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Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities

Derek R. Johnson,* April N. Covington, and Nigel N. Clark

Mechanical and Aerospace Engineering Department, Center for Alternative Fuels, Engines, and Emissions, West Virginia University, 151 B Engineering Sciences Building, Morgantown, West Virginia 26506, United States

ABSTRACT: As part of the Environmental Defense Fund's Barnett Coordinated Campaign, researchers completed leak and loss audits for methane emissions at three natural gas compressor stations and two natural gas storage facilities. Researchers employed microdilution high-volume sampling systems in conjunction with in situ methane analyzers, bag samples, and Fourier transform infrared analyzers for emissions rate quantification. All sites had a combined total methane emissions rate of 94.2 kg/h, yet only 12% of the emissions total resulted from leaks. Methane slip from exhausts represented 44% of the total emissions. Remaining methane emissions were attributed to losses from pneumatic actuators and controls, engine crankcases, compressor packing vents, wet seal vents, and slop tanks. Measured values were compared with those reported in literature. Exhaust methane emissions were lower than emissions factor estimates for engine exhausts, but when combined with crankcase emissions, measured values were 11.4% lower than predicted by AP-42 as applicable to emissions factors for four-stroke, lean-burn engines. Average measured wet seal emissions were 3.5 times higher than GRI values but 14 times lower than those reported by Allen et al. Reciprocating compressor packing vent emissions were 39 times higher than values reported by GRI, but about half of values reported by Allen et al. Though the data set was small, researchers have suggested a method to estimate site-wide emissions factors for those powered by four-stroke, lean-burn engines based on fuel consumption and site throughput.

■ INTRODUCTION

The United States has experienced a natural gas (NG) boom due to unconventional well development. The U.S. Energy Information Administration has forecasted natural gas production to increase by 56% by 2040,[1] with the main contributor from growth in shale gas production which increased by 30% from 2011 to 2012.[2] With increased production comes the need for increased transmission and storage. This study focused on methane leaks and losses associated with transmission and storage facilities. Data collected in this campaign were compared to emissions factors presented in AP-42,[3,4] the 1996 Gas Research Institute (GRI) report,[5] and Allen et al.[6]

Direct quantification teams audited facilities associated with the Barnett field in Texas during the Barnett Coordinated Campaign.[7] The focus was to complete methane leak and loss audits at three compressor stations (used to boost transmission line pressure) and two underground natural gas storage facilities. All facilities audited were owned by a single transmission company and were audited in an order of convenience for the operator. Audits were conducted to detect and quantify leaks associated with fittings, pipes, valves, tanks, and other equipment. Data were also collected on engine and compressor combinations. This data included engine-operating parameters, exhaust samples, flow and concentration measurements associated with engine crankcases, compressor seals, wet seals, and storage tanks.

A "leak" was defined as a release of NG that occurred due to an unintentional malfunction of the originally intended design and operation of a component, while a "loss" was defined as a release of natural gas that was a result of the intended use or design of a component. For this study, released natural gas associated with the following components were defined as "leaks": fittings, valves, connections, and instruments. Released natural gas from the following components were classified as "losses": engine exhaust, reciprocating engine crankcase vents, compressor packing vents, wet seal vents, slop tanks, and pneumatic actuators. Total natural gas emissions were not reported in this work, but speciation of leak components showed that methane comprised at least 94% of the natural gas at all sites.

Site Summary. Researchers required two days at each site to complete audits. Assessment of day-to-day variability did not occur. For each site, all site emissions were attributed to normal operating conditions. Episodic emissions, such as blowdowns, were not included. Though all components were scanned for leaks, a thorough inventory of nonleaking components was not recorded due to time constraints and number of components.

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Table 1 presents summary details for each site. Note that all reciprocating engines were coupled to Ariel compressors.

Consistent Leak/Loss Sources. The following components had leaks or losses at multiple sites or multiple locations at each site. These sources represented 85% of methane emissions from sites audited. Remaining emissions were associated with leaks (12%) and wet seal vents (2%). The largest single leak was equivalent to wet seal emissions at 2% of total emissions. A brief description of major components follows.

Globe Control Valve. A globe control valve was operated by a plug moving in and out of a globe to allow precise throttling or flow shutoff.

Directional Control Valve. A directional control valve operated using a pneumatic actuator that worked on either natural gas or compressed air depending upon the station configuration. The pneumatic actuator operated using the same principle, in which the gas filled a chamber and applied pressure on a diaphragm and spring, which operated the valve.

Compressor Packing. Compressor packing referred to the seal around the reciprocating rod of the compressor. The main purpose of this seal was to prevent leakage of natural gas between a cylinder and a piston rod. The compressor packing was vented to the atmosphere at all sites. Wet seals referred to the sealing mechanism of centrifugal compressors used in conjunction with gas turbines and were analogous to the compressor packing vents from reciprocating compressors.

Crankcase. Crankcase referred to the void spaces of an internal combustion engine outside of the combustion cylinders. The mixture of intake air and gas was pressurized inside the cylinder during the compression and power strokes and a small portion leaked into the crankcase past piston rings and valve seals. For proper engine operation, the crankcases were vented.[8] The typical method was to vent these to atmosphere.

Slop Tank. Slop tanks referred to the on-site storage tanks that stored bulk volumes of liquids produced at sites. These liquids included oils from the compressors and oil removed from the gas entering the site. Most sites used dehydrators to remove excess water from the pipeline and this liquid was plumbed into the storage tanks. These tanks also served as storage for material caught in various filtering systems installed at the sites. Tanks were vented to the atmosphere at all sites.

Engine Exhaust. Exhaust that emanated from engines included hydrocarbon emissions from incomplete combustion. Flame quenching at the cylinder wall, misfires, and unburned gases in crevices added to the total emissions.[8] Some engines used catalysts to reduce pollutants such as carbon monoxide. Under lean-burn conditions and at low temperatures, however, methane is difficult to catalyze and even advanced on-road natural gas engines face difficulty in reducing engine-out methane emissions.[9,10] Exhaust samples were also collected from gas turbines at Site 3.

EXPERIMENTAL SECTION

Detection. The first level of detection involved the measurement of local concentration using hand-held Eagle II methane detectors (RKI Instruments, Union City, CA). Detector calibration occurred on ambient air and 5000 ppm (ppm) NIST traceable gas. In this way, the zero point of the detector was set to the ambient methane level. The lower detection limit of the Eagle II was 5 ppm, above background. The perimeter of each fitting or component that was accessible at ground level, or by use of a ladder, was examined for leaks. The second level of detection employed a FLIR GF-320 infrared camera

Table 1. Details for Each Site Visited[a]

	site 1		site 2		site 3					site 4			site 5	
type	compression		storage		compression					compression			storage	
no. of engines	2		2		5					3			2	
no. of slop tanks	0		1		2					1			2	
daily throughput (MMSCFD)	164, 173		3.5, 8.2		706, 712					109, 109			22, 22	
valve operation	NG		compressed air		NG					NG			NG	
engines (make, model)	Caterpillar, G3612		Caterpillar, G3512		SOLAR, Taurus 60	SOLAR, Centaur 40	SOLAR, Centaur 40	Caterpillar, G3612		Caterpillar, G3516			Clark, TLA-6	Clark, TLAD-8
type	4LB		4LB		GT	GT	GT	4LB		4LB			2LB	
speed (RPM)	799	N/A	1350, 1351	N/A				800	N/A	1399−1403			310, 310	N/A
rated power (HP)	3785		1004		7600	4694		3785		1408			2100	3200
load (%)	79	N/A	91.2, 90.5	N/A				83.7	N/A	91.8, 83.4	91.4	88.9	89, 89	N/A
operating time (hrs/day)	24, 24	0, 0	8.9, 22.4	0, 0	18, 18	17, 24	13, 8	24, 24	0, 0	24, 24			24, 24	0,0

[a]4SLB = four-stroke, lean-burn, 2SLB = two-stroke, lean-burn. Cells including data separated by a comma represent day 1 and day 2 values, respectively.

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(FLIR Systems, Inc., Wilsonville, OR). Elevated points of interest, such as slop tank hatches or vents, were scanned with the camera. FLIR camera use decreased time required for component inspections as opposed to inspection with hand-held detectors. The FLIR camera was also used to verify that the microdilution high volume sampling (HVS) systems adequately captured leaks. The lower detection limit of the FLIR for methane was 0.8 g per hour.[11] Previous studies used a threshold of 10 000 ppm for leak classification;[12] a screening threshold of 500 ppm was used in this study. Once detected, leaks were marked with ribbon for subsequent quantification. A photograph and description of components were recorded via a smartphone application for inventory purposes. It was noted that detection and subsequent quantification focused only on the station as operated, separate detection and quantification did not occur for the same components in a nonoperational state.

Leak/Loss Quantification. Components that emitted methane were quantified using a microdilution HVS system developed by the researchers. Other studies[5,6] used alternative devices (HI Flow Sampler) or timed bag collection. The HVS was developed such that a large array of leaks and losses were quantifiable while measurement error was minimized (4.4% compared to 10% of the HI Flow Sampler[13]). HVS systems consisted of an explosion-proof blower mounted on a cart. Inlets to the blowers were connected to hoses or pipes that drew a diluted sample from leak and loss locations. Windblocks were used to ensure full leak capture in some circumstances. All hose and pipe connections were grounded to the blower and portable cart. A grounding wire, strap, and rod were used to ground the entire system, which eliminated any static discharge when leaks were approached. Outlets of blowers were connected to a length of pipe. The diameter of the pipe was 3.75 in. and flow exited through at least 40 in. of pipe for mixing and flow development. At the exit of this pipe was a hot-wire anemometer-based mass airflow (MAF) sensor (Abaco Performance, LLC, AB-DBX97). The MAF was calibrated against a laminar flow element (LFE) with an accuracy of ±0.7%. The MAF measured the total mass flow rate of the leak and dilution air. A sample probe was placed after the MAF and was connected to the portable methane analyzer, which drew in a slipstream of the diluted sample for concentration measurement. Two HVS systems were used as separate units but were sometimes combined in series and parallel when high emissions components were encountered.

Portable methane analyzers were Los Gatos Research Ultraportable Greenhouse Gas Analyzers (LGRs; Los Gatos Research, Inc., Mountain View, CA). LGRs used enhanced cavity absorption for measurement of methane, carbon dioxide, and water vapor. LGRs were supplied with factory calibrations that yielded a measurement uncertainty of ±1%. Precision of the LGRs was two parts per billion. LGRs were externally calibrated with NIST traceable bottled methane of varying concentrations (balance of air). Calibration gases had an uncertainty of ±1%. These analyzers had internal pumps that operated at a constant volume sample rate of 0.5 SLPM and drew sample through a 1/4 in. line. LGRs measured diluted concentrations up to 5000 ppm. MAF and LGR outputs were recorded on a laptop at a rate of 10 Hz. Volumetric and mass flow rate of leaks were reported and based on steady-state time-averaged values (5−10 s of data collection). In-house software collected wet and dry values as reported from the LGR, which eliminated underestimation of methane flow rates. Figure 1 shows the methane concentration and total flow during the measurement of a leaking component. The area labeled "A" was the background. The area labeled "B" was the steady-state portion used for leak calculation.

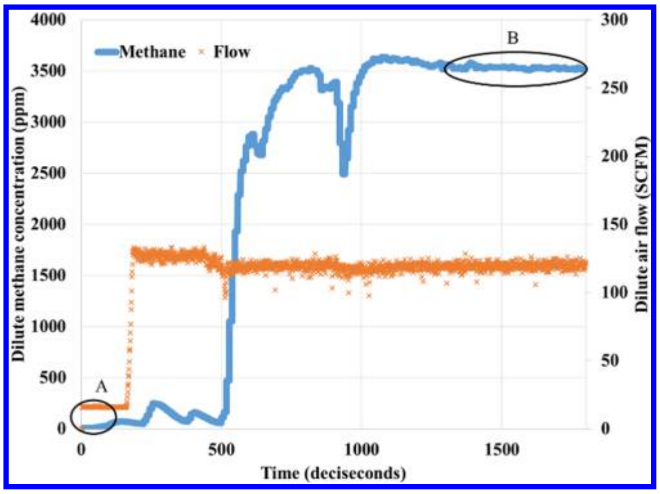

Figure 1. Example of leak measurement data including dilute methane concentration and total dilute flow.

All engines had exhaust sampling ports. These ports were connected to LGRs for in situ measurements of CH_4 and CO_2. Engine parameters were collected during the sampling period. The output of the LGRs filled 10-L Tedlar bags that were analyzed off-site with an MKS Multigas 2030-HS FTIR analyzer (MKS Instruments, Andover, MA). Tedlar bag samples were collected at each site for background, the largest leak components, engine exhausts, and slop tanks. The Tedlar bags were shielded from sunlight and were analyzed offsite daily. The measurement principle of the LGR was non-destructive, which allowed for additional analysis of the exhaust sample. The FTIR was a high-speed unit that measured at 5 Hz. The unit used a 5.11-m high-optical-throughput 200-mL gas sample cell and was cooled with liquid nitrogen. The FTIR was commonly used for measuring exhaust emissions. The FTIR uncertainty was ±5%. The FTIR was used for verification of high concentration samples and speciated the main gas constituents, methane, ethane, propane, and CO_2, as well as carbon monoxide and oxides of nitrogen of exhaust gas samples. Exhaust gas concentrations were converted to volumetric or mass emissions from parameters reported onsite, which included engine speed, manifold air pressure, manifold air temperature, fuel flow rate, and engine intake flow rate, along with manufacturer specifications.

Researchers employed the law of propagation of uncertainty;[14] the relative uncertainty of measurements with the LGR and HVS system was ±4.4%. The relative uncertainty of FTIR and HVS system was ±6.6%. Exhaust mass emissions were calculated from parameters reported by the engine control unit. The uncertainty in engine broadcast parameters was not known, but prior work showed that parameters such as fuel consumption varied by as much as 5−7%.[15] Using this value the uncertainty of exhaust emissions was 7.2%.

■ RESULTS

Table 2 presents a summary of the leaks and losses by site. The first numbers are the count or emissions rate (kg/h) while the numbers in parentheses are percentages. Leaks by count were a majority of emitters, but on a mass basis, losses were the dominant source of emissions.

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Table 2. Leak and Loss Statistics by Site[a,b]

	site 1	site 2	site 3	site 4	site 5
measured leaks	38 (91)	37 (82)	26 (72)	30 (71)	51 (94)
measured losses	4 (9)	8 (18)	10 (28)	12 (29)	3 (6)
total sources	42 (100)	45 (100)	36 (100)	42 (100)	54 (100)
leak emissions (kg/h)	3.6 (17)	0.8 (3)	4.5 (21)	0.8 (3)	2.5 (32)
loss emissions (kg/h)	17.1 (83)	21.9 (97)	16.5 (79)	24.9 (97)	5.4 (68)
total emissions (kg/h)	20.7 (100)	22.6 (100)	21.0 (100)	25.7 (100)	8.0 (100)

[a]Includes 1.4 kg/h estimate of unmeasured wet seal. [b]Includes estimate of 1.2 kg/h for slop tank.

Table 3. Component Level Measurements by Site[a]

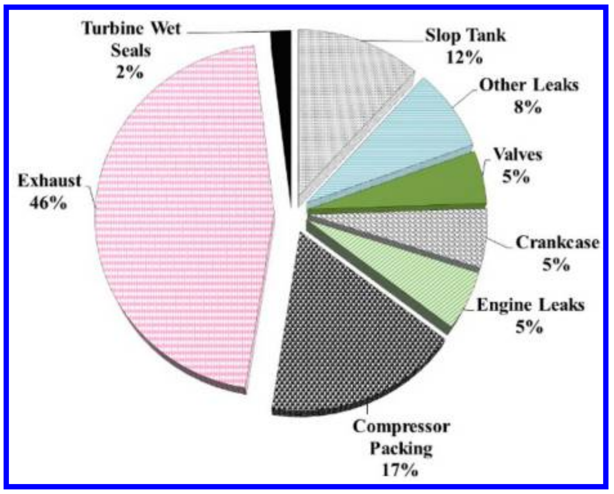
	site 1	site 2	site 3	site 4	site 5
largest leak component	globe valve	well-head regulator	engine filter valve	gate valve	withdraw gas valve
largest leak rate (kg/h)	1.1 (5)	0.2 (0.01)	1.8 (8)	0.3 (1)	0.7 (8)
exhaust emissions (kg/h)	12.4 (60)	8.8 (39)	9.8 (46)	10.5 (43)	1.5 (23)
crankcase emissions (kg/h)	1 (5)	0.3 (1)	2.2 (11)	1.1 (4)	0.5 (8)
wet seal emissions (kg/h)	N/A	N/A	3.2 (15)[b]	N/A	N/A
packing emissions (kg/h)	1 (5)	2.9 (13)	0.1 (0.5)	11.6 (45)	0.3 (4)
slop tank emissions (kg/h)	N/A	9.8 (43)	1.2 (5.5)	1.2[c] (5)	1.2[c] (15)

[a]The first numbers are emissions rates in kg/h. Numbers in parentheses are percentages of site emissions (including estimates). [b]Includes an estimated wet seal that was not measured (1.4 kg/h). [c]Lower measured value of two measured sites.

Table 3 presents data regarding loss emissions and the largest leak emissions by site. At all sites, the three largest leaks emitted about 50% of leak related emissions. The majority of emissions were from losses and the top loss emitters were engine exhausts, packing vents, or slop tanks.

All sites had a combined total methane emissions rate of 94.2 kg/h. Methane emissions that included estimated wet seal and slop tank emissions were 97.9 kg/h. Chart 1 depicts the total emissions from each category. Note that 12% of the total emissions resulted from malfunctioning components and are classified as leaks. Emissions from losses were 85.7 kg/h.

Chart 1. Breakdown of Contributors to Overall Methane Emissions from All Sites Combined (without Estimates)



DISCUSSION

Slop Tank Emissions. Slop tank emissions were measured at two of four locations that utilized these tanks. Site 2 contained two slop tanks that emitted methane at 9.8 kg/h. Site 3 utilized a single slop tank that emitted methane at 1.2 kg/h. Bag samples were collected from tanks and were speciated with the FTIR to obtain emissions rates of propane and ethane. The combined ethane and propane emissions from slop tanks, which were located at Sites 2 and 3, were 1.8 and 0.7 tons per year. These values were well below six tons per year regulation[16] but did not include all volatile organic compound emissions. No known gaseous vents were directed to these tanks, though processed oils and water, which had contacted the natural gas, were directed to these tanks. Increased methane emissions may have been due to lower solubility of methane as compared with propane and ethane.[17]

Comparison with AP-42. AP-42 presented emissions factors (EFs) for natural gas turbines and reciprocating engines.[4] EFs were in units of pounds (lbs) of pollutant per MMBTU of natural gas consumed as fuel. It was noted that the standard heating content of natural gas was assumed 1020 BTU per SCF to match AP-42 assumptions. EFs for turbines, 2SLB engines, and 4SLB engines were 0.0086, 1.45, and 1.25 lbs/MMBTU, respectively.

Table 4 presents measured exhaust emissions rates as compared to those calculated using AP-42 EFs. Emissions rates for the three turbines were calculated by multiplying their reported fuel flow rate by the AP-42 EF. For all cases but Site 2, the measured values were lower than reported by AP-42 EF and

Table 4. Measured and Calculated Engine Exhaust Methane Emissions, Including the Percent Difference between Measured Values and Those Calculated from AP-42

site	engine	type	measured emissions (kg/h)	calculated AP-42 (kg/h)	percent difference
1	G3612	4SLB	12.2	13.4	−10%
2	G3512	4SLB	5.7	4.4	31%
3	Taurus 60	GT	−0.2	0.1	−255%
	Centaur 40	GT	0.0	0.2	−90%
	Centaur 40	GT	−0.2	0.2	−189%
	G3612	4SLB	10.8	13.6	−20%
4	G3516	4SLB	3.1	5.8	−47%
	G3516	4SLB	3.2	5.8	−46%
	G3516	4SLB	4.3	5.8	−27%
5	TLA-6	2SLB	1.5	13.8	−89%

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design capacities. Measured values ranged from 30.8% higher to 255% lower than those estimated from AP-42. It was noted that 255% lower yielded a net negative value, which was attributed to the net cleaning effect of the turbines as compared to local ambient background. The average was 74.2% lower than that calculated using AP-42. When only 4SLB engines were considered, measured exhaust emissions were 20% lower. The discrepancy between measured and calculated values resulted in part from the difference between operating capacity (fuel flow rate into the engine MMBTU/h) and design capacities (fixed assumed value). Design capacity was used by the AP-42 method and was a measure of fuel flow rate or load. Average fuel consumption for reciprocating engines was 7.5% lower than that calculated by design capacity.

Crankcase Emissions. AP-42 did not provide a separate EF for crankcase emissions. The Control of Emissions from Nonroad Large Spark-Ignition Engines was reviewed and no EF for crankcase emissions was found.[18] The EPA NON-ROAD model assumed an EF for hydrocarbon crankcase emissions of 2% of the exhaust.[19] Caterpillar estimated that the blow-by rates for crankcases were related to engine power and differed between new and worn engines and doubled for worn engines.[20] This research yielded an average ratio of crankcase-to-exhaust emissions of 14.4%.

Table 5 presents the measured crankcase and exhaust methane emissions as compared to the AP-42 EF for six 4SLB engines.

Table 5. Comparison of Combined Exhaust and Crankcase (CC) Methane Emissions Rates with Those Predicted by AP-42

site	CC/exhaust (%)	exhaust + CC (kg/h)	AP-42 (kg/h)	percent difference
1	8	13.3	13.4	−1
2	4	6.0	4.4	38
3	22	13.1	13.6	−4
4	12	3.4	5.8	−41
	13	3.6	5.8	−39
	7	4.5	5.8	−22

Total emissions rate (crankcase plus exhaust) was 44.0 kg/h while exhaust emissions rates calculated from AP-42 were 48.9 kg/h. For 4SLB engines, the AP-42 EF over predicted the combined emissions by only 11.4% and this value was just above the calculated uncertainty for exhaust emissions of 7.2%. The percent difference ranged from −41% to +38%.

Wet Seal and Packing Emissions. Wet seal and packing vents were measured at all sites. Table 6 presents the two measured wet seal vent emissions rates. It was noted that both emissions rates were higher than 1996 GRI[5] values, but lower than those reported by Allen et al.[6] Average emissions rates of wet seals were 570 thousand standard cubic feet per year (MSCFy). This value was 3.5 times greater than GRI, but was 14.3 times lower than Allen et al. Table 6 also presents the emissions from all compressor-packing vents measured during the campaign. Average packing emissions rate were 15 500 MSFCy. This value was 39 times greater than the 1996 GRI value and about half of Allen et al.

Additional Emissions Factors. Estimation of site emissions from various components proved to be a complex task, which resulted in EFs that varied by up to 46% across inventories.[21] Many emission estimates for compressor stations in the oil and gas industry applied to a site as a whole, without component granularity. EFs for a typical compressor station as reported by GRI were 990 000 m^3/year,[20] whereas the International Gas Union assigned an EF for a compressor station based on a statistical approach of low (6000 m^3/MW), medium (20 000 m^3/MW), and high values (100 000 m^3/MW), based on compressor power.[22] An alternative approach (Tier 3) required more detailed knowledge (including age, working pressure, construction material, dimensions, technical design, and maintenance details).[23,24] It was nearly impossible to use the Tier 3 approach from an economic and resource standpoint.

Table 6. Comparison of Measured Packing and Wet Seal Vent Methane Emissions to Those Provided by GRI and Allen et al.

turbine/centrifugal compressors			1996 GRI	Allen et al.
			wet seal (run)	
measured	SCFM	MSCFy	MSCFy	
wet seal 1	0.37	197	165	8,137
wet seal 2	1.79	943		
average	1.08	570		
reciprocating compressor packing			packing (run)	
1	0.92	8,052	396	29,603
2	1.56	13,648		
3	0.08	731		
4	4.96	43,421		
5	3.50	30,685		
6	1.07	9,414		
7	0.29	2,547		
average	1.77	15,500		

Other approaches resolved emission estimates for a compressor station into subcategories that consisted of the engine, fugitive leaks, and others. GRI/EPA estimated that miscellaneous fugitive emissions (valves, flanges, etc.) from a compressor station were 180 MSCFy per reciprocating compressor. This method was applied to site data and a comparison examined how the estimated emissions related to the direct source measurements. See Table 7 for results, which also includes the estimated yearly volumetric losses for each site as compared to the fixed GRI estimate. Site totals varied from 1/10 to 1/3 of the GRI value; it was noted that emissions were measured during typical operation and did not include emissions due to episodic blowdowns in which contents of compressors and associated equipment were vented to atmosphere. The fugitive emission estimate method resulted in emission rates lower by factors of 1.1 to 7.4. It was noted that Site 3 operated three GT and centrifugal compressors in addition to reciprocating units. It was noted that slop tanks at Sites 4 and 5 were not quantified so that these estimates were conservative.

Table 7. Comparison of Total Measured Methane Emissions Per Site and Fugitive Methane Emissions Per Site (Leaks)

	total site			fugitive methane		
site	WVU (MSCFy)	GRI estimate (MSCFy)	ratio (WVU/GRI)	WVU measured (MSCFy)	GRI/EPA estimate (MSCFy)	ratio (WVU/GRI)
1	8,970	34,962	0.3	2,658	360	7.4
2	9,794		0.3	2,458	360	6.8
3	8,494		0.2	2,681	360	7.4
4	10,617		0.3	572	540	1.1
5	2,947		0.1	1,898	360	5.3

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A legitimate and reliable method of establishing a single site or national inventory was difficult to perform due to the size of natural gas systems, variety of system designs (in terms of material, age, construction, and condition), employed engine technology, annual throughput, limitations of measuring methods employed, and economic considerations. Thus, it was important to establish a method for emission estimates that was both effective and economic. Researchers proposed that a total site EF might prove as a valuable metric to account for all site methane emissions.

Fuel-specific methane emissions were plotted against site throughput for Sites 1−4 (those employing 4SLB technologies) as shown in Figure 2. Throughput referred to the volume of gas passed through the compressors, but it did not account for direction of flow at storage facilities. During the audits, the storage facilities were sending gas to the reservoirs as opposed to pumping gas from the reservoirs. Storage facilities faced a leak and loss penalty on both injection and withdrawal. The abscissa represented the station throughput in MMBTU/h while the ordinate represented the fuel-specific methane emission in grams of methane emitted per MMBTU of fuel consumed. Relationships such as this, which included a measure of site activity and efficiency, could be derived from station and facility reports, may prove as a valuable metric to estimate site emissions if a statistically significant data set were obtained. Site 5 employed older 2SLB integral technology and was omitted from the regression. The proposed method was only applicable to sites that used 4SLB technologies as the prime mover.

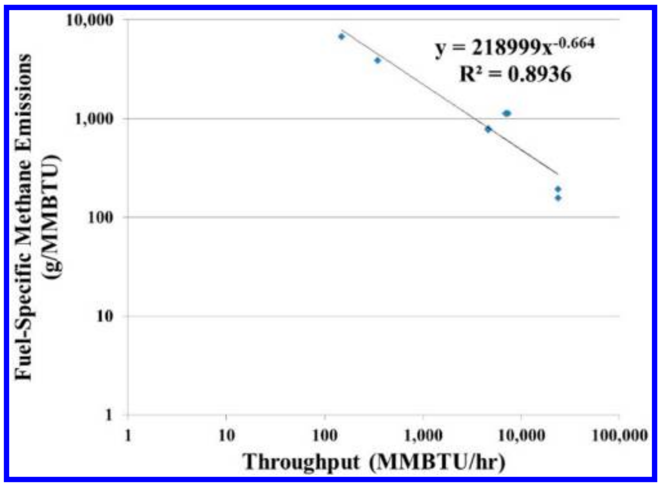

Figure 2. Measured fuel-specific methane emissions as compared to site throughput.

CONCLUSIONS AND RECOMMENDATIONS

Researchers conducted methane leak and loss audits as part of the EDF Barnett Coordinated Campaign. The measured methane emissions from Sites 1−5 were 20.7, 22.6, 19.6, 24.5, and 6.8 kg/h, respectively. Total measured emissions from all sites were 94.2 kg/h. Some wet seal emissions and slop tanks were not quantified to due height restrictions. Compressor blowdown emissions were not measured but these events did occur while researchers were on site. The engine exhaust emissions measured values were lower than EFs provided by AP-42 in all but one case. For the case of only 4SLB engines, and including crankcase emissions, the average of measured values were only 11.4% lower than average AP-42 estimates, but the uncertainty of exhaust measurements was 7.2% and sample size was limited. Measured wet seal and compressor packing emissions were higher by an order of magnitude as compared to GRI EFs, but were lower than those reported by Allen et al. A site EF methodology was proposed which determined fuel-specific methane emissions as a function of total station throughput, but it was recommended that more research be conducted for improved data on the variety of facility configurations used. Although sample size was limited, researchers suggested that updated EFs be developed as a method for reduced disparity among varied methods.

AUTHOR INFORMATION

Corresponding Author

*Phone: 304-293-6457; fax: 304-293-6689; e-mail: derek.johnson@mail.wvu.edu.

Notes

The authors declare no competing financial interest.

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ABBREVIATIONS

CC	crankcase
HVS	high volume sampling
WVU	West Virginia University
MAF	mass air flow
LGR	Los Gatos Research analyzer
LPM	liters per minute
FTIR	Fourier transform infrared
NIST	National Institute of Standards and Technology
EPA	Environmental Protection Agency
EF	emissions factor
BTU	British Thermal Units
MMBTU	million BTU
SCF	standard cubic feet
lbs	pounds
GRI	Gas Research Institute
MSCFy	thousand SCF per year
4SLB	four-stroke, lean-burn
2SLB	two-stroke, lean-burn
m^3	cubic meters

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