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A Better Way to Estimate Emissions from Oil and Gas Sites

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Abstract

This research was performed by the Texas A&M Institute of Renewable Natural Resources (IRNR) who traveled to a hydraulic fracturing site on the Eagle Ford Shale Play and collected real time activity data from equipment that has the potential to release large amounts of air pollutants. Actual run times and load factors of the engines were measured. The activity data was then compared to data collected in the traditional manner of conservative off-site emission assumptions. This study demonstrated that the difference between an emissions inventory using worst case estimates and an emissions estimate using field data resulted in 539 pounds per hour overestimation of NOx emissions at oil and gas sites.

Keywords: Emission; Engine; Horsepower

List of Acronyms: ΔP: The difference between pump discharge and pump suction; ANSI: American National Standards Institute; AP-42: USEPA's primary compilation of emission factor information; bbl/min: Barrels per minute; BHp: Unit of Measure for Brake Horse Power; BSFC: Brake Specific Fuel Consumption; CARB: California Air Resources Board; CAT: Caterpillar engine; (e): Pump efficiency; Epoll: Emissions for pollutant of interest including NOx, VOC, CO, PM/PM10; ENOx: NOx Emissions measured in pounds per hour; g: Unit of measure for grams; gal: Gallon; g/kW-hr: Unit of measure for grams per kilowatt-hour; gpm: Unit of measure for gallons per minute; GPSA: Gas Processors Suppliers Association engineering data book; Hp: Unit of measure for engine horse power; IRNR: Institute of Renewable Natural Resources; kW: Unit of measure for kilowatt; lb: Unit of measure for pound; LF: Load Factor; N: Number of engine units; NO_2: Nitrogen dioxide; NOx: Oxides of nitrogen; psi: Unit of measure for pounds per square inch; PM: Particulate Matter; Q: Fluid flow rate in gallons per minute; rpm: revolutions per minute -a unit of measure for the frequency of a rotation; SO_2: Sulfur dioxide; USEPA: United States Environmental Protection Agency; VOCs: Volatile Organic Compounds

Introduction

Regulatory requirements are being put in place that entail the measurement and reporting of such air emissions as oxides of nitrogen (NO_x), volatile organic compounds (VOCs), Greenhouse gases (such as methane), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and more [1]. Historically, air emission estimation has been conducted using an inventory method that gathers data on number of engines potentially operating at a site. A series of multipliers are applied to complete the estimate. These include such factors as: engine emission controls, total horse power, total engine run time and engine load. The resulting number is an emission estimate in pounds per hour. However, without good field data, these multiplied values are set to assume a worst case scenario. Therefore, in a worst case estimate, it is assumed that the engines have no emission controls on them (or Tier zero) and that all available engines are running at full (100%) engine load or full horsepower for the entire duration of the job.

Due to the manner in which these estimates are calculated, one can safely assume that estimation error will increase as available engine horsepower increases. Therefore, this study demonstrated the difference between an emissions estimate using Tier Zero, 100% engine load and run time with an emissions estimate using tiered engine data (Tier 2) at actual engine load (39.2% load for 7.5 hours and 15% idle for 4.5 hours). The results indicated that the Tier 2, Caterpillar fracture pump engines were emitting 539 pounds per hour less emissions than the worst case estimation would assume.

Materials and Methods

Planning

Planning began through coordination efforts with both the operator and service provider of a natural gas fracture site located in the Eagle Ford Shale Play. A key element was to ensure that the team would have full site access during the complete fracture phase. In order to do this, all members of the field team were prepared with safety training, personal protective equipment, and site-specific safety rules. Logistics such as site access, points of contact, site work schedule, lodging, transportation arrangements, and other considerations were set in advance to the extent possible. Since the San Antonio-New Braunfels Metropolitan Statistical Area is on the verge of nonattainment for ground-level ozone, and since these areas are downwind of the Eagle Ford, it was determined that precursor pollutants of ground-level ozone such as NOx and VOCs would be examined and characterized.

Safety preparation

Prior to arriving on site, all field researchers attended Safe Land USA Safety Training for on-shore oil and gas operation as well as Hydrogen Sulfide Safety Training. On-site researchers were required to wear approved personal protective equipment which included safety glasses, hydrogen sulfide monitors; ANSI Z-89.1 approved hard hats, hearing protection, fire retardant clothing, and steel toed shoes at a minimum. In addition, researchers reviewed and signed a copy of the site-specific safety rules and attended daily safety briefings given by the

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service company. Furthermore, on-site researchers were required to comply with directives of the Site Safety Officer.

Process description

The hydraulic fracturing process must be understood before the data gathering, interpretation, and analysis of air emissions data can be properly collected. Fracturing is a well-orchestrated yet logistically complex phase of the natural gas production process requiring a significant amount of planning/scheduling, materials, monitoring, equipment, and manpower. The process involves perforation of the well casing from the toe (or end) of the well followed by plugging and fracturing of that stage so that subsequent stages can be perforated, plugged, and fractured. The fracturing phase of the process can be broken down into three basic categories: Rig-Up Process, Hydraulic Fracturing and Perforating, and Rig-Down.

After the well is drilled and cased, it is ready to be fractured to stimulate production. The well stimulation technique used at this site was a multi-stage hydraulic fracturing process designed for maximum formation yield. Two wells were alternately perforated and fractured for each the ten stages (or sections) of the wells.

Data collection

Data collected for the phase-specific emissions profile began with identification of equipment that had the potential to emit NOx and VOC emissions. Field researchers collected equipment activity data to include hours of operation, fuel used, equipment specifications and amount of time spent in various modes (idle vs. percent load). Fugitive emissions from pipe fittings, connectors, valves, and other nonpoint sources were not part of this study. Only essential personnel were allowed in the core perforating and fracturing areas due to safety precautions. Therefore, the team collected activity data outside of core operations during this time. It was helpful that all large equipment had been catalogued prior to commencement of the hydraulic fracturing phase of the process. After the operations began, the team collected hourly activity data during two 10 hour morning and evening shifts. Fracturing operations were shut down over night. The activity data was written as daily shift notes which reported activity and information received from personnel doing various functions on site. The shift notes were utilized to capture the process and determine information such as start-stop timeframes for the fracturing operations, equipment run times, vehicular traffic (e.g., sand trucks), perforating operations, as well as other routine and non-routine occurrences (e.g., equipment malfunctions). Off-road equipment with a potential to emit are listed in Table 1.

Equipment with the largest potential to emit was twelve hydraulic fracture pump engines that utilized Diesel Tier 2 2,250 hp CAT3512B engines.

Calculating engine load

Emissions calculated for the large pump trucks were based on a load factor determined by the fluid flow rate (gallons per minute) and pressure (6000 pounds per square inch or psi). The Gas Processors Suppliers Association Engineering Data Book [2] and Carl Branan's Process Engineer's Pocket Handbook [3] provided the equation for required brake-horsepower from the engines as well as desired flow rate and pressure. This was used to determine the load factor percentage of the available pump engines brake-horsepower. The calculation for determining the estimated factor while engine was under load follows:

$$BHp = Q \times \Delta P / 1714(e)$$

Where,

BHp = Required brake horsepower

Q = Fracturing fluid flow rate (gal/min)

ΔP = Pump discharge – Pump suction (inlet pressure) (psi)

1714 = Conversion factor (converting to BHp)

(e) = Pump efficiency = 90% (see Note)

Notes:

Note 1 – Inlet pressure was not recorded so it was conservatively assumed to be zero (psi)

Note 2 - The combination of mechanical and volumetric efficiency is normally 90% or higher for non-compressible fluids [2].

$$BHp = (65\ \text{bbl/min}) \times (42\ \text{gal/bbl}) \times (6000\ \text{psi} - 0\ \text{psi} / 1714) / (0.90) = 10{,}618\ \text{hp}$$

Calculating the load factor (LF) as a fraction of the full load horsepower:

Equipment	Make/Model	Fuel	Rating	Number
Pumper - Operating Engine	SPF343 - Engine-Caterpillar 3512B	Diesel	2250 hp	12
Perf & Plug Truck - Operating Engine	Caterpillar - 3512B	Diesel	2240 hp	2
Light Tower (mobile)	TEREX RL4000	Diesel	13.6 hp	6
Frac Water Pump Engine	Cornell 18F8A Pumps w/Engine-John Deere 6090HF485B	Diesel	384 hp	5
Sand Storage Unit (Trailer/High Rate Feeder)	APPCO FS-40/Slumberger SSF-353 Deck Engine	Diesel	78 hp	3
Blow Out Control System Engine	Engine - Hatz Diesel-8HZXL.667V83	Diesel	9.4 kW	1
Telehandler (Forklift)	GRADALL - 534D9-45 w/Engine - John Deere 4045TF275B	Diesel	110 hp	1
Generator (small) -fire control trailer	TITAN 8500 High Performance	Diesel	8500 kW	1
Bulldozer	Angus-Palm TR95 w/Engine-John Deere 4045TF270B	Diesel	99 hp	1
Backhoe	Caterpillar 420D	Diesel	88 hp	1
High Pressure Water Cannon	Twin Disc 1G4539 Model SP211HP3	Diesel		1
Generator - Mobile Office	Terex T70C	Diesel	91 hp	1
Generator - Cooling Room	ATLAS COPCO - Model QAS25	Diesel	29.6 hp	1
Boss HLTG - Oilfield BH - Light Towers	Lighting Towers	Diesel	15 kW	2
Shower Trailer w/Engine	Engine - 5500 Watt Troy-Bilt	Diesel	5.5 kW	1

Table 1: Off road equipment with a potential to emit were inventoried. Table includes type, make/model, fuel, rating, and equipment number (how many are operating).

LF = (10,618 hp) / (2250 hp)×(12 engines)=27,000 hp = 39.2% while the engine was under load.

Using this data, the total load would be:

BHp = (2,730 gpm) / (232 gpm)×(6,000 psi) / (7,630 psi)×(1,137 Bhp)=10,500 Bhp

These engines did not run at 39.2% load the entire 12 hour work day. Rather, they ran at load (39.2%) for 7.5 hours and at idle (15% load) for 4.5 hours. The emissions estimation considered both the time the engine was under load as well as the time the engine idled. Therefore, the emissions estimation included a weighted average of 39.2% at 7.5 hours and 15% at 4.5 hours.

Calculating emissions with field data

The United States Environmental Protection Agency (USEPA) off-road certified diesel emissions factors were located by searching the California Air Resources Board (CARB) databases [4]. The certified emissions factors were provided in grams per kilowatt-hour (g/kW-hr) but were converted to pounds per horse power hour (lb/hp-hr) for comparison with the USEPA AP-42 factors later in the report.

Emissions were calculated for the highest source group (fracture pumps) and were as follows:

Basic Formula:

Epoll = EF×P×N×LF

Where,

Epoll = Emissions for pollutant of interest including NOx, VOC, CO, PM/PM10

EF = Emission factor in lb/hp-hr

P = Brake horsepower in hp

N = Number of units

LF = Load factor (39% from LF analysis)

The pump truck engine was a Tier 2 diesel, 2250 horse power Caterpillar 3512B. Using the calculation above, and estimating a weighted average for load factor, the estimated engine emissions for this model are as follows:

NOx: $E_{NOx\text{-}EPA\ CERT}$ (1.34E-02 lb/hp-hr×2250 hp/engine×12 engines)×(39%×7.5 hr/day+15%×4.5 hr/day)/12 hr/day

= 108.5 lb NOx/hr

VOC: $E_{VOC\text{-}EPA\ CERT}$ (7.07E-04 lb/hp-hr×2250 hp/engine×12 engines)×(39%×7.5 hr/day+15%×4.5 hr/day)/12 hr/day

= 5.7 lb VOC/hr

CO: $E_{CO\text{-}EPA\ CERT}$ (2.47E-03 lb/hp-hr×2250 hp/engine×12 engines)×(39%×7.5 hr/day+15%×4.5 hr/day)/12 hr/day

= 20.0 lb CO/hr

PM/PM$_{10}$: $E_{PM\text{-}EPA\ CERT}$ (2.08E-04 lb/hp-hr×2250 hp/engine×12 engines)×(39%×7.5 hr/day+15%×4.5 hr/day)/12 hr/day

= 1.6 lb PM/PM10/hr

Results

Comparing worst case estimates with field data

Worst case engine load was estimated at 100%. Likewise, worst case engine run-time was estimated at 100%. This is typical in emission inventories that lack appropriate field data.

Worst case emission factors are from the USEPA AP-42 Standards. These standards assume that the engines do not have any emissions controls and therefore default to the maximum allowable emissions limit for the engine in question. All AP-42 standard emissions factors are given a rating of "D" by the USEPA which is the lowest accuracy and therefore the least preferred approach to emissions estimation. According to the AP-42 standard, "D = Tests based on a generally unacceptable method, but the method may provide an order-of-magnitude value for the source [5]."

Alternatively, more accurate emission factors can be obtained through the CARB who issues a certificate for each engine. These certificates provide a more accurate emission factor that takes into account newer emission control devices that now come standard on all off road engines used in pumping fracture fluids.

Understanding tiered engines

The first USEPA federal standards (Tier 1) for new non-road (or off-road) diesel engines were adopted in 1994 for engines over 37 kW (50 hp), to be phased-in from 1996 to 2000. In 1996, a Statement of Principles pertaining to non-road diesel engines was signed between USEPA, CARB and engine makers including Caterpillar, Cummins, Deere, Detroit Diesel, Deutz, Isuzu, Komatsu, Kubota, Mitsubishi, Navistar, New Holland, Wis-Con, and Yanmar. On August 27, 1998, the USEPA signed the final rule. The 1998 regulation introduced Tier 1 standards for equipment under 37 kW (50 hp) and increasingly more stringent Tier 2 and Tier 3 standards for all equipment with phase-in schedules from 2000 to 2008. The Tier 1-3 standards are met through advanced engine design, with no or only limited use of exhaust gas after treatment (oxidation catalysts). Tier 3 standards for NOx and hydrocarbons are similar in stringency to the 2004 standards for highway engines; however Tier 3 standards for PM were never adopted [6].

On May 11, 2004, the USEPA signed the final rule introducing Tier 4 emission standards, which are to be phased-in over the period of 2008-2015 [7]. The Tier 4 standards require that emissions of PM and NOx be further reduced by 90%. Such emission reductions can be achieved through the use of control technologies.

Example calculation using worst case estimates

2,250 hp/pump truck engines x 12 pump truck engines = 27,000 total potential hp

E_{NOx} = EF×HP×LF

Where,

E_{NOx} = NOx Emissions (lb/hr)

EF_{NOx} = NOx Emission Factor (lb NOx/hp-hr)

HP = Total power output (hp)

LF = Load factor (assumed to be 100%)

So,

E_{NOx} = 2.4×10^{-02} lb NOx/hp-hr×27,000 hp=648 lb NOx/hr

Calculating both estimates from AP-42 and tiered engine yield the following results

NOx: $E_{NOx\text{-}AP42}$ = 2.4E-02 lb/hp-hr×2250 hp×12 engines×100%=648 lb NOx/hr

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$E_{NOx\text{-}EPA\ CERT}$ with actual LF (1.34E-02 lb/hp-hr×2250 hp/engine×12 engines)×(39%×7.5 hr/day+15%×4.5 hr/day)/12 hr/day

= 108.5 lb NOx/hr

VOC: $E_{VOC\text{-}AP42\ \&\ 100\%\ LF}$ = 7.05E-04 lb/hp-hr×2250 hp×12 engines×100%=9 lb VOC/hr

$E_{VOC\text{-}EPA\ CERT}$ with actual LF (7.07E-04 lb/hp-hr×2250 hp/engine×12 engines)×(39%×7.5 hr/day+15%×4.5 hr/day)/12 hr/day

=5.7 lb VOC/hr

CO: $E_{CO\text{-}AP42\ \&\ 100\%\ LF}$ = 5.5E-03 lb/hp-hr×2250 hp×12 engines×100%=149 lb CO/hr

$E_{CO\text{-}EPA\ CERT}$ with actual LF (2.47E-03 lb/hp-hr×2250 hp/engine×12 engines)×(39%×7.5 hr/day+15%×4.5 hr/day)/12 hr/day

= 20.0 lb CO/hr

PM/PM_{10}: $E_{PM/PM10\text{-}AP42\ \&\ 100\%\ LF}$ = 7.0E-04 lb/hp-hr×2250 hp×12 engines×100%=19 lb PM/PM_{10}/hr

$E_{PM/PM10\text{-}EPA\ CERT}$ with actual LF (2.08E-04 lb/hp-hr×2250 hp/engine×12 engines)×(39%×7.5 hr/day+15%×4.5 hr/day)/12 hr/day

=1.6 lb PM/PM_{10}/hr

The results indicate that emissions are over estimated. Figure 1 graphically represents the results.

- For NOx, using AP-42 at 100% engine load yielded overestimation of emissions by 539 pounds per hour.
- For VOCs, using AP-42 at 100% engine load yielded overestimation of emissions by 13 pounds per hour.
- For CO, using AP-42 at 100% engine load yielded overestimation of emissions by 129 pounds per hour.
- For PM/PM10, using AP-42 at 100% engine load yielded overestimation of emissions by 17 pounds per hour.

Discussion

The amount of time that fracture pump engines operate at high load during a fracture stage can vary substantially based on various characteristics of the shale and on what an individual operator feels is the best hydraulic fracturing design for maximum well production. For instance, fracture pump engines might operate at load for only 2-2.5 hours of a 4-5 hour fracture stage for a typical Barnett Shale or Marcellus fracture job. In the Haynesville, the fracture pumps might operate at load for 3-4 hours in a longer time length fracture stage. It is good to note that the number of fracture stages required and the amount of time that the fracture pump engines are at high load during each fracture stage can vary substantially among shale plays and operators.

This study does not mean that the high engine load for fracture pump engines is always 39%. The high engine load for a specific hydraulic fracturing job depends on the design pump discharge pressure, the design total flow rate, and the number of fracture pumps used. Moreover, the number of fracture pumps required is dependent on the model of fracture pump being used. However, ignoring minor variations in engine fuel efficiency at various engine loads, the total amount of horsepower required for two similarly designed fracture stages (similar flow rates and discharge pressures, total time for fracture stage, and total time the fracture pump engines are at a high load per fracture stage) will be roughly the same. Also, the brake specific fuel consumption (BSFC) of these 2,250-hp diesel engines will typically only vary about +/- 10% from a good average of 0.35 lb/bhp-hr [8]. Therefore, the total amount of fuel consumed for a particular designed fracture stage will be roughly the same.

The actual NOX and VOC emissions (g/bhp-hr) can vary somewhat around an engine's Tier rating depending on the engine's load; with a fully loaded engine capable of slightly lower emissions per hp and a lightly loaded engine typically having higher emissions per hp. Also, for example, two CAT3512B engines could have slightly higher or lower emissions depending on the age of the engine, lifetime maintenance, recent tune-ups, etc. However, without taking detailed engine emissions measurements during various engine loadings, these variations are very difficult to account for and the use of an engine's Tier rated emissions should be acceptable.

The above discussions point to a simpler method for determining the approximate amount of NOX and VOC emitted during a particular hydraulic fracturing job. Most vendors will know the total amount of diesel fuel consumed during a particular hydraulic fracture job, perhaps even daily fuel consumption. Using the total diesel fuel consumption, an average BSFC of 0.35 lb/bhp-hr and a diesel density of 7 lb/gallon, the approximate total Hp-hr per fracture job would be:

Hp-hr / job = (fuel for frac job, gallons)×7 lb/gal / 0.35 lb/bhp-hr

And, emissions for a given hydraulic fracture job would be:

Tons = Hp-hr / job×Tier rated emissions g/hp-hr×1/454 g/lb×1/2000 lb/ton

For example, assume a fracture job uses 5,000 gallons of fuel per day for 5 days. The NOX emissions if all the large engines were rated Tier 1 would be:

NOx tons = 500,000 hp-hr×6.9 g/hp-hr×1/454×1/2000=3.8 tons

If all engines were rated Tier 2, then the total NOx emissions for the fracture job would be 4.8/6.9×3.8 = 2.6 tons.

The total Hp-hr/job value will vary depending on the particular shale play characteristics, such as hardness and depth, which determine how the hydraulic fracturing job must be designed (fracture discharge pressure, total flow rate, and amount of fracture time per stage). However, for inventory purposes and for a given shale play, an average Hp-hr/fracture job times the average Tier rating of the fracture pump

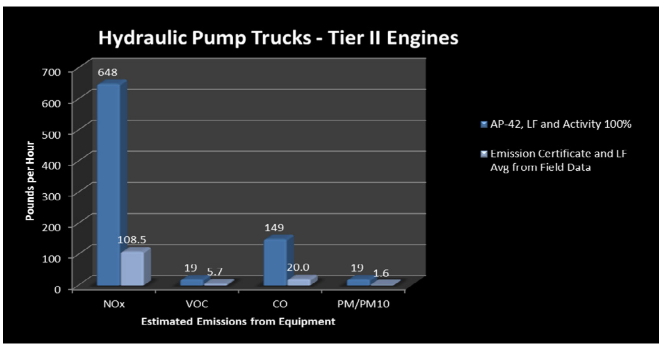

Figure 1: Overestimation is largely due to the differences in default emission factors from USEPA AP-42 Standards and the CARB Certificates. Larger horsepower diesel engines such as fracture fluid pumps are typically Tier 2 or higher. As of 2008, Tier 4 engines have been phased in which require PM and NOx to be reduced by 90%. AP-42 assumes Tier zero while the CARB certificates take into account emission reductions imposed by the USEPA and categorized by Tier rating.

engines used can provide a reasonable approximate amount of NOx and VOC emissions per fracture job.

If a more accurate emissions estimate is wanted, the specific fuel rate for the actual model(s) of engine used at actual loads can replace the 0.35 lb/bhp-hr assumption. For example, the CAT3512B engine has a specific fuel rate of 0.33 lb/bhp-hr at engine rpm of 1,400 to 1,900 (high loads) dropping to 0.385 lb/bhp-hr at 800 rpm. Its average specific fuel rate is approximately 0.35 lb/bhp-hr.

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