August 19, 2015

Ms. Darcy Bybee Via email: darcy.bybee@dnr.mo.gov
Missouri Department of Natural Resources
Air Pollution Control Program
P.O. Box 176
Jefferson City, MO 65102-0176

RE: Bridgeton Landfill, L.L.C. – Response to Request for additional background information related to Flare Air Permitting.

Dear Ms. Bybee,

This letter is in response to the August 5, 2015, MDNR request for additional information from Leanne Tippet Mosby to Brian Power. The letter included six (6) items of request. This submittal addresses items 1, 5, and 6. As per your August 17, 2015 email, the response to requested items 2, 3 and 4 will be provided by August 24, 2015.

The response letter includes the MDNR's question for reference, followed by Bridgeton Landfill's response.

Q1. A copy of the power point presentation presented during the June 16, 2015, meeting.

The requested copy is attached to this letter.

Q5. Documentation of New Source Performance Standards compliance. Specifically, data justifying Bridgeton Landfill's alternative compliance scenario using hydrogen values and information regarding the ability and any planned usage of assist gas.

In accordance with NSPS compliance standards (included for reference below) and as highlighted in Bridgeton Landfill's Title V permit, flare records are compiled each month and included in the site's records. See Monthly 60.18 Compliance Table attached.

The table details the lab analysis provided Hydrogen content (% vol), the LFG Net Heating Value (Btu/scf), and the associated regulatory paragraph chosen for compliance. Since October 2013, this has been governed by the hydrogen content. Should Bridgeton Landfill not be able to maintain compliance under paragraph (c)(3)(i), the site has installed and has operational ready to provide natural gas supplemental fuel to meet the heat content specifications in of paragraph (c)(3)(ii) of the referenced 60.18 section below.

40 CFR § 60.18 General control device and work practice requirements.

(b) Flares. Paragraphs (c) through (f) apply to flares.
(c)
(1) Flares shall be designed for and operated with no visible emissions as determined by the methods specified in paragraph (f), except for periods not to exceed a total of 5 minutes during any 2 consecutive hours.
(2) Flares shall be operated with a flame present at all times, as determined by the methods specified in paragraph (f).
(3) An owner/operator has the choice of adhering to either the heat content specifications in paragraph (c)(3)(ii) of this section and the maximum tip velocity specifications in paragraph (c)(4) of this section, or adhering to the requirements in paragraph (c)(3)(i) of this section.
(i)
(A) Flares shall be used that have a diameter of 3 inches or greater, are nonassisted, have a hydrogen content of 8.0 percent (by volume), or greater, and are designed for and operated with an exit velocity less than 37.2 m/sec (122 ft/sec) and less than the velocity, Vmax, as determined by the following equation:
$V_{max}=(X_{H2}-K_1)* K_2$
Where:
Vmax=Maximum permitted velocity, m/sec.
K1=Constant, 6.0 volume-percent hydrogen.
K2=Constant, 3.9(m/sec)/volume-percent hydrogen.
XH2=The volume-percent of hydrogen, on a wet basis, as calculated by using the American Society for Testing and Materials (ASTM) Method D1946-77. (Incorporated by reference as specified in § 60.17).
(B) The actual exit velocity of a flare shall be determined by the method specified in paragraph (f)(4) of this section.

Q6. Air Model inputs files used for the May 29, 2015, report. Include additional documentation/justification or information on the radiative heat loss value of 0.08 and 0.11.

The Air Model inputs files were provide to MDNR via email correspondence dated August 8, 2015.

The radiative heat loss, or radiative heat fraction (RF) as referred to by John Zink, utilizes a proprietary design program based on the API Standard 521. Their proprietary methods are further explained in the attached article titled "Accurately Predict Radiation from Flare Stacks, June 2006". The article notes that RF depends highly on the flame surface emissivity (temperature, gas composition, gas radiation, gas absorption and soot radiation). As described, they have developed a flare specific thermal radiometer cube that provided full scale field test data to "calibrate" the API 521 modeling to the type of waste gas and flare tip configuration specific to the project conditions. As stated in the attached article titled "Industrial-Scale Flare Testing, May 2006", effective tip design can have a tremendous impact on the radiation characteristics of a flare, as the tip design can reduce the RF.
The RF values calculated by John Zink for the two Bridgeton Landfill site specific scenarios are 0.11 and 0.08, for high flow rate and low flow rate, respectfully. These values are within the range of values provided in API Standard 521, Table 10, attached.

Sincerely,

Bridgeton Landfill, LLC

James Getting

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Power, Brian (BPower@republicservices.com) – Republic Services

Attachment – Question 1

Bridgeton Landfill

June 2015

Bridgeton Landfill LLC

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Bridgeton Landfill

Key Topics and Talking Points

- **Bridgeton Landfill** – Overview & Background
- **Bridgeton Reaction** – Unique project conditions
- **Sulfur Testing**– Atypical constituents; Variability
- **Gas Flow data**– History & challenges with flow metering
- **Sulfur Calculations - **Current data review
- **Control Technology-** Engineering challenges and Path Forward

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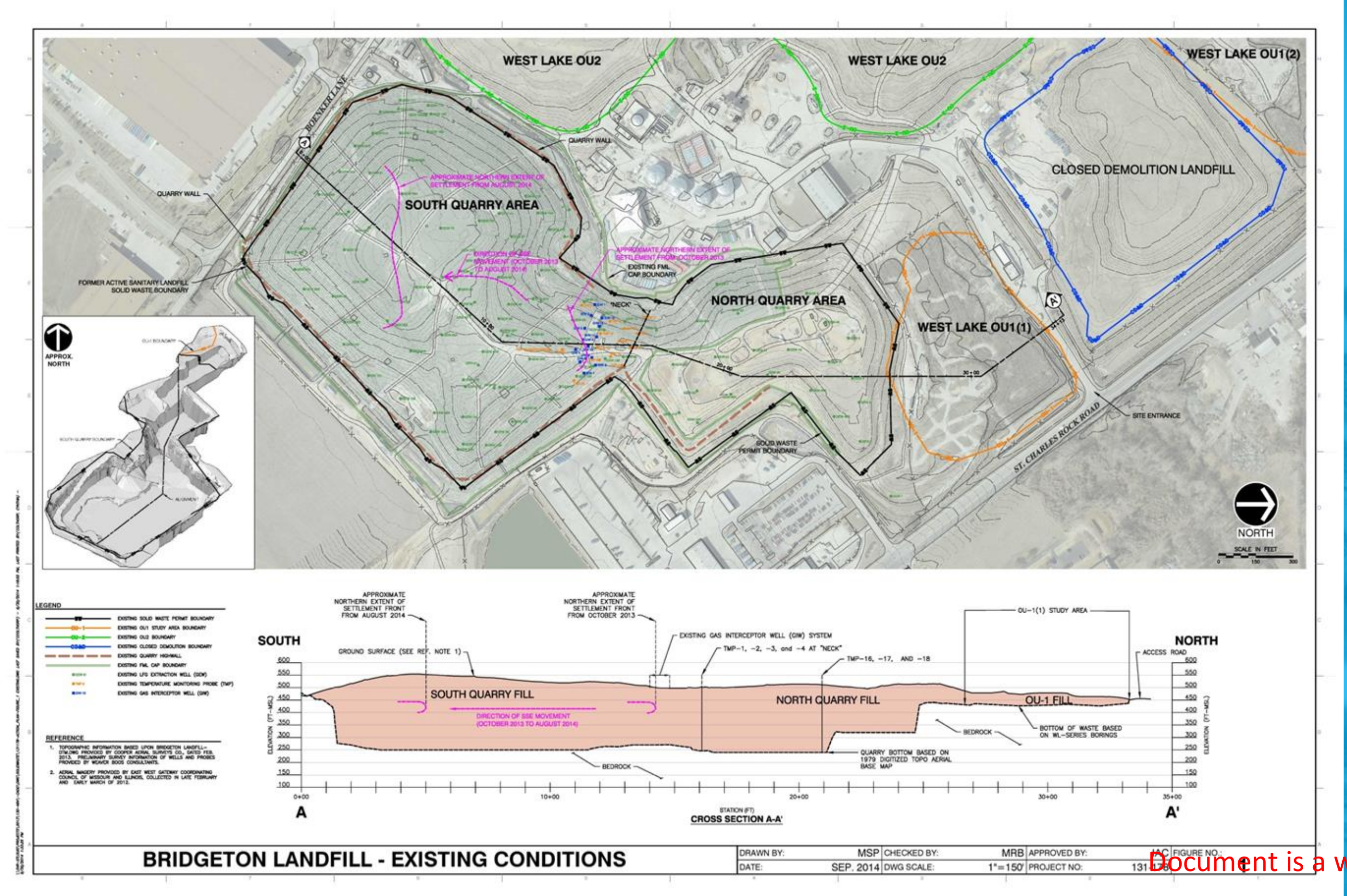
Bridgeton Landfill Overview and Background



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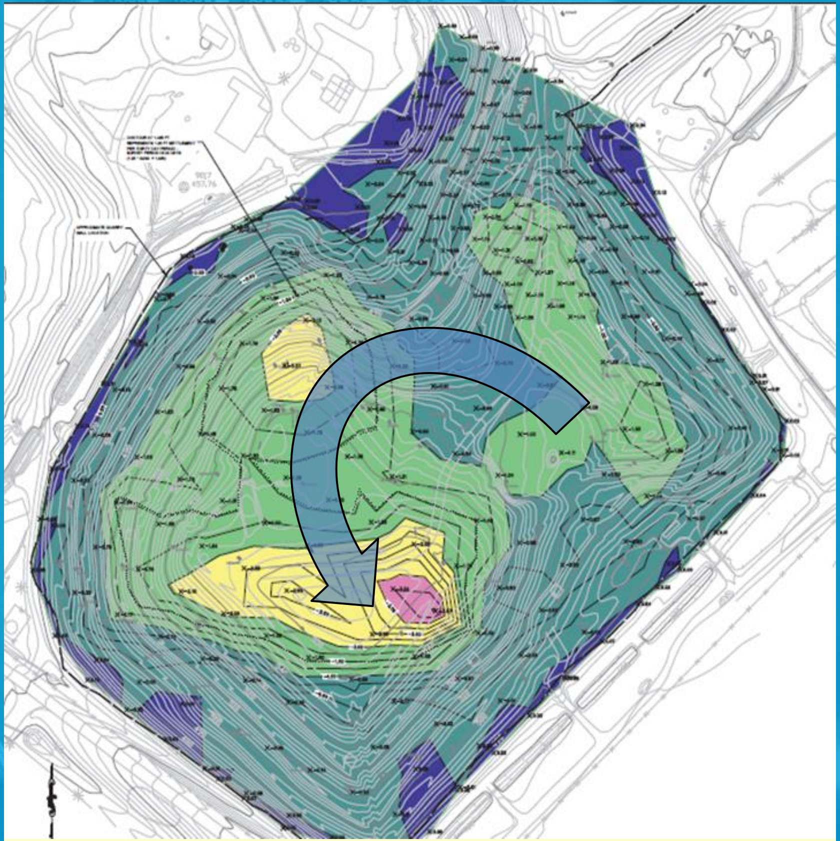
Bridgeton Landfill – Movement of Reaction

	Reaction Area	Typical MSW Landfill
Bridgeton Landfill:	South Quarry	North Quarry
Landfill Temperatures:	Elevated Temperature	Typical Temperature
Settlement Rate:	High Settlement Rate	Typical Settlement Rate
Landfill Gas Composition:	H2, CO2, CO	CH4, CO2
Landfill Gas Flow Rate	Variable, High Air content	Consistent with Normal LFG Generation Trends

Reaction Summary Points

- No predictive gas generation model for South Quarry.
- **Reaction moves, impacting different, non homogenous waste zones —causing unpredictable variability in gas composition.**



Reaction has migrated south in the general path shown above.

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Bridgeton Landfill Gas Management

Gas Collection:

- Comprehensive Coverage - *Odor control objectives.*
- Gas system originally designed for typical Landfill operation; significant changes to manage reaction.
- Significant air component of total flow (+/-50% air), highly variable.
- Gas collection is dynamic and ever changing to manage reaction odors.

Flare Capacity:

- Flares are pollution/emission control devices.
- **Total Flare/Blower capacity far exceeds gas generation capacity of landfill.**
- Equipment capacity is redundancy & back up required for odor control.

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Bridgeton Landfill Air Quality

Air Quality Monitoring & Modeling Results

- Air Modeling Results:
  - No exceedances NAAQS identified.
  - Utilized conservative emission rates.
- Ambient Air Monitoring validates modeling results:
  - Stantec – Comprehensive Air Monitoring Program.
  - MDNR Monitoring Program.
  - EPA Ambient Air Monitoring Program.

Questions?

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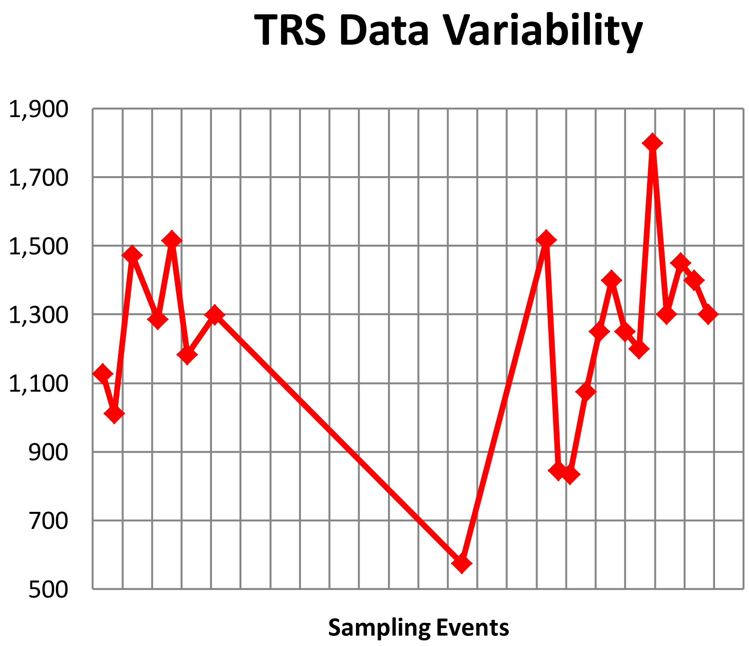
Bridgeton Landfill Sulfur Testing

- Current approach (past 3 months+/-):
  - ➢ Test location at main blower outlet (Method 1 Laminar Flow).
  - ➢ Two samples 30 minute apart in summa canisters.
  - ➢ Method EPA 15/16, ASTM 1946D.
  - ➢ Sample collection paired with valid flow measurement (EPA method 2C/ATM055).
- The test methods utilized: ASTM 5504; EPA method 15/16.
- Large variability in sample data (same day samples and different sample events).
- Utilized different labs, test method and sample media (i.e. summa, tedlar bags) to evaluate/confirm variability in TRS.
- Initial sampling initiated by Bridgeton Landfill was to evaluate potential odor control technologies. Sampling prior to March 12, 2015 were grab samples, not validated with flow measurement data.

Bridgeton Landfill Sulfur Testing

- Sulfur Compounds not typical for landfills;
  - H2S in results at less than typical AP-42 values for landfills and less than values used for permitting.
  - DMS, DMDS, Mercaptans present at highest concentrations.
- Test result variability observed concentrations greater than 50% in samples taken 30-minutes apart.
- Test results variability observed greater than 400% in samples taken on different days.
- Determined use of averages from all samples on test date to calculate daily TRS concentration- eliminate spikes in data.



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Bridgeton Landfill Gas Flow Data

- Site historically used thermal mass flow meter - industry standard.
- Reaction Gas Issues: moisture, air intrusion, hydrogen variability, meter fouling (excludes other meter types).
- Meter Calibrations- Compliant with Industry BMP.

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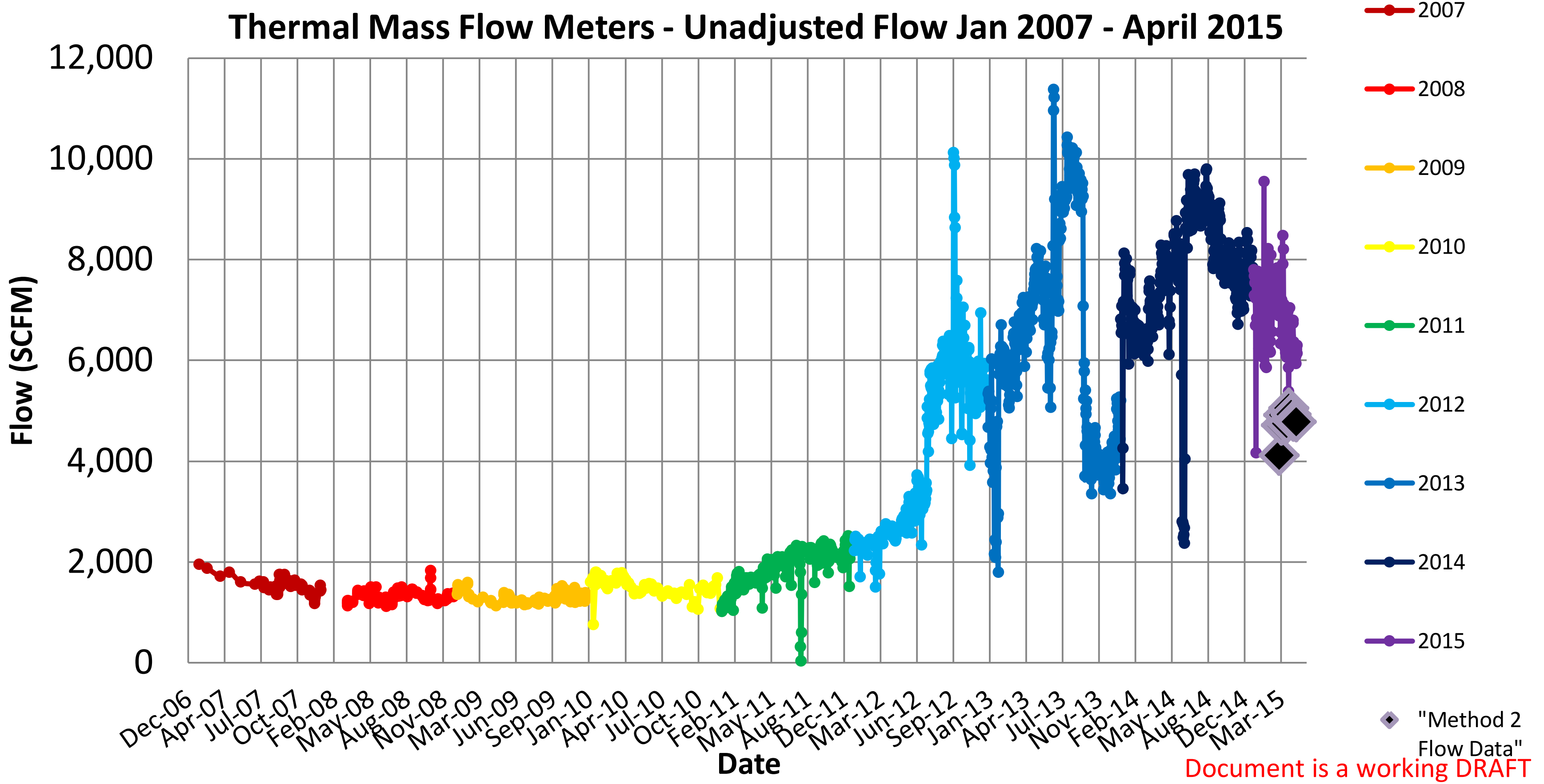
Bridgeton Landfill Gas Flow Data



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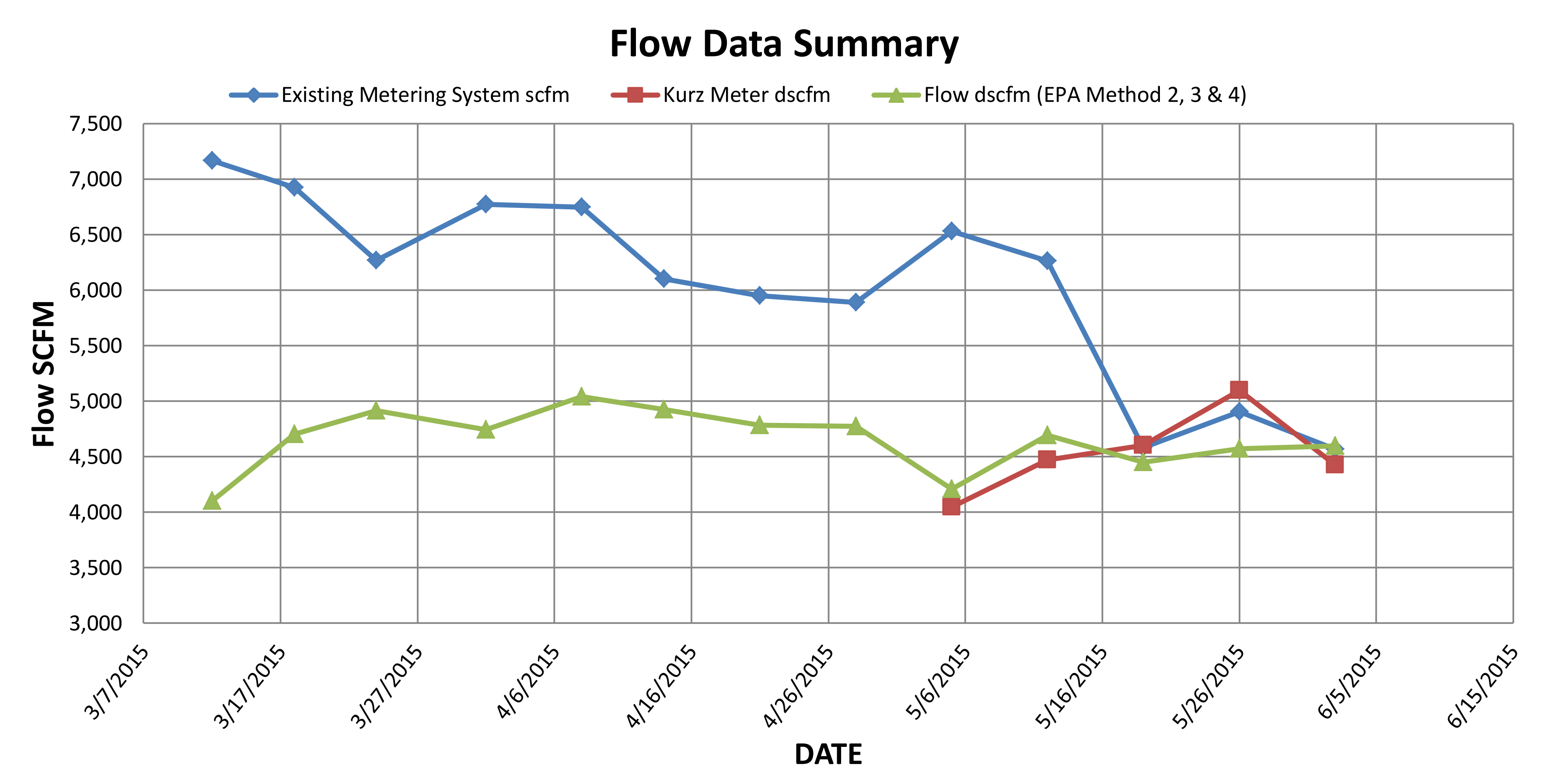
Bridgeton Landfill Gas Flow Data

- Existing meters-discovered accuracy issue in March-Method 2 testing.
- Variability TCI meters vs. method 2- Over reporting 20% to 45%.
- Extensive evaluation; tested and purchased updated meter technology (Kurz).

Bridgeton Landfill Gas Flow Test Data



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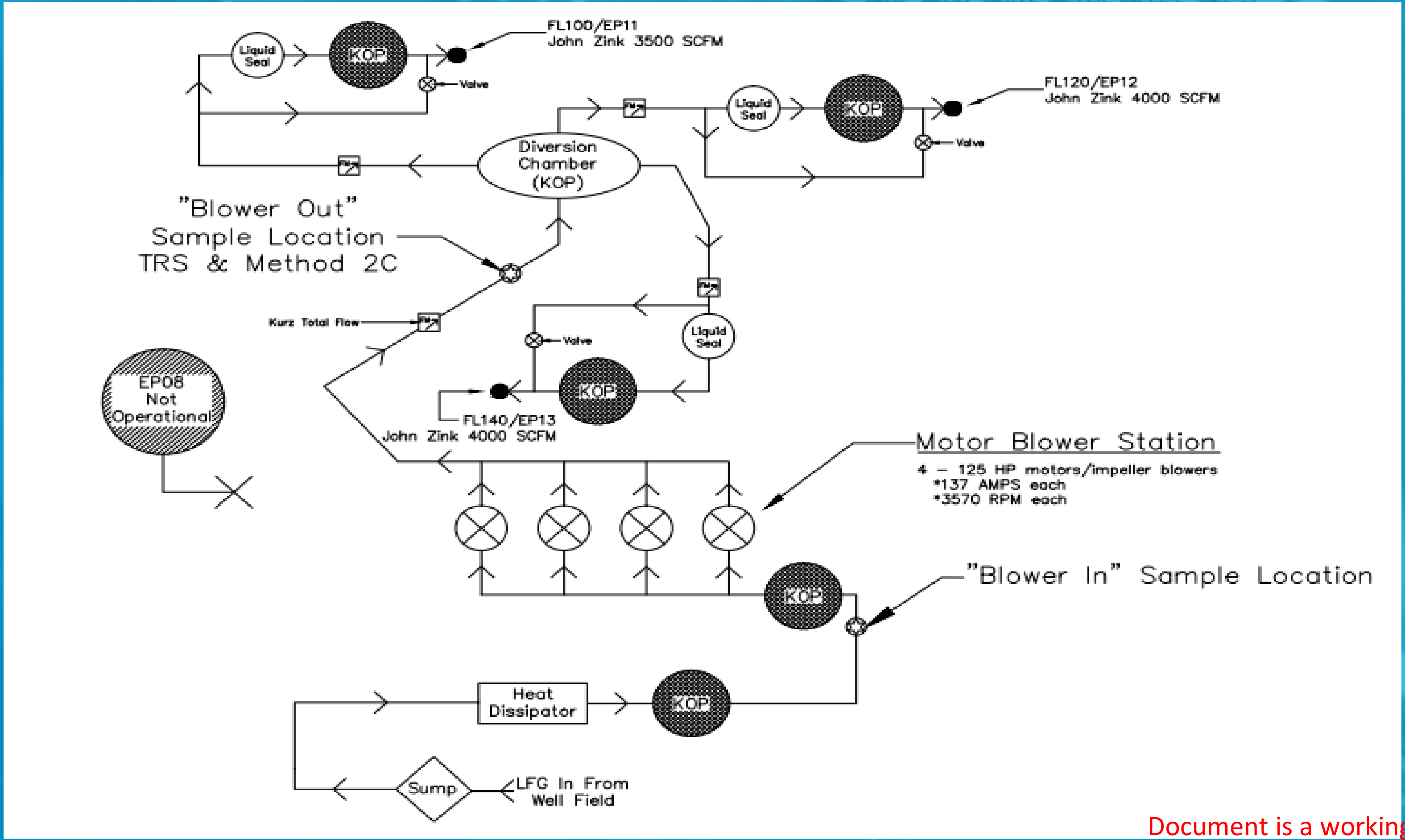
Bridgeton Landfill Sulfur Testing Location



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Bridgeton Landfill Sulfur Calculations

Demonstration of Annual Emissions Variability Based on Current Operating conditions:

- Logic for SO2 Emission Calculation
  - Daily averages of test event sulfur data by date,
  - Same test event date flow data using EPA approved method 2C for flow measurement,
  - AP-42 calculation for estimating SO_2 rate,

- Issues with past flow data (invalid prior to March 12, 2015),

- ‘mix and match’ approach of using sulfur concentration data and flow data from different days is invalid (i.e. Variability in air intrusion, spiking, gas operation),

- Assumptions with converting sulfur in LFG to SO2 (i.e. AP-42 SO2 calculation)

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Bridgeton Landfill Preliminary Sulfur Calculations

Date	TRS PPMV	DCFM Method 2	Q_p (m^3/yr)	UM_P (kg/yr)	TRS Flow/Input (lbs/day)	Daily Flow Rate - CM_{SO2} (in TPY)	Controlled "Future" PTE (TPY)
3/12/2015	1,518	4,104	92,721	129,221	71221	268	67
3/18/2015	846	4,702	59,169	82,461	45449	171	43
3/24/2015	833	4,913	60,910	84,888	46786	176	44
4/1/2015	1,076	4,742	75,923	105,810	58318	219	55
4/8/2015	1,250	5,042	93,802	130,727	72051	271	68
4/14/2015	1,400	4,925	102,621	143,017	78824	296	74
4/21/2015	1,250	4,785	89,021	124,064	68378	257	64
4/28/2015	1,200	4,774	85,264	118,828	65492	246	62
5/5/2015	1,800	4,210	112,786	157,184	86633	326	81
5/12/2015	1,300	4,695	90,840	126,600	69776	262	66
5/19/2015	1,450	4,452	96,078	133,899	73799	277	69
5/26/2015	1,400	4,573	95,286	132,795	73191	275	69
6/2/2015	1,300	4,596	88,925	123,930	68305	257	64

-Controlled "Future" PTE assumes 75% reduction of TRS

-CM_{SO2} Value determination performed based on daily TRS & DSCM values. Each row should be treated independently. Values are for informational purposes only.

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Bridgeton Landfill SO2 Control Technology

- Initial Pilot Test- Iron Sponge/MV Technologies.
- Technology Review- Stages 1 and 2.
- Technical Challenges- No commercially available control technology.
- Second pilot test- R&D Selected candidate Technologies.
- Propose using Temporary Treatment option- continuation of larger scale pilot system.
- Long Term control system, based on applicable air permitting requirements.

Bridgeton Landfill – Closing Points

- Ambient Air Monitoring has not identified any air quality issues.
- Air Modeling Results- No NAAQS exceedances identified.
  - Utilized conservative emission rates.
- Need to finalize Stage 2 pilot study
  - Current data is not representative of normal operations.
  - Insufficient data to estimate actual or potential emissions at this time.
  - Interim controls to be potentially installed by end of Summer 2015 to control TRS to below major source levels.


Thank You
Bridgeton Landfill LLC
bridgetonlandfill.com

Attachment – Question 5

Bridgeton Landfill, LLC.
Installation's Flares
MONTHLY 60.18 COMPLIANCE

SLCHD/APCP Permit No. 7840
Special Condition No. 3
FIPS ID = 189-0312

COMPLIANCE MONTH (MM/YYYY)	SAMPLE DATE (MM/DD/YYYY)	FLARE ID	FLARE UNOBSTRUCTED EXIT CROSS SECTION AREA (ft^2)	HYDROGEN CONTENT (%)	LFG NET HEATING VALUE (Btu/scf)	APPLICABILITY	MAXIMUM EXIT VELOCITY [V_{max}] (ft/sec)	AVG FLARE LFG INLET FLOW [Q_{LFG}] (scfm)	AVG ACTUAL EXIT VELOCITY [V_{actual}] (ft/sec)	COMPLIANCE with 60.18 and Permit Cond #5? (Yes/No)	MAX Q (scfm)
08/2015	08/04/15	EP-011 (FL100: Flare #1)	0.674	11.0	123.0	60.18©(3)(i)	64.00		0.00	Yes	2,588
	08/04/15	EP-012 (FL120: Flare #2)	0.936	11.0	127.0	60.18©(3)(i)	64.00		0.00	Yes	3,594
	08/04/15	EP-013 (FL140: Flare #3)	0.936	11.0	126.0	60.18©(3)(i)	64.00		0.00	Yes	3,594
	08/04/15	EP-014 (FXA1212: LFG CSU Flare)	0.8332	14.0	129.0	60.18©(3)(i)	102.40		0.00	Yes	5,119
07/2015	07/01/15	EP-011 (FL100: Flare #1)	0.674	10.0	127.0	60.18©(3)(i)	51.20	1592	39.37	Yes	2,071
	07/01/15	EP-012 (FL120: Flare #2)	0.936	10.0	128.0	60.18©(3)(i)	51.20	1663	29.61	Yes	2,875
	07/01/15	EP-013 (FL140: Flare #3)	0.936	10.0	130.0	60.18©(3)(i)	51.20	1840	32.76	Yes	2,875
	07/01/15	EP-014 (FXA1212: LFG CSU Flare)	0.8332	10.0	110.0	60.18©(3)(i)	51.20	0	0.00	Yes	2,560
06/2015	06/02/15	EP-011 (FL100: Flare #1)	0.674	11.0	140.0	60.18©(3)(i)	64.00	1435	35.49	Yes	2,588
	06/02/15	EP-012 (FL120: Flare #2)	0.936	11.0	139.0	60.18©(3)(i)	64.00	1650	29.39	Yes	3,594
	06/02/15	EP-013 (FL140: Flare #3)	0.936	10.0	142.0	60.18©(3)(i)	51.20	1765	31.43	Yes	2,875
	06/02/15	EP-014 (FXA1212: LFG CSU Flare)	0.8332	14.0	145.0	60.18©(3)(i)	102.40	740	14.80	Yes	5,119
05/2015	05/05/15	EP-011 (FL100: Flare #1)	0.674	11.0	157.0	60.18©(3)(i)	64.00	1387	34.30	Yes	2,588
	05/05/15	EP-012 (FL120: Flare #2)	0.936	11.0	158.0	60.18©(3)(i)	64.00	1809	32.21	Yes	3,594
	05/05/15	EP-013 (FL140: Flare #3)	0.936	11.0	159.0	60.18©(3)(i)	64.00	2165	38.55	Yes	3,594
	05/05/15	EP-014 (FXA1212: LFG CSU Flare)	0.8332	12.0	135.0	60.18©(3)(i)	76.80	347	6.95	Yes	3,839
04/2015	04/01/15	EP-011 (FL100: Flare #1)	0.674	10.0	128.0	60.18©(3)(i)	51.20	1832	45.31	Yes	2,071
	04/01/15	EP-012 (FL120: Flare #2)	0.936	9.9	130.0	60.18©(3)(i)	49.92	2223	39.58	Yes	2,804
	04/01/15	EP-013 (FL140: Flare #3)	0.936	10.0	127.0	60.18©(3)(i)	51.20	2229	39.68	Yes	2,875
	04/01/15	EP-014 (FXA1212: LFG CSU Flare)	0.8332	10.0	104.0	60.18©(3)(i)	51.20	467	9.34	Yes	2,560
03/2015	03/12/15	EP-011 (FL100: Flare #1)	0.674	11.0	119.0	60.18©(3)(i)	64.00	2005	49.58	Yes	2,588
	03/12/15	EP-012 (FL120: Flare #2)	0.936	10.0	117.0	60.18©(3)(i)	51.20	1849	32.92	Yes	2,875
	03/12/15	EP-013 (FL140: Flare #3)	0.936	11.0	124.0	60.18©(3)(i)	64.00	2936	52.28	Yes	3,594
	03/12/15	EP-014 (FXA1212: LFG CSU Flare)	0.8332	10.0	109.0	60.18©(3)(i)	51.20	828	16.56	Yes	2,560
02/2015	02/10/15	EP-011 (FL100: Flare #1)	0.674	10.0	104.0	60.18©(3)(i)	51.20	1873	46.32	Yes	2,071
	02/10/15	EP-012 (FL120: Flare #2)	0.936	10.0	105.0	60.18©(3)(i)	51.20	2425	43.19	Yes	2,875
	02/10/15	EP-013 (FL140: Flare #3)	0.936	10.0	106.0	60.18©(3)(i)	51.20	2484	44.23	Yes	2,875
	02/10/15	EP-014 (FXA1212: LFG CSU Flare)	0.8332	10.0	94.3	60.18©(3)(i)	51.20	672	13.44	Yes	2,560
01/2015	01/02/15	EP-011 (FL100: Flare #1)	0.674	13.0	141.0	60.18©(3)(i)	89.60	1844	45.60	Yes	3,623
	01/02/15	EP-012 (FL120: Flare #2)	0.936	13.0	139.0	60.18©(3)(i)	89.60	2221	39.55	Yes	5,032
	01/02/15	EP-013 (FL140: Flare #3)	0.936	11.0	118.0	60.18©(3)(i)	64.00	2890	51.47	Yes	3,594
	01/02/15	EP-014 (FXA1212: LFG CSU Flare)	0.8332	12.0	128.0	60.18©(3)(i)	76.80	521	10.41	Yes	3,839
12/2014	12/22/14	EP-011 (FL100: Flare #1)	0.674	12	125.0	60.18©(3)(i)	76.80	2226	55.05	Yes	3,106
	12/22/14	EP-012 (FL120: Flare #2)	0.936	12	131.0	60.18©(3)(i)	76.80	2953	52.58	Yes	4,313
	12/22/14	EP-013 (FL140: Flare #3)	0.936	12	132.0	60.18©(3)(i)	76.80	2613	46.53	Yes	4,313
	12/22/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	12	128.0	60.18©(3)(i)	76.80	0	0.00	Yes	3,839
12/2014	12/12/04	EP-011 (FL100: Flare #1)	0.674	9.2	106.0	60.18©(3)(i)	40.96	2338	57.81	NO-Corrective Action Needed	1,656
	12/12/04	EP-012 (FL120: Flare #2)	0.936	8.9	105.0	60.18©(3)(i)	37.12	2711	48.27	NO-Corrective Action Needed	2,085
	12/12/04	EP-013 (FL140: Flare #3)	0.936	8.0	93.4	60.18©(3)(i)	25.60	3091	55.03	NO-Corrective Action Needed	1,438
	12/12/04	EP-014 (FXA1212: LFG CSU Flare)	0.8332	12.0	128.0	60.18©(3)(i)	76.80	650	13.00	Yes	3,839
11/2014	11/03/04	EP-011 (FL100: Flare #1)	0.674	11.0	136.0	60.18©(3)(i)	64.00	2018	49.89	Yes	2,588
	11/03/04	EP-012 (FL120: Flare #2)	0.936	11.0	135.0	60.18©(3)(i)	64.00	2726	48.53	Yes	3,594
	11/03/04	EP-013 (FL140: Flare #3)	0.936	11.0	143.0	60.18©(3)(i)	64.00	2778	49.47	Yes	3,594
	11/03/04	EP-014 (FXA1212: LFG CSU Flare)	0.8332	8.3	95.0	60.18©(3)(i)	29.44	271	5.43	Yes	1,472
10/2014	10/01/14	EP-011 (FL100: Flare #1)	0.674	12.0	152.0	60.18©(3)(i)	76.80	2365	58.47	Yes	3,106
	10/01/14	EP-012 (FL120: Flare #2)	0.936	12.0	150.0	60.18©(3)(i)	76.80	3134	55.81	Yes	4,313
	10/01/14	EP-013 (FL140: Flare #3)	0.936	12.0	155.0	60.18©(3)(i)	76.80	2714	48.32	Yes	4,313
	10/01/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	11.0	137.0	60.18©(3)(i)	64.00	573	11.46	Yes	3,199
09/2014	09/03/14	EP-011 (FL100: Flare #1)	0.674	12.0	155.0	60.18©(3)(i)	76.80	2104	52.03	Yes	3,106
	09/03/14	EP-012 (FL120: Flare #2)	0.936	12.0	158.0	60.18©(3)(i)	76.80	3061	54.51	Yes	4,313
	09/03/14	EP-013 (FL140: Flare #3)	0.936	12.0	151.0	60.18©(3)(i)	76.80	3310	58.94	Yes	4,313

Bridgeton Landfill, LLC.
Installation's Flares
MONTHLY 60.18 COMPLIANCE

SLCHD/APCP Permit No. 7840
Special Condition No. 3
FIPS ID = 189-0312

COMPLIANCE MONTH (MM/YYYY)	SAMPLE DATE (MM/DD/YYYY)	FLARE ID	FLARE UNOBSTRUCTED EXIT CROSS SECTION AREA (ft^2)	HYDROGEN CONTENT (%)	LFG NET HEATING VALUE (Btu/scf)	APPLICABILITY	MAXIMUM EXIT VELOCITY [V_{max}] (ft/sec)	AVG FLARE LFG INLET FLOW [Q_{LFG}] (scfm)	AVG ACTUAL EXIT VELOCITY [V_{actual}] (ft/sec)	COMPLIANCE with 60.18 and Permit Cond #5? (Yes/No)	MAX Q (scfm)
	09/03/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	10.0	147.0	60.18©(3)(i)	51.20	714	14.28	**Yes**	**2,560**
08/2014	08/05/14	EP-011 (FL100: Flare #1)	0.674	13.0	162.0	60.18©(3)(i)	89.60	2140	52.92	**Yes**	**3,623**
	08/05/14	EP-012 (FL120: Flare #2)	0.936	13.0	164.0	60.18©(3)(i)	89.60	3278	58.36	**Yes**	**5,032**
	08/05/14	EP-013 (FL140: Flare #3)	0.936	13.0	164.0	60.18©(3)(i)	89.60	3679	65.52	**Yes**	**5,032**
	08/05/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	17.0	191.0	60.18©(3)(i)	140.80	807	16.14	**Yes**	**7,039**
07/2014	07/03/14	EP-011 (FL100: Flare #1)	0.674	12.0	157.0	60.18©(3)(i)	76.80	2187	54.09	**Yes**	**3,106**
	07/03/14	EP-012 (FL120: Flare #2)	0.936	12.0	158.0	60.18©(3)(i)	76.80	3224	57.40	**Yes**	**4,313**
	07/03/14	EP-013 (FL140: Flare #3)	0.936	12.0	158.0	60.18©(3)(i)	76.80	3682	65.56	**Yes**	**4,313**
	07/03/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	06/25/2014 EP-014 source on standby status. Operated on "as needed" basis"				630	12.61	Yes	
06/2014	06/04/14	EP-011 (FL100: Flare #1)	0.674	13.0	180.0	60.18©(3)(i)	89.60	1866	46.14	**Yes**	**3,623**
	06/04/14	EP-012 (FL120: Flare #2)	0.936	12.0	180.0	60.18©(3)(i)	76.80	2774	49.39	**Yes**	**4,313**
	06/04/14	EP-013 (FL140: Flare #3)	0.936	13.0	180.0	60.18©(3)(i)	89.60	3172	56.47	**Yes**	**5,032**
	06/04/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	12.0	170.0	60.18©(3)(i)	76.80	590	11.80	**Yes**	**3,839**
05/2014	5/6/14	EP-011 (FL100: Flare #1)	0.674	12.0	170.0	60.18©(3)(i)	76.80	1456	35.99	**Yes**	**3,106**
	5/6/14	EP-012 (FL120: Flare #2)	0.936	11.0	170.0	60.18©(3)(i)	64.00	2866	51.03	**Yes**	**3,594**
	5/6/14	EP-013 (FL140: Flare #3)	0.936	11.0	170.0	60.18©(3)(i)	64.00	2965	52.79	**Yes**	**3,594**
	5/6/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	13.0	160.0	60.18©(3)(i)	89.60	636	12.71	**Yes**	**4,479**
04/2014	4/4/14	EP-011 (FL100: Flare #1)	0.674	12.0	130.0	60.18©(3)(i)	76.80	2108	52.12	**Yes**	**3,106**
	4/4/14	EP-012 (FL120: Flare #2)	0.936	11.0	130.0	60.18©(3)(i)	64.00	1855	33.04	**Yes**	**3,594**
	4/4/14	EP-013 (FL140: Flare #3)	0.936	11.0	130.0	60.18©(3)(i)	64.00	2731	48.63	**Yes**	**3,594**
	4/4/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	9.5	120.0	60.18©(3)(i)	44.80	865	17.30	**Yes**	**2,240**
03/2014	3/11/14	EP-011 (FL100: Flare #1)	0.674	12.0	150.0	60.18©(3)(i)	76.80	1524	37.69	**Yes**	**3,106**
	3/11/14	EP-012 (FL120: Flare #2)	0.936	13.0	160.0	60.18©(3)(i)	89.60	2251	40.08	**Yes**	**5,032**
	3/11/14	EP-013 (FL140: Flare #3)	0.936	13.0	160.0	60.18©(3)(i)	89.60	2459	43.78	**Yes**	**5,032**
	3/11/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	8.4	140.0	60.18©(3)(i)	30.72	813	16.27	**Yes**	**1,536**
02/2014	2/4/04	EP-011 (FL100: Flare #1)	0.674	9.2	120.0	60.18©(3)(i)	40.96	1416	35.01	**Yes**	**1,656**
	2/4/04	EP-012 (FL120: Flare #2)	0.936	9.5	120.0	60.18©(3)(i)	44.80	2438	43.41	**Yes**	**2,516**
	2/4/04	EP-013 (FL140: Flare #3)	0.936	9.5	120.0	60.18©(3)(i)	44.80	1879	33.46	**Yes**	**2,516**
	2/4/04	EP-014 (FXA1212: LFG CSU Flare)	0.8332	9.0	120.0	60.18©(3)(i)	38.40	1216	24.32	**Yes**	**1,920**
01/2014	01/02/14	EP-011 (FL100: Flare #1)	0.674	9.9	130.0	60.18©(3)(i)	49.92	1891	46.77	**Yes**	**2,019**
	01/02/14	EP-012 (FL120: Flare #2)	0.936	9.9	130.0	60.18©(3)(i)	49.92	1892	33.68	**Yes**	**2,804**
	01/02/14	EP-013 (FL140: Flare #3)	0.936	9.9	130.0	60.18©(3)(i)	49.92	1988	35.39	**Yes**	**2,804**
	01/02/14	EP-014 (FXA1212: LFG CSU Flare)	0.8332	11.0	150.0	60.18©(3)(i)	64.00	1028	20.57	**Yes**	**3,199**
12/2013	12/10/13	EP-011 (FL100: Flare #1)	0.674	8.1	110.0	60.18©(3)(i)	26.88	1358	33.58	**NO-Corrective Action Needed**	**1,087**
	12/10/13	EP-012 (FL120: Flare #2)	0.936	8.5	120.0	60.18©(3)(i)	32.00	2140	38.11	**NO-Corrective Action Needed**	**1,797**
	12/10/13	EP-013 (FL140: Flare #3)	0.936	8.8	120.0	60.18©(3)(i)	35.84	1767	31.47	**Yes**	**2,013**
	12/10/13	EP-014 (FXA1212: LFG CSU Flare)	0.8332	7.4	120.0	Non Compliant	0.00	967	19.35	**NO-Corrective Action Needed**	**0**
11/2013	11/20/13	EP-011 (FL100: Flare #1)	0.674	10.0	130.0	60.18©(3)(i)	51.20	918	22.69	**Yes**	**2,071**
	11/20/13	EP-012 (FL120: Flare #2)	0.936	9.9	130.0	60.18©(3)(i)	49.92	1763	31.39	**Yes**	**2,804**
	11/20/13	EP-013 (FL140: Flare #3)	0.936	9.8	130.0	60.18©(3)(i)	48.64	2059	36.66	**Yes**	**2,732**
	11/20/13	EP-014 (FXA1212: LFG CSU Flare)	0.8332	8.0	140.0	60.18©(3)(i)	26.11	1093	21.86	**Yes**	**1,305**
10/2013	10/30/13	EP-011 (FL100: Flare #1)	0.674	9.6	188.0	60.18©(3)(i)	46.08	1152	28.48	**Yes**	**1,863**
	10/30/13	EP-012 (FL120: Flare #2)	0.936	9.6	188.0	60.18©(3)(i)	46.08	1861	33.14	**Yes**	**2,588**
	10/30/13	EP-013 (FL140: Flare #3)	0.936	9.6	188.0	60.18©(3)(i)	46.08	2147	38.23	**Yes**	**2,588**
	10/30/13	EP-014 (FXA1212: LFG CSU Flare)	0.8332	8.4	212.0	60.18©(3)(i)	30.72	1175	23.50	**Yes**	**1,536**

Attachment – Question 6

JOHN ZINK HAMWORTHY COMBUSTION

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Ingrid McKoy
Vapor Controls Project Manager

TO: Mr. Jim Getting.
Bridgeton Landfill LLC, Environmental Manager

DATE: May 28, 2015

REFERENCE: Sales Orders 9128755 & 9136795
Elevated ZEF™ Flare Radiant Heat Fraction

John Zink Hamworthy Combustion (John Zink) has over more than 80 years of combustion experience and has remained a global leader in emissions-control and clean-air systems, delivering next-generation technologies backed by proven experience and expertise, along with unmatched service and support. Since our establishment in 1929, John Zink has more installed equipment than any other manufacturer in our industry. We have more than 250 U.S. patents (and hundreds more worldwide). Our three research and development test centers make up the largest and most advanced combustion testing complex in the industry. Finally, *The John Zink Combustion Handbook* is an industry standard reference and has been a top-seller since 2006.

John Zink provided three Elevated ZEF Flares to Bridgeton Landfill LLC (Bridgeton Landfill), one of which is 14" diameter, (FL-100) and the other two are 16" diameter (FL-120 and FL-140). John Zink understands that Bridgeton Landfill is required to perform air emission modeling for these flares that, in part, is based on the calculated radiant heat fraction of the flares.

As part of our design process, John Zink utilizes a proprietary design program that incorporates methods based on the American Petroleum Institute (API) Standard 521 as well as our own proprietary methods. This topic is addressed in *The John Zink Combustion Handbook* and the John Zink Company, *Flare Radiation* paper included. The calculation method considers a number of factors including flare tip exit area, gas composition, and gas flow rate. Our design program is proprietary and as a result we cannot provide detailed information on the equations that are incorporated in this program. John Zink was asked by Bridgeton Landfill to run the design program for two scenarios for each of the three flares.

The following are the inputs that were entered and the resulting average radiant fraction (for determining thermal radiation levels at a given point):

Scenario 1- Flare FL-100:

Methane (%): 28
Carbon Dioxide (%): 38
Oxygen (%): 5
Nitrogen (%): 19
Hydrogen (%): 10
Nominal Diameter (in): 14
Gas Temperature (˚F): 100
Flow rate (scfm): 2,327

Calculated Average Radiant Fraction = 0.11

Scenario 1- Flare FL-120:

Methane (%): 28
Carbon Dioxide (%): 38
Oxygen (%): 5
Nitrogen (%): 19
Hydrogen (%): 10
Nominal Diameter (in): 16
Gas Temperature (˚F): 100
Flow rate (scfm): 3,243

Calculated Average Radiant Fraction = 0.11

Scenario 1- Flare FL-140:

Methane (%): 28
Carbon Dioxide (%): 38
Oxygen (%): 5
Nitrogen (%): 19
Hydrogen (%): 10
Nominal Diameter (in): 16
Gas Temperature (˚F): 100
Flow rate (scfm): 3,430 (exceeds maximum velocity limitation per 40 CFR 60.18)

Calculated Average Radiant Fraction = 0.11

Scenario 2- Flare FL-100:

Methane (%): 9.11
Carbon Dioxide (%): 38.99
Oxygen (%): 8.24
Nitrogen (%): 32.52
Hydrogen (%): 11.02
Carbon Monoxide (%): 0.12
Nominal Diameter (in): 14
Gas Temperature (˚F): 100
Flow rate (scfm): 955

Calculated Average Radiant Fraction = 0.08

Scenario 2- Flare FL-120:

Methane (%): 9.11
Carbon Dioxide (%): 38.99
Oxygen (%): 8.24
Nitrogen (%): 32.52
Hydrogen (%): 11.02
Carbon Monoxide (%): 0.12
Nominal Diameter (in): 16
Gas Temperature (˚F): 100
Flow rate (scfm): 1,331

Calculated Average Radiant Fraction = 0.08

Scenario 2- Flare FL-140:

Methane (%): 9.11
Carbon Dioxide (%): 38.99
Oxygen (%): 8.24
Nitrogen (%): 32.52
Hydrogen (%): 11.02
Carbon Monoxide (%): 0.12
Nominal Diameter (in): 16
Gas Temperature (˚F): 100
Flow rate (scfm): 1,408

Calculated Average Radiant Fraction = 0.08

JOHN ZINK COMPANY

FLARE RADIATION

LOCATION

Radiation is a Major Factor

GENERALLY

ACCEPTABLE RADIATION LEVELS

(BTU/Hr-Sq. Ft.)

Public access areas 440 - 1000

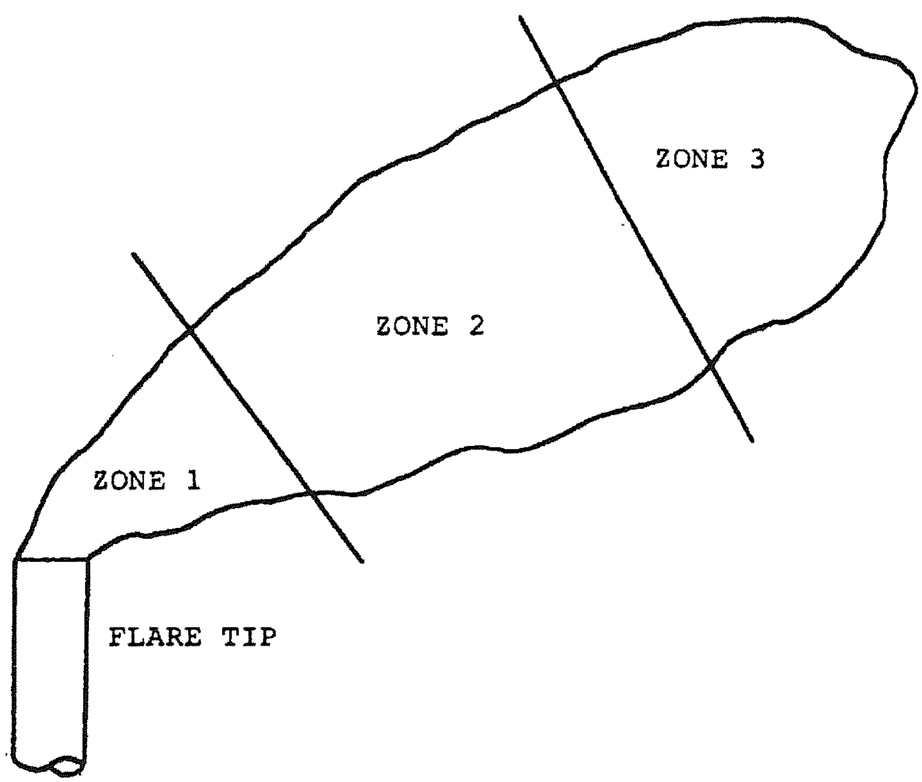
Plants (normal access) 1500 - 1650

Plants (limited access) 2000+

NOTE: Due to the complexity of calculations, we have computerized these calculations. Please check with Tulsa for this information.

RADIATION CALCULATION METHOD

John Zink Company uses a three-point model to predict radiation from a flare flame. This allows us to model three distinct zones in a typical flare flame. Each zone may have a different emissivity and a different fraction of the total heat release. The sketch below illustrates a typical propane fire.



THEORY

Zone 1 is a clean, yellow, highly oxygenated portion of the flame. The emissivity in this zone is approximately the same as the average for the entire flame. The fraction of the heat release associated with this zone depends on the smoking tendency of the waste stream. Zone 1 size decreases as the smoking tendency of the gas increases.

Zone 2 is a portion of the flame where much of the oxygen inspirated in Zone 1 has been consumed. As a result, a higher concentration of hot uncombined carbon causes the flame color to change from yellow to dirty orange. The emissivity in this zone can be nearly twice that in Zone 1.

Zone 3 is a portion of the flame where the hot uncombined carbon from Zone 2 has cooled to the point where it no longer glows. The cooler uncombined carbon forms smoke. This portion of the flame has a relatively low emissivity due to the thick covering of smoke. The size of Zone 3 increases with the smoking tendency of the waste stream.

Our calculation procedure uses an API type method to calculate flame length and lean. Three points along the API flame line are selected according to the theory outlined previously. Each point is assigned an emissivity and a fraction of the total heat release. The exact locations, emissivities and fractions for these points are calculated by a proprietary computer program. The radiation from each point is calculated using the familiar API formula:

$$RAD_i = \frac{E}{4} \frac{Q}{d^2}, \quad i = 1, 2, 3$$

RAD = Radiation (BTU/HR-SQ.FT)
E = Emissivity
Q = Heat Released (BTU/HR)
d = Distance to point of interest (ft)

The total radiation at the point of interest is the sum of the contributions from the three points.

Table 10 — Radiation from gaseous diffusion flames

Gas	Burner diameter cm	Fraction of heat radiated
Hydrogen	0,51	0,095
	0,91	0,091
	1,90	0,097
	4,10	0,111
	8,40	0,156
	20,30	0,154
	40,60	0,169
Butane	0,51	0,215
	0,91	0,253
	1,90	0,286
	4,10	0,285
	8,40	0,291
	20,30	0,280
	40,60	0,299
Methane	0,51	0,103
	0,91	0,116
	1,90	0,160
	4,10	0,161
	8,40	0,147
Natural gas (95 % CH_4)	20,30	0,192
	40,60	0,232

Several formulas for calculating flame length and approximating flame tilt are presented in the literature [70], [94], [96], [97], [98]. Each formula has its own special range of applicability and should be used with caution, particularly since the combined impact of several factors (radiation, radiant heat fraction, flame length and centre and flame tilt) shall be considered.

The example in C.3 is another approach to calculating the probable radiation effects, using the more recent method of Brzustowski and Sommer [94]. The principal difference between these methods is the location of the flame centre. The curves and graphs necessary to simplify the calculations are included in Annex C.

There are other methods that can be utilized to calculate radiation from flares. More sophisticated models that consider wind velocity, exit flare gas velocity, flame shape and flame segmental analysis can be appropriate for special cases, especially with large release systems.

Most flare manufacturers have developed proprietary radiation programs based on empirical values. The F factor (fraction of heat radiated) values used in these programs are specific to the equations used, and might not be interchangeable with the F factor values used in Equation (24). These programs have not been subject to review and verification in the open literature. The user is cautioned to assess the applicability of these methods to his or her particular situation.

6.4.3 Combustion methods

6.4.3.1 General

Disposal of combustible gases, vapours and liquids by burning is generally accomplished in flares. Flares are used for environmental control of continuous flows of excess gases and for large surges of gases in an emergency. The flare is usually required to be smokeless for the gas flows that are expected to occur from

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Accurately predict radiation from flare stacks

Using this technique can take the guess work out of design calculations and improve costs

J. HONG, J. WHITE and **C. BAUKAL,** John Zink Co., LLC, Tulsa, Oklahoma

Elevated flares are commonly used in the hydrocarbon processing industry. They are typically designed to handle a wide range of flowrates from purge to very large emergency release rates. Flare stack height has to be properly designed to address safety considerations such as thermal radiation and flue gas dispersion. In many cases, thermal radiation forms the basis for determining flare stack height and location, as well as sizing the limited-access area surrounding the flare. Overestimating flare radiation (FR) results in a taller-than-required stack and increased costs. Underestimating FR results in a shorter-than-required stack, which exposes personnel and equipment to potentially dangerous radiation levels. Thus, it is very important to predict radiation from flares as accurately as possible.

Many models exist for estimating FR.[1] Predicted radiation levels at a certain location can differ by a factor of three depending on the model used.[1] This highlights the importance of validating models with scientifically measured data. Unfortunately, very little reliable radiation data is available to determine which model(s) fits the data best. Plant designers and end users should recognize that traditional calculation methods for radiant heat intensities are neither consistently too optimistic nor consistently too conservative.[2]

FR prediction. Radiation from a solid body is directly related to its emissivity and the fourth power of the absolute surface temperature. Calculating radiation from a flare's flame is not as simple as calculating it for a solid surface. Because flames have a turbulent nature, it is difficult to determine a "surface." Even if the surface can be defined and its temperature determined, it is very difficult to estimate the flame's surface "emissivity" as it depends on the reacting volume's temperature and composition inside the surface. In fact, FR involves gas radiation, gas absorption and soot radiation.[2] Gas absorbs and emits radiation in discrete energy bands, unlike solid surfaces that absorb and emit radiant energy over a continuous spectrum. Predicting soot concentration and size distribution is very difficult and currently not practical for predicting FR.

A realistic approach to predicting radiation is to treat the flame as a single point source or as a number of point sources, and then use a certain "fraction" of the total heat release as the radiant energy emitted by the flare.[3] A term called the radiant fraction (RF) is used to describe all uncertainties in the theoretical radiation calculation in an absorbing-emitting-scattering medium. Although selecting a flame shape model is also important, radiation prediction is only as accurate as the radiant fraction, no matter which theoretical model is used.

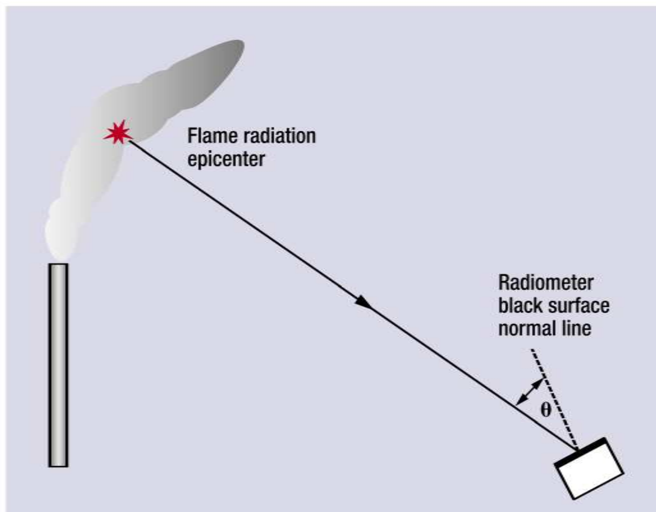

FIG. 1 Traditional measuring method for FR where the radiometer is aligned for maximum radiation reception.

It is well known that some waste gases tend to have higher RFs than others. For example, propylene tends to have a higher RF than propane under similar flow conditions. In the past, researchers have attempted to correlate RFs with individual fuel gases, lower heating value, molecular weight or the waste gas mixture's hydrogen/carbon ratio.[3–6] However, these previous studies failed to consider many other factors influencing the RF. These include, but are not limited to, gas pressure at the flare exit, the flare tip's size, the amount of air or steam supplied if the flare is assisted and the flare tip's geometry. Due to the RF's convoluted nature, it is very difficult to predict. The most reliable model needs to be based on RF values measured in full-scale tests with a sophisticated radiation measurement system.

FIG. 2 Phased array radiometer cube consisting of three radiometer sensors strategically placed at certain angles to measure the incident radiation HF vector components.

FIG. 3 Pressure-assisted flare before firing (left) [note one of the tripod mounted radiometer cubes on the ground]. Same flare firing natural gas at a relatively low pressure (right).

Radiation measurement. A radiometer measures thermal radiation. It usually has a transducer that converts heat flux (HF) into an electrical signal. The transducer is often a thermopile which is an array of tiny thermocouples, embedded in a thin cross-section with a blackened surface. It is important that only radiation is measured and not any forced convection caused by ambient air blowing over the detector's surface. Radiation prediction models do not include any convective cooling, which means that it would need to be subtracted out of or excluded from the measurement. Since forced convection can also be relatively complicated, it is better to exclude it from the measurement.

Historically two approaches have been used to minimize or eliminate the effects of convective cooling. One is to place the detector in a cavity, without any window covering the opening. The cavity is thought to mitigate the convective cooling effect of ambient air blowing over the detector. The cavity's actual effectiveness in minimizing convective cooling is not well understood, especially on windy days. Caution should be used with this radiometer type making sure the flare flame is well within the radiometer's viewing field. Otherwise, some of the incident radiation may be inadvertently shielded by the relatively narrow cavity opening.

The second approach to mitigating convective cooling is to use a cover adjacent to the black surface. Caution should be used in selecting cover material. Most common materials, such as window glass, are not suitable. It appears transparent to human eyes but is partially or completely opaque in the infrared range, which is the dominant region for FR. This means that some portion of the radiation is absorbed by the window before reaching the detector. The actual FR would then be under predicted.

A radiometer suited for solar radiation is not necessarily appropriate for FR. The sun's effective surface temperature is much higher than a flare's flame temperature. A large portion of energy from solar radiation is distributed in the short wavelength range up to the visible range.[7] In contrast, FR is predominantly infrared, which is in the longer wavelength range. One may argue that a partially opaque cover can be calibrated for FR measurements. However, flare flames differ from each other in terms of spectral distribution. The cover material's transmissivity may vary according to the flame's spectral distribution, and its value for the specific flare under precise conditions is often unknown to the user. Therefore it is important to use the right cover material for the radiometer sensor.

Traditionally, radiation intensity has been measured by aiming a radiometer at the flare's flame as shown in Fig. 1. The radiometer is manually scanned across the flame in an up-and-down, left-and-right motion. The maximum measured radiant HF is then recorded. This manual scanning requires a trained person to stand at the point of interest, which could be a hazardous location due to potential exposure to high thermal radiation. The person must often wear personal protection equipment, which makes the manual data recording difficult. If the waste gas flowrate is fluctuating, or if the wind causes the flare's flame to move, it becomes much more challenging to find the maximum radiant HF. Also, it is important that the radiometer is perpendicular to the flame at the point of maximum radiation. Otherwise, the measured radiation HF will be less than the actual value by a factor of $\cos\theta$. Fortunately, this deviation is relatively small for small angles.

Radiometer cube. After testing various commercially-available devices used to measure thermal radiation, numerous deficiencies were found. Thus a device was developed to automate FR measurements. It utilizes a phased array of radiometers to measure vector components of the incident radiation HF. Three radiometers are strategically placed at certain angles to measure certain fractions of incident radiant HF. These vector components are used to calculate the total radiation HF from the radiation epicenter, as well as the direction of the radiation HF. There is no need to scan the radiometer or place a person in a hazardous location. The radiometer system can be equipped with data acquisition equipment to continuously record thermal radiation HF readings. The radiometer cube (Fig. 2) uses single radiometer sensors covered with special polished optical

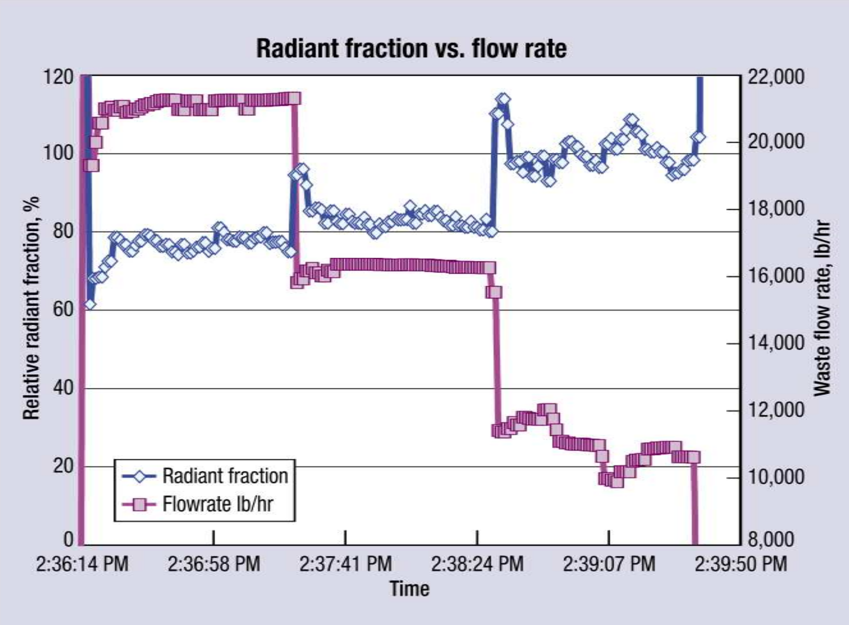

FIG. 4 Calculated RF and measured waste gas flowrate as a function of time. The RF values are normalized with the base case which is at the lowest flowrate among the flow rates shown here. This illustrates the dependence of RF on flowrate (or pressure).

material. If the flare waste gas flowrate and composition are also known, the RF can be estimated from the measured total radiant HF by using one radiometer cube.

The radiometer cube not only measures total radiant HF, but also the HF's direction. By using two radiometer cubes in different locations, the radiation epicenter can be calculated, by intersecting the two beams of incident radiation toward the two cubes, using a sophisticated mathematical manipulation. If the flowrate and waste gas composition are also known, the RF and flame epicenter can be calculated simultaneously in real time. The RF and radiation epicenter location are the two key parameters in the API 521 radiation model.[3] This device helps reduce uncertainties in estimating these two parameters.

Test results. Two phased array radiometers were used to measure the radiation epicenter and RF from a pressure-assisted flare (Fig. 3). Before the test started, the coordinates of the radiometers and the flare tip were determined by using a laser range finder and surveying equipment. The flare tip and the two radiometer cubes' coordinates, along with the orientation angles for the radiometer cubes, were then entered into a computer. During the test, the HF readings and the waste gas flowrate were sent to the computer for data processing. The total heat release was computed from the measured flowrate and known waste gas composition. The radiation epicenter coordinates were computed in real time. Then, the RF was computed in real time. The RF and flowrate as a function of time is shown in Fig. 4. The RF increased as the flowrate decreased because the flame became less aerated and produced more soot due to reduced turbulence.

Overview. A new device has been developed to simultaneously determine an industrial flare's RF and flame epicenter. These are both needed to use the API 521 model for calculating FR. The device does not require any manual scanning, thus reducing measurement errors and avoiding placing personnel in a hazardous situation to operate equipment. It also significantly reduces the uncertainty in determining these two key parameters.

Failure to properly estimate the radiation from a flare could result in a flare that is either taller or shorter than required. This means that the flare system could cost more than necessary or expose personnel and equipment to potentially dangerous thermal radiation levels. Accurate flare prediction requires a proven and reliable technique for estimating the parameters used in the model which are dependent on the specific flare design and operating conditions. It is recommended that these parameters be determined from validated experimental data because of their importance in the overall flare system design. **HP**

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Industrial-Scale Flare Testing

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Advanced flare testing at full-scale can help ensure that the system operates as designed. This article explains what's involved and the parameters that should be measured and evaluated to demonstrate performance, reliability and safety.

Figure 1. An industrial-scale flare test facility should be able to evaluate a wide range of flows.

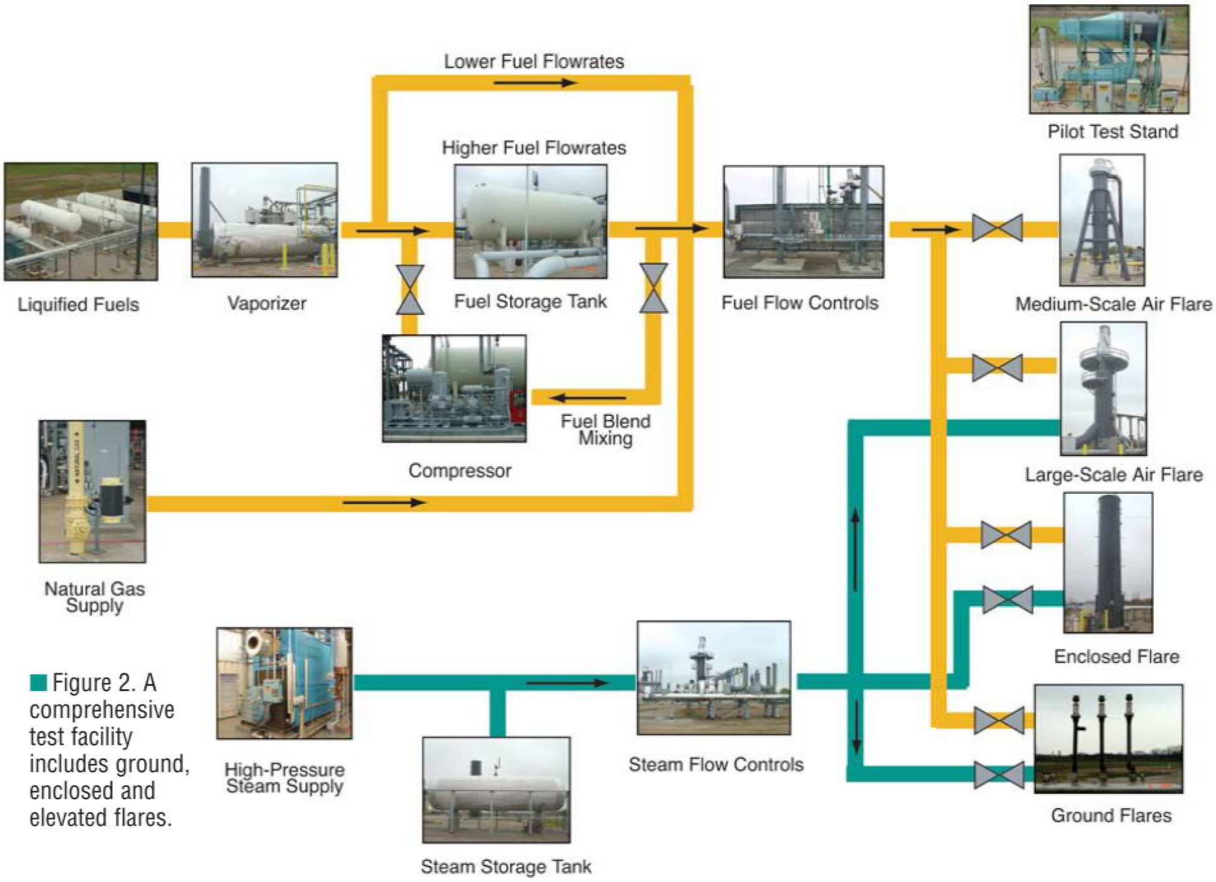
Today's process industries expect more from flare systems than ever before. Chemical and petroleum processing plants depend on flares to burn hydrocarbons, such as propane, propylene, ethylene, butadiene, butane and natural gas, found in waste gases. Landfills and wastewater treatment plants, oil-and-gas exploration and production facilities, and loading terminals also use flares to destroy potentially harmful gases.

In each case, the flare system must separate the gases from any liquids present, ignite the gases, and provide the stable combustion necessary for destruction, while minimizing smoke, thermal radiation and noise. And, it must operate reliably and safely under a wide range of operating conditions, including weather extremes.

With a greater demand for increased smokeless capacities, higher turndown and more-efficient plant production, a flare failure can carry a big price tag. Factor in the essential role flares play in the safe and environmentally acceptable disposal of waste gases produced from industrial operations *(1, 2)*, and it's easy to understand why processing industries can benefit from flare testing as a safeguard against unexpected problems in the field. Testing a flare before installation is a proactive measure to minimize the uncertainty of flare performance, emission levels, and the expense of repairs in the event of a problem.

But testing flares *in the field* is generally difficult or impossible for several reasons. Operating flares usually do not have the instrumentation required for assessing performance. Operating conditions are not easily modified or controlled, and taking the plant off-line to test the flare is impractical. In addition, flares are nearly impossible to test under critical design conditions once installed.

Characterizing flare performance for reliability and safety requires comprehensive, accurate testing at full-scale and under controlled conditions to collect and analyze critical data. Although flare performance might be estimated based



■ Figure 2. A comprehensive test facility includes ground, enclosed and elevated flares.

on scaled-down experimentation and empirical data, industrial-scale testing is the most reliable method due to the complexity of the process. While testing custom-designed burners for process heaters has been common for decades, that has not been true for large industrial flares, primarily due to the lack of adequate testing facilities. With the advent of state-of-the-art flare test facilities, large-scale flare testing is recommended to ensure proper performance.

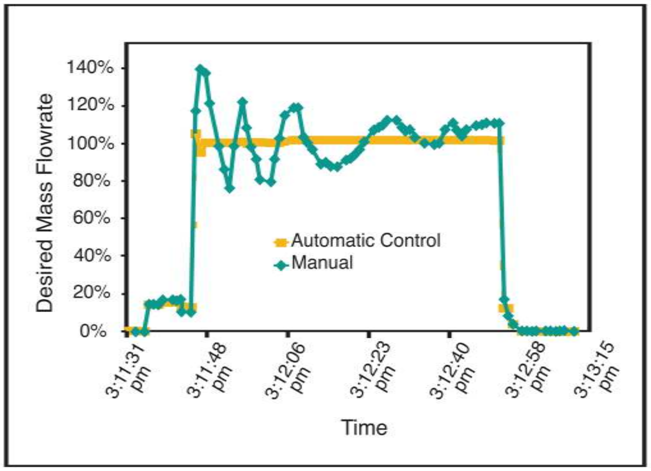
Advanced flare testing

Just as flares have evolved into modern-day, technology-based systems, flare test facilities must also mature into state-of-the-art, full-scale operations, offering extensive capabilities with sophisticated tools and instrumentation. While flare manufacturers view these flare test facilities as the vehicle for developing cleaner, more-efficient flare innovations, global industries and environmental agencies recognize them as a valuable resource to measure flare performance, system reliability and environmental compliance.

In the past, industry lacked the ability to test flares in a comprehensive manner. Today's test facilities (such as in Figures 1 and 2) should offer industrial-scale testing and measurement of smokeless capacity, required purge rate, blower horsepower or steam requirements for assisted flares, radiation and noise. To properly characterize flare performance, a test facility must have the capability and flexibility to evaluate a wide range of ground, enclosed and elevated flares, including a variety of flare sizes, operating conditions at full-scale, fuel compositions, flowrates, assist media and other factors. Advanced flow control and data acquisition systems are required to control the tests and ensure accurate measurements.

Safety is one of two critical features of a world-class flare test facility. In addition to in-plant safety protocols, equipment safety features and trained specialists, a test facility should include exhaustive, redundant safety measures within its controls, automation software and operating procedures to protect against potential problems.

The second critical feature is flexibility. A test facility should support a wide range of fuel flowrates and test fuels, such as propane, propylene, ethylene, butane, natural gas, and blends of these, including inerts such as nitrogen. Higher flowrates can be achieved with a storage vessel filled with fuel



■ Figure 3. Target flowrates can be reached quickly and maintained more tightly with automatic controls.

gases at an elevated pressure to increase the available hydraulic capacity. A compressor can circulate the gases in the storage vessel to ensure that blends are well-mixed. The fuel flows should be accurately controlled and measured before going to the flare. Multiple metering runs of different sizes can significantly increase the available flow range. Between tests, the lines should be purged with an inert gas for safety and to prevent fuel contamination in subsequent tests.

A test facility should offer a variety of flare testing venues to accommodate virtually every flare size and type used in industry. In Figure 2, flare-testing venues are in place to test enclosed flares, multi-point ground flares, air-assisted flares, steam-assisted flares, high-pressure flares, and flare pilots.

A facility should have the capability of testing flares with capacities up to 300,000 lb/h or more of fuel. Flare-pilot test stands should be capable of simulating wind speeds in excess of 150 mph (blowing against both the pilot and the pilot mixer) and rain at more than 30 in./h *(3)*.

Because many flares use some type of assisting media, typically steam or air, to meet the specified smokeless capacity, a test facility must be able to provide adequate quantities of both media. For flares that do not require any assisting media, such as high-pressure flares, the facility should be able to produce the higher gas pressures encountered in those applications.

Test parameters

Depending on the information required, the variables typically measured during a flare test include flame length, smokeless capacity, blower horsepower for air-assisted flares, steam consumption for steam-assisted flares, and cross-lighting distance for multi-point flares. Two types of measurements are taken — inputs and outputs.

Inputs are the controlled parameters set by the test objectives. These include, for example, the gas flowrates, fuel pressures and compositions specified by the test protocol. For assisted flares, the steam or air flowrate to the flare is generally controlled for a given test point. Atmospheric conditions (wind speed and direction, ambient temperature and pressure, and relative humidity), while not controllable, need to be measured because they may have a significant effect on flare performance.

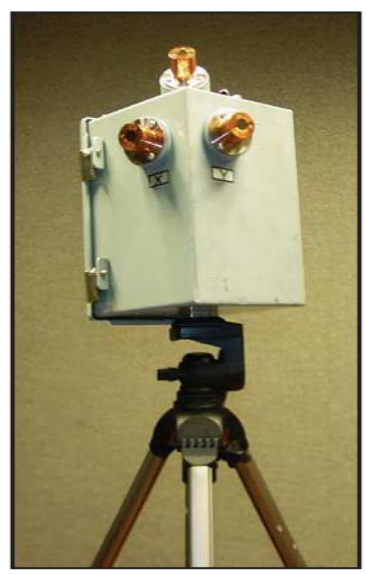
Outputs, on the other hand, include noise, thermal radiation, flame stability, smokeless capacity and flame quality. Some of these measurements (*e.g.,* flame stability) are subjective and require the expertise of qualified engineering staff, while others (*e.g.,* noise) can be measured with appropriate instrumentation.

To ensure data accuracy and to minimize testing costs, the facility's flow control system must be capable of reaching the target flowrate very quickly and maintaining that rate. This is best accomplished with automatic controls (Figure 3). Because a wide range of flows may be tested — from purge rates up to the maximum hydraulic capacity of a large flare tip — multiple sets of flow metering and control runs are recommended to ensure accuracy and controllability for both extremes.

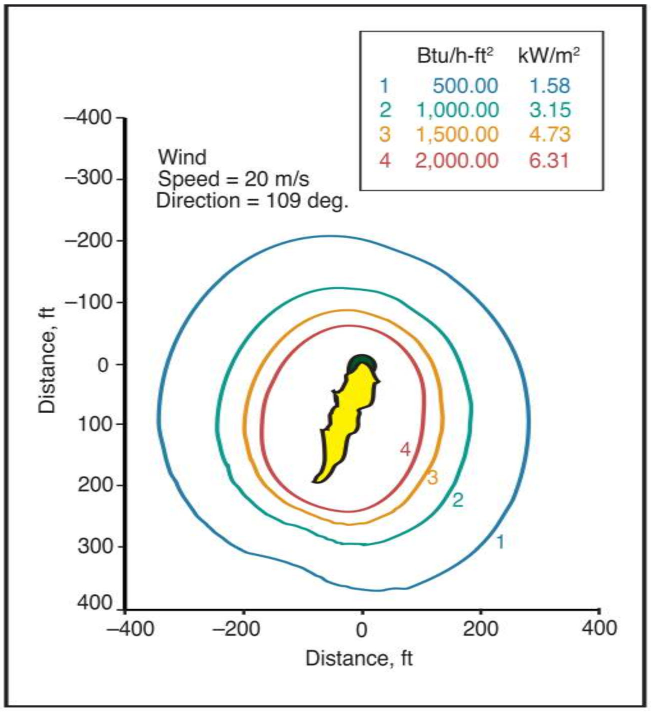
Thermal radiation

Thermal radiation is one of the most important considerations in flare design. Stack height is often chosen so the flare is tall enough to meet certain radiation heat-flux criteria at specified locations. Effective tip design, however, can have a tremendous impact on the radiation characteristics of a flare, as it can reduce the radiation fluxes from the flame and make it possible to use a shorter flare stack, which reduces the cost of the flare system.

To test a flare's radiation flux, multiple radiometers (Figure 4) are recommended to measure the radiation field, which is typically non-uniform due to wind effects and varies with distance from the flare. Through sophisticated mathematical analysis, the measured radiant fluxes can be



■ Figure 4. This radiometer is used, as part of an array, to determine the radiation field from a flare.



■ Figure 5. Isoflux radiation profiles for a high-pressure flare.

■ Figure 6. This microphone is part of the sound measurement system used for flare testing.

used to determine the coordinates of the effective epicenter of the flame and the radiant fraction (*i.e.,* the fraction of heat released from combustion that is emitted as thermal radiation).

Numerous calculation methods have been proposed for estimating the radiation from a flare. Predictions can vary over a wide range, depending on which model is used and what assumptions are made *(4).* Overestimating radiation results in a flare stack that is taller and more costly than necessary. Underestimating radiation means the radiant flux at the ground will be higher than desired, which may be dangerous to personnel and equipment in the area during a flaring event.

Figure 5 is a plot of constant radiation lines (isoflux lines) at ground level for a high-pressure flare test. This plot was generated using measurements from an array of radiometers positioned at various distances and angles from the flare.

Noise

Noise from a flare must be adequately controlled to protect personnel in the vicinity of a flare event. To study the effects of noise from flares, a test facility requires a sound measurement system that includes multiple microphones, such as the one shown in Figure 6. The duration of measurements, microphones, type of data recorded, and

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type of spectrum analyzers used are among the numerous conditions that can be varied for noise testing.

Figure 7 illustrates the sound pressure data recorded by two microphones at different locations during a typical flare test. The spikes at 0 s and 10 s are not related to flare noise, but represent noise from the safety horn alerting personnel in the area of an impending flare test. In this example, there is a rapid rise in the sound level at the start of the test, followed by a steady decline as the fuel flowrate is reduced according to the test plan.

Collecting accurate data for measurement and analysis requires a sophisticated data-acquisition system. In the control room pictured in Figure 8, three time-synchronized computers capture critical test information, which is recorded on a single test record. The first computer collects general data, such as ambient conditions, fuel temperature and flowrates, tip pressure, radiation fluxes, and locations of radiometers and microphones. Another computer records digital video from multiple cameras strategically positioned at various locations, while the third computer records noise data.

A new era in problem-solving

In the past, flares have been designed using semi-empirical and simplified analytical models that can sometimes produce less-than-optimum results. This has primarily been due to the inability to gather comprehensive experimental data from industrial-scale flares and the lack of industrial-scale flare testing capabilities. Today, industrial-scale test facilities should provide important data for greatly improving flare design and in-field performance of existing flares.

The quest for flare knowledge has taken many leaps forward with the advancement of these test facilities, and hydrocarbon and chemical processing industries will benefit from this progress. Through a better understanding of combustion science, full-scale testing and real-world simulation, cleaner, more-reliable flare performance can stay a step ahead of industry requirements. CEP

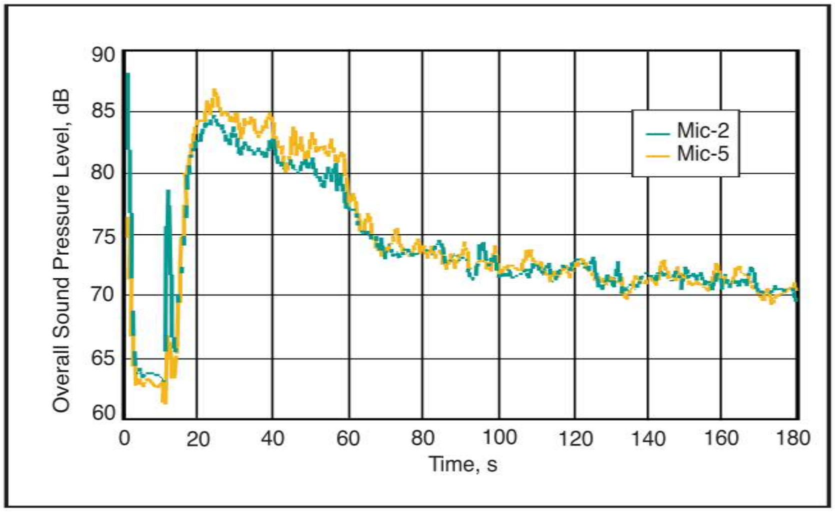

Figure 7. Sound levels decrease as flowrate is reduced during a flare test.

Figure 8. Data acquisition during tests is monitored from the control room.

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