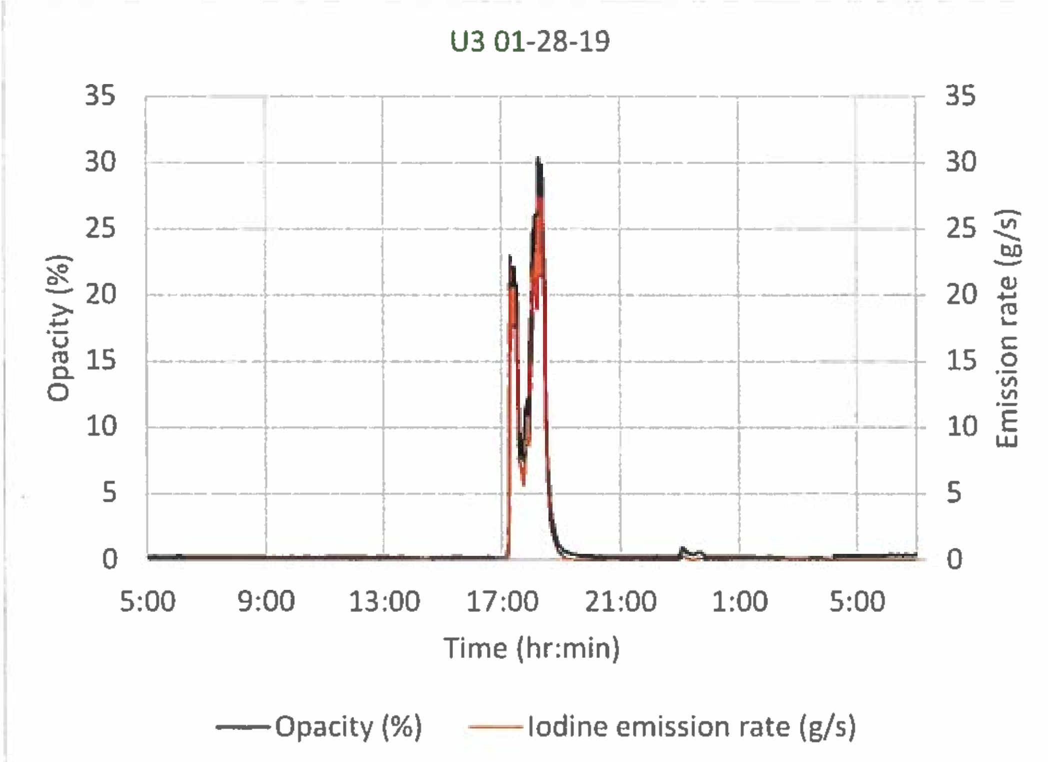

U2 05-02-19
Opacity (%)
Emission rate (g/s)
16
14
12
10
8
6
4
2
0
4:00
8:00
12:00
16:00
20:00
0:00
4:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)

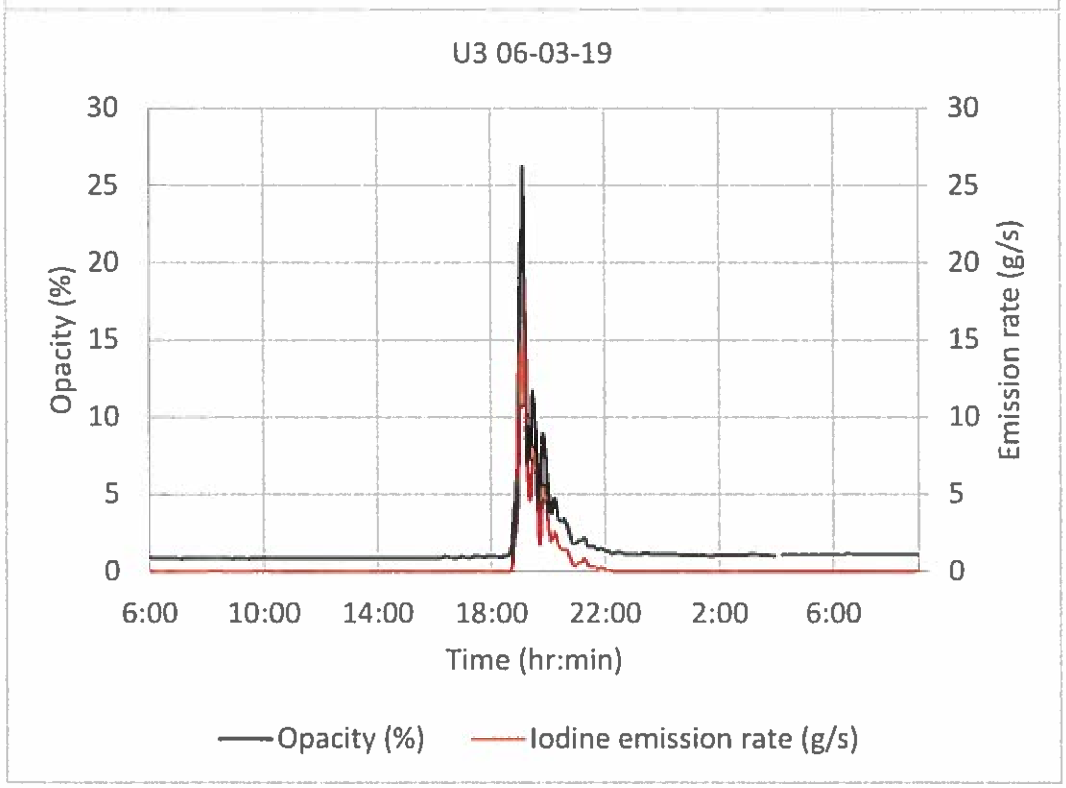

U2 06-03-19
50
45
40
35
30
25
20
15
10
5
0
Opacity (%)
Emission rate (g/s)
7:00
11:00
15:00
19:00
23:00
3:00
7:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)

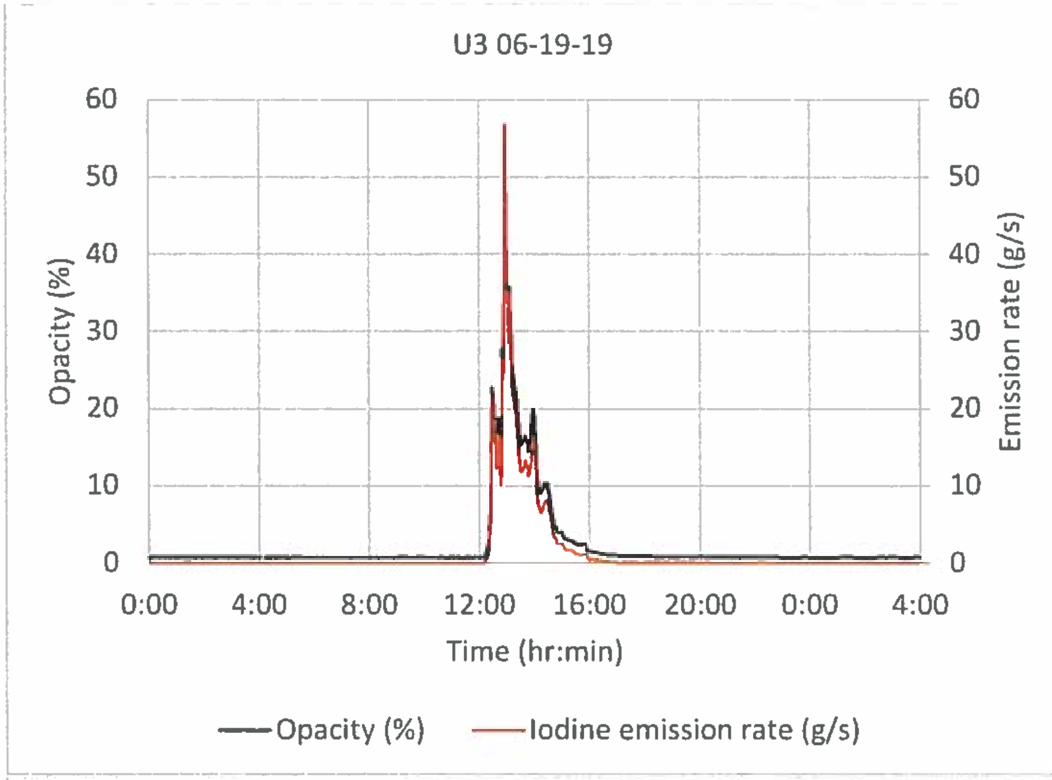

U2 06-19-19
60
50
40
30
20
10
0
Opacity (%)
Emission rate (g/s)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)

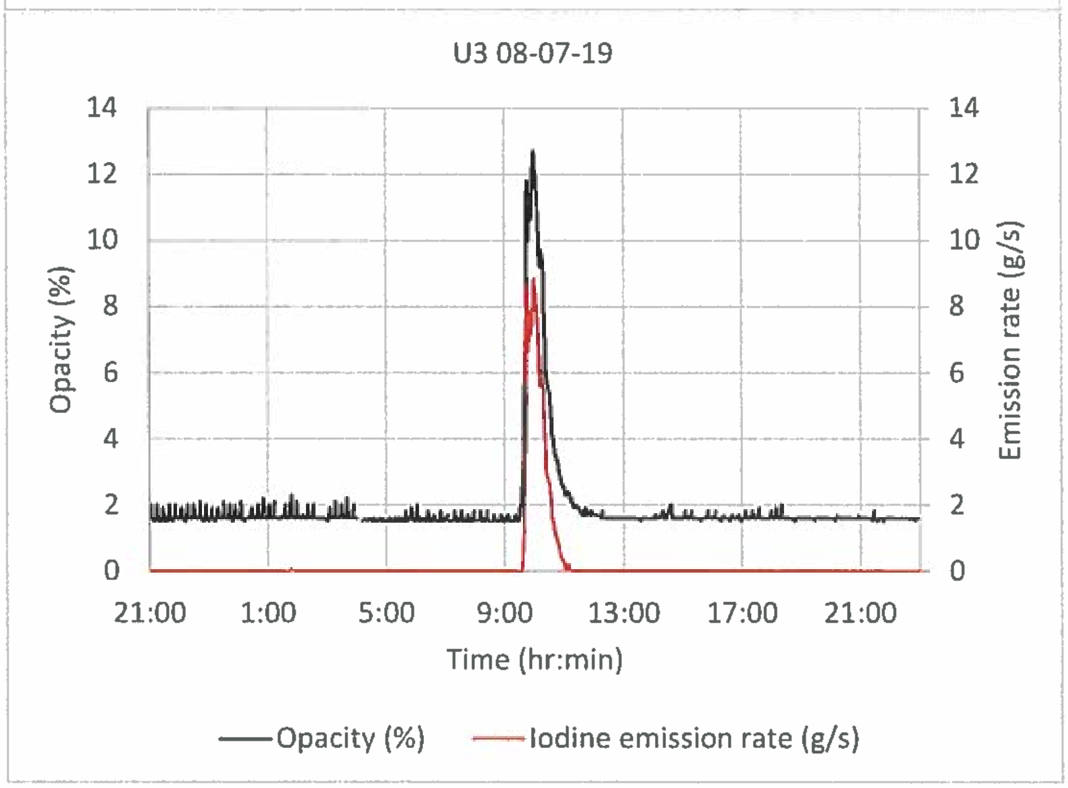

U2 06-24-19
Opacity (%)
Emission rate (g/s)
20
18
16
14
12
10
8
6
4
2
0
13:00
17:00
21:00
1:00
5:00
9:00
13:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)

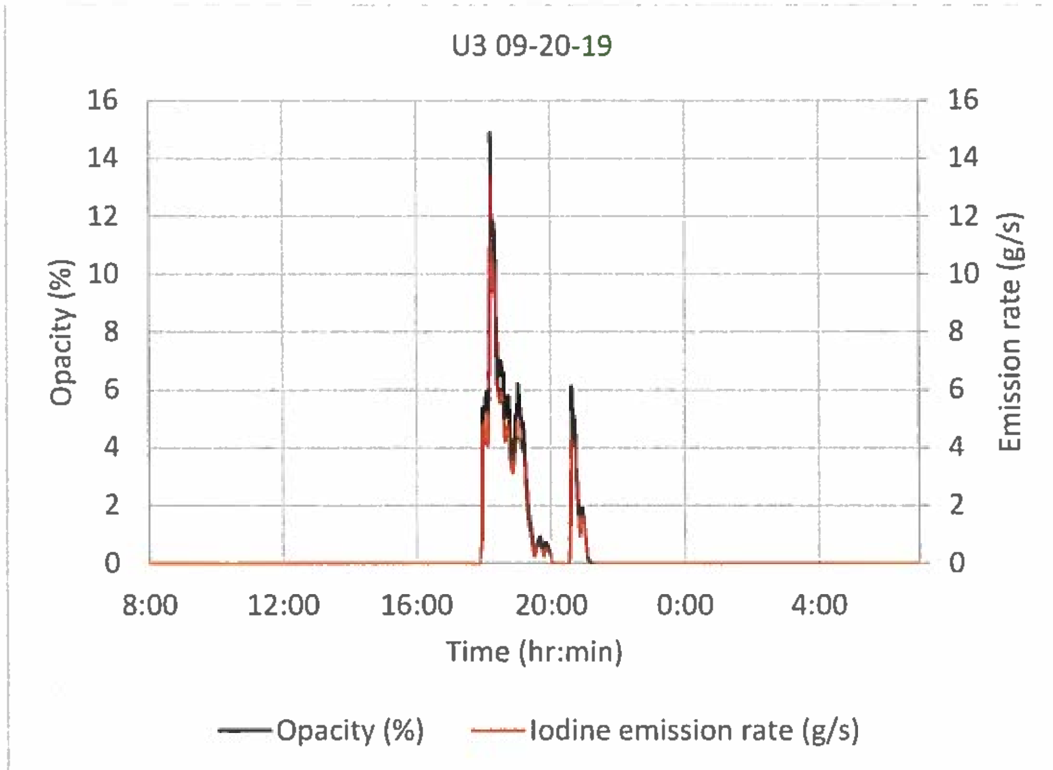

U3 01-14-19
Opacity (%)
Emission rate (g/s)
30
25
20
15
10
5
0
4:00
8:00
12:00
16:00
20:00
0:00
4:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)


U3 01-28-19
35
30
25
20
15
10
5
0
Opacity (%)
Emission rate (g/s)
5:00
9:00
13:00
17:00
21:00
1:00
5:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)


U3 06-03-19
30
25
20
15
10
5
0
Opacity (%)
Emission rate (g/s)
6:00
10:00
14:00
18:00
22:00
2:00
6:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)


U3 06-19-19
60
50
40
30
20
10
0
Opacity (%)
Emission rate (g/s)
0:00
4:00
8:00
12:00
16:00
20:00
0:00
4:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)


U3 08-07-19
14
12
10
8
6
4
2
0
Opacity (%)
Emission rate (g/s)
21:00
1:00
5:00
9:00
13:00
17:00
21:00
Time (hr:min)
Opacity (%)
Iodine emission rate (g/s)



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