Noise Testing and Prediction Methods for Multi-Point Ground Flares

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Abstract

With increasing demand for Multi-Point Ground Flares both domestically and internationally, noise generation from these flares have become a focal point of discussion. Currently, there are no set industry standards for noise predictions and theoretical noise values, which often vary between flare suppliers.

Over the years, Zeeco has conducted numerous noise measurement tests on Multi-Point Ground Flares. This paper will cover the testing and test results obtained in conjunction with one of the foremost noise consultants in the industry. In addition, this paper will address in detail noise generation from various gases at multiple sonic and sub-sonic flow rates. Further information and analysis will be provided to discuss the impact of jet noise vs. combustion noise, as well as calculating noise at various distances.

Zeeco hopes to set standards within the combustion industry in regards to predicting noise for Multi-Point Ground Flares based on the relationships correlated from the test data.

Overview of Multi-Point Ground Flares

Developed in the 1970's, Multi-Point Ground Flares (MPGF) derive their name from their physical layout. Instead of the flare flame being on an elevated structure, the flame is spread out in a grade mounted field of multiple pressure assisted flare tips. The tips are then arranged in stages that open as the upstream pressure and gas flow increases and close as pressure and flow decreases.

MPGF are often selected for heavy hydrocarbon service with high available pressure; however, they can be used for a wide range of gas compositions. High pressure assists in obtaining full smokeless operation, which can be difficult to do with other assist mediums. Each tip in a MPGF has unobstructed air access, allowing the momentum from the high exit velocity of the flare gas to entrain the necessary air for full combustion. MPGF are designed to provide maximum smokeless performance, while minimizing radiation impacts and the need for a large sterile area around the flare. Installing a fence around the field can block the visibility of the flare flame, serving a dual purpose of reducing radiation and the likelihood that flaring operations will be a nuisance to the public. Figure 1 is an example of a typical MPGF installation.
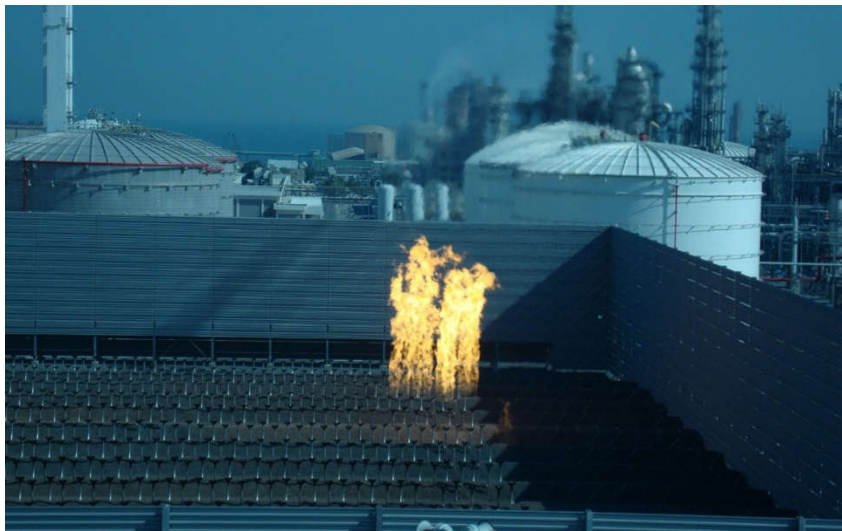

FIGURE 1: TYPICAL MPGF INSTALLATION

Unlike elevated flares, MPGF provide easy access for maintenance. Typically, all staging equipment is located at grade and outside the fence. As a result, workers can safely perform normal operations near the flare without being affected by a flaring event. Figure 2 illustrates a typical fence installed with a MPGF.


FIGURE 2: TYPICAL MPGF FENCE

Noise

Noise can be defined as "excessive or unwanted sound. In general, any sound that is annoying, interferes with speech, damages the hearing, or reduces concentration or work efficiency may be considered noise. In air, sound is radiated spherically from its source as a compressional wave, being partly reflected, absorbed or transmitted by hitting an obstacle. Noise is usually a non-periodic sound wave, as opposed to a periodic pure musical tone or sine –wave combination. It is characterized by its intensity (measured in decibels), frequency, and spatial variation." (Darling, 2016)

A decibel (dB) is a log base scale developed to quantify sound. There are two common uses of decibel levels. One is sound power (PWL) and the other is sound pressure (SPL).

Sound power (PWL) or acoustic power is the rate at which sound energy is emitted, reflected, transmitted or received, per unit time. Sound pressure or acoustic pressure is the local pressure deviation from the ambient atmospheric pressure, caused by a sound wave. The sound pressure scale usually ranges from 0 to 140 dB. The 0 value of the scale occurs when sound pressure equals the threshold of human hearing. Figure 3 shows a comparison of sound pressure levels and sound pressures for a variety of different common objects.
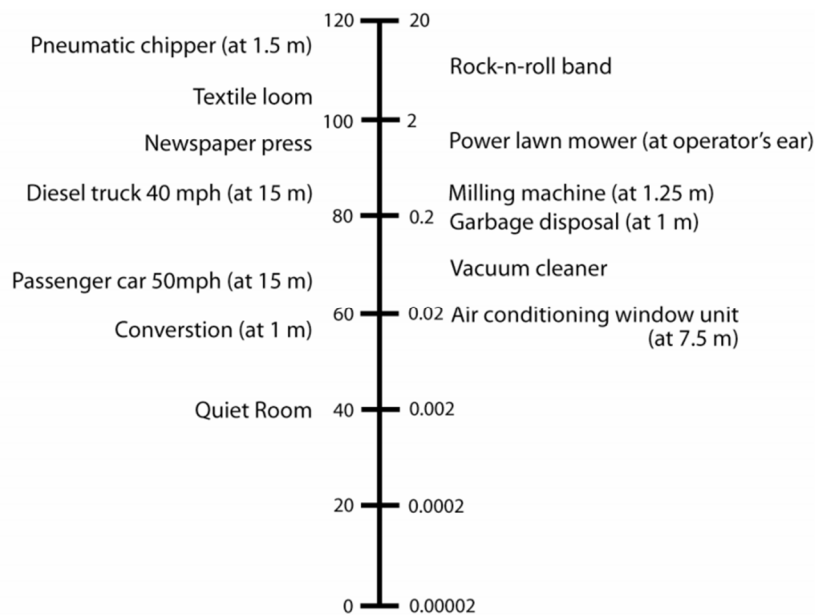
(Breysse, 2006)

FIGURE 3: SOUND PRESSURE LEVEL (SPL) AND SOUND PRESSURE (PA) OF COMMON ITEMS

Even though a decibel has a unit of dB, noise valves are often given in dBA. The "A" designation means the noise level has been modified (i.e. A-Weighted) to de-emphasize the low and very high frequencies which pose less of a risk to hearing. In this paper, all noise values will be shown as unweighted unless stated otherwise.

Another important item when looking at noise data is Leq. When a noise varies over time, the Leq is the equivalent continuous sound which would contain the same sound energy as the time varying sound. In essence, this is the average measurement over a duration of time.

Test Setup

Testing was conducted at Zeeco's test facility in Broken Arrow, Oklahoma. One MPGF flare tip was installed on the test stand which can be seen in Figure 4.

FIGURE 4: MPGF TEST SETUP

With this test setup, gas flow was measured using a 4-inch orifice run. The upstream pressure in the orifice run was measured using a digital pressure transmitter and the temperature was measured using a thermocouple. The differential pressure across the orifice was measured using a differential pressure transmitter.

Tip pressure and gas temperature were also recorded for secondary flow measurement verification. Tip pressure was recorded using a digital pressure transmitter. Gas temperature was recorded using a thermocouple. All aforementioned data was recorded simultaneously using a data acquisition system (DAQ). A weather station was also connected to the DAQ that measured wind speed, wind direction, ambient temperature, barometric pressure, and relative humidity throughout the entire test, which allowed for accurate accounting of atmospheric attenuation in the analysis.

The test fuels used were Tulsa Natural Gas (TNG) and Propane.

Noise measurements were recorded at distances of 100'-0" and 200'-0" to the East of the flare tip using two Norsonics NOR140 Type I noise meters. One meter was placed at each distance to measure simultaneously during the test points. Each measurement point lasted 60 seconds.

In order to minimize the amount of background noise, testing was conducted at night with all non-essential equipment (compressors, forklifts, etc.) shut off to avoid contamination of the noise results.

To aide in the testing, Zeeco partnered with Hoover & Keith, a well renowned noise consultant located in Houston, Texas. A consultant from Hoover & Keith was present during all testing and was involved in data analysis.

Results

Background Noise

To ensure accuracy of the test data, background noise points were taken before and after testing. The average ambient sound pressure level was approximately 64 dB. As observed in Figure 5, ambient noise was dominated by low frequencies. While every action was taken to reduce ambient noise, proximity to city streets and highways were uncontrollable factors that likely led to the slightly elevated levels of low frequency sound.
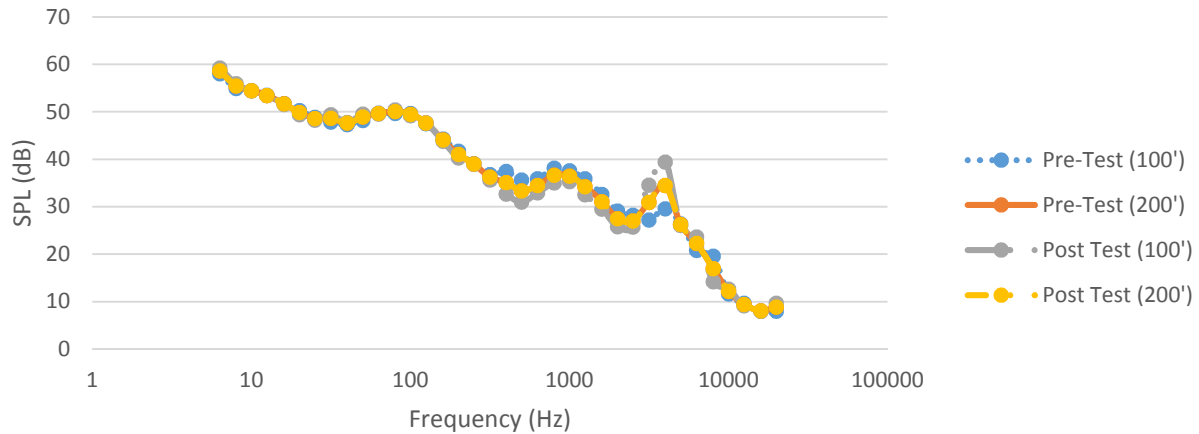

FIGURE 5: AMBIENT NOISE AS SOUND PRESSURE LEVEL IN 1/3 OCTAVE BANDS

Sound Power Levels as a Function of Sonic and Subsonic Flows

All resulting noise data was analyzed on an unweighted basis as sound pressure levels in 1/3 octave bands. All noise measurements were recorded over a 60 second measurement duration. During the measurement duration, a 1/3 octave band spectrum was recorded at 1-second intervals. The 60 measured 1-second 1/3 octave band spectra were then used to compute a single 60-second Leq 1/3 octave band spectrum. The data presented in this paper are the computed 60-second Leq 1/3 octave band spectra or the overall (or total) level derived from these 1/3 octave band spectra.

Shown in Figure 6 is the sound pressure level (SPL) in dB versus fuel flow rate in pounds mass per hour.
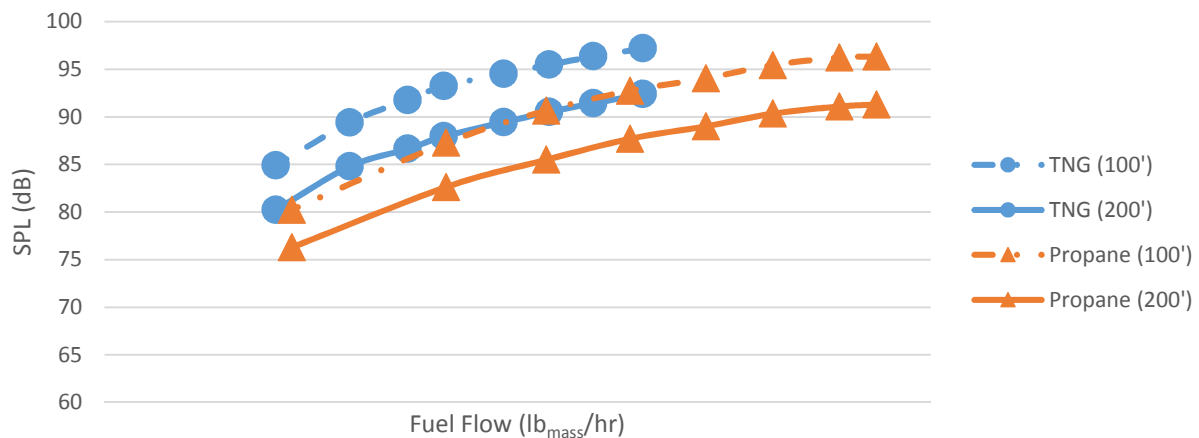

FIGURE 6: SOUND PRESSURE LEVEL (SPL) AS A FUNCTION OF FUEL MASS FLOW RATE

The sound pressure level for each test point was converted to a sound power level using Eq. (1).

$$PWL = SPL + 20Log(r) + 0.5$$ Eq. (1) (Cunha-Leite, 1988)

Variable "r" is the direct distance in feet from the noise source to the noise measurement location. When converting to sound power level, atmospheric attenuation was taken into account using onsite meteorological data. Upon analysis of the calculated sound power levels, as shown in Table 1 and Table 2, the largest percent difference between the two measurement points was 0.6%, with an average percent difference of 0.4% for TNG. A maximum percent difference of 1.5% was observed for propane with an average percent difference of 0.4%. Each type I meter has an accuracy range of ± 1 dB. When comparing both meters this yields a ± 2 dB range. Therefore, the percent differences in the measurements between the two noise meters fall within the combined accuracy range of the meters. The following results are analyzed as a sound power level. Figure 7 shows a graph of the data from Tables 1 and 2.

TP#	PWL - 60 Second Log Average			
	100'	200'	Δ dB	% Diff
1	138.7	139.3	0.6	0.4
2	137.9	138.4	0.5	0.4
3	137.0	137.4	0.5	0.3
4	136.0	136.4	0.4	0.3
5	134.7	134.9	0.1	0.1
6	133.2	133.5	0.3	0.2
7	130.9	131.7	0.8	0.6
8	126.3	127.1	0.8	0.6
Average % Difference			0.5	0.4

TABLE 1: COMPUTED SOUND POWER LEVEL (PWL) – TNG

TP#	PWL - 60 Second Log Average			
	100'	200'	Δ dB	% Diff
9	137.8	138.2	0.4	0.3
10	137.7	138.0	0.3	0.2
11	136.9	137.2	0.3	0.2
12	135.5	135.9	0.4	0.3
13	134.2	134.6	0.4	0.3
14	132.1	132.4	0.3	0.2
15	128.7	129.5	0.8	0.6
16	121.7	123.1	1.5	1.2
Average % Difference			0.5	0.4

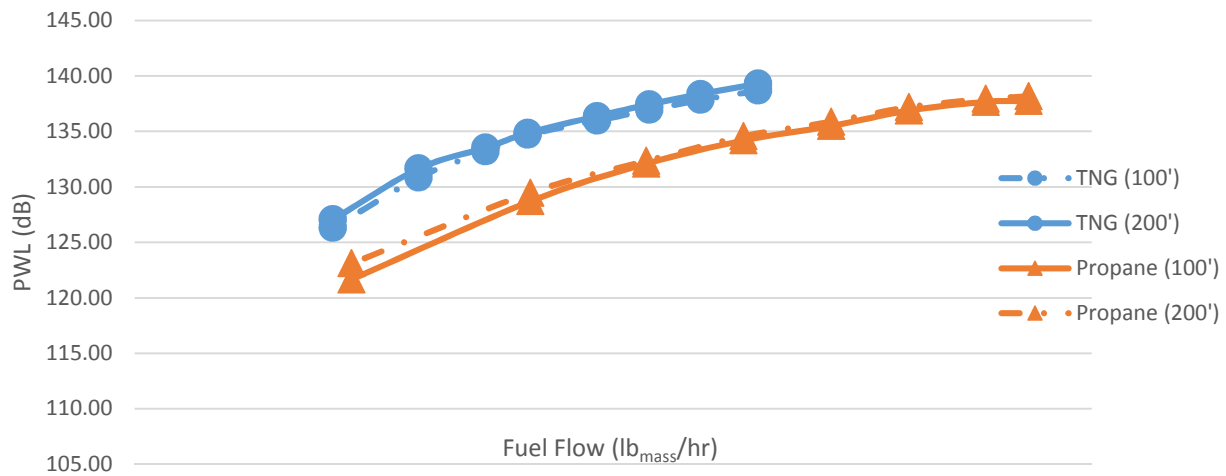TABLE 2: COMPUTED SOUND POWER LEVEL (PWL) - PROPANE

FIGURE 7: SOUND POWER LEVEL (PWL) AS A FUNCTION OF FUEL MASS FLOW RATE

Shown in Figure 8, the sound power levels versus tip static pressure. Also noted are the calculated critical pressures for both TNG and Propane. The critical pressures were calculated from the specific heat ratio of the fuel gas at their respective flowing temperatures per Eq. (2) and correspond to the point at which the fuel gas reaches sonic velocity.

$$p_c = p_2 \left(\frac{k+1}{2}\right)^{\frac{k}{k-1}}$$ **EQ. (2)**

$P_c = Critical\ Pressure, psia$

$P_2 = Ambient\ pressure. psia$
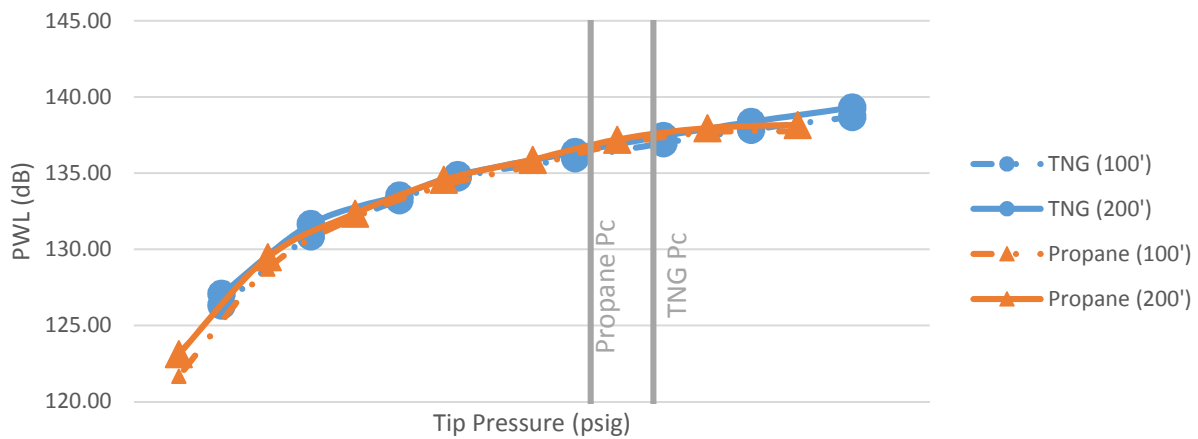
$k = Ratio\ of\ Specific\ Heat$ (Reed, 2001)

FIGURE 8: SOUND POWER LEVEL (SPL) AS A FUNCTION OF TIP STATIC PRESSURE

Acoustical Efficiency

Using the empirical sound power level, fuel flow rate, and fuel composition, the acoustical efficiency was calculated for each test point. Figure 9 shows the observed trend such that as the fuel flow rate increases, the acoustical efficiency increases for a constant exit area.
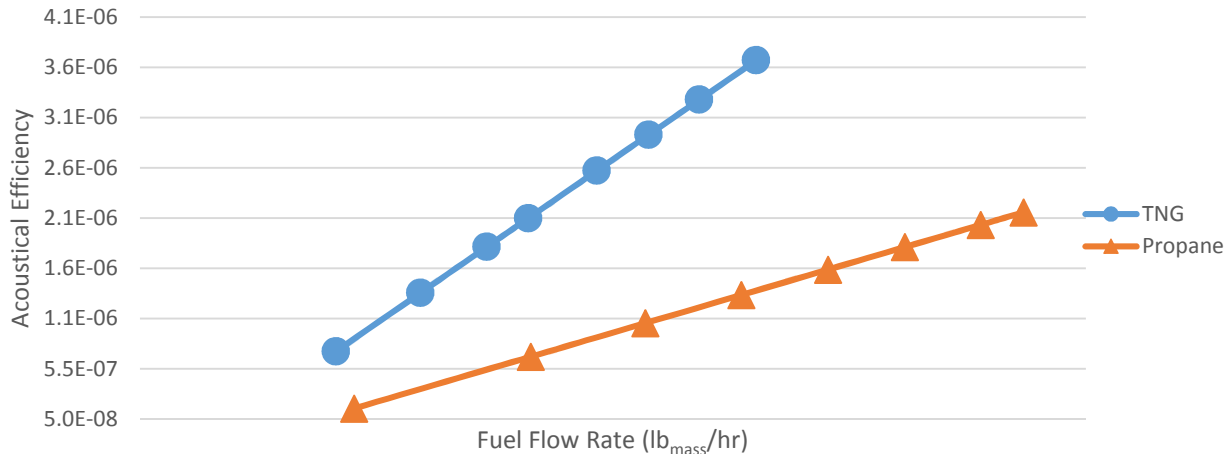

FIGURE 9: ACOUSTICAL EFFICIENCY TREND AS A FUNCTION OF FUEL FLOW RATE

Combustion vs. Venting

Two sets of data points were tested to compare venting jet noise to combustion noise. Shown in Table 3, venting without combustion produced an average 20 dB decrease in sound power level of TNG and an average 23 dB decrease for propane.

Test Point	PWL (Leq dB) at Respective Meter Locations		
	100' (dB)	200' (dB)	Average Δ (dB)
TNG Sonic - Combustion	139	139	20
TNG Sonic - Venting	119	119	
TNG Subsonic - Combustion	136	136	20
TNG Subsonic - Venting	116	116	
Propane Sonic - Combustion	138	138	23
Propane Sonic - Venting	114	117	
Propane Subsonic - Combustion	136	136	23
Propane Subsonic - Venting	112	114	

TABLE 3: SONIC VS SUBSONIC SOUND POWER LEVEL

A further analysis of individual 1/3 octave bands indicates that combustion noise predominantly occurs at frequencies below approximately 500 Hz and jet noise predominantly occurs at frequencies above approximately 2500 Hz. It is important to note that the venting test point low frequency noise could be influenced by the proximity to city streets and highways. The higher trends of the venting case for low frequencies less than 1000 Hz does not appear to correlate to noise mechanisms of the flare, but when compared to background noise frequency appears to be originating from test site surroundings. At these lower frequencies for the venting case, the ambient noise pressure level is higher than that of the flare tip. When analyzing the data as sound power level, the

calculation is not applicable to these lower frequencies due to the measured sound pressure level being from ambient surroundings and not the venting point source. When the sound power level is calculated from sound pressure level of ambient noise, the ambient noise is arbitrarily calculated as though it is a point source at 100' to 200' from the noise measurement location. This arbitrarily amplifies the sound power level, but is necessary to be applied over the full noise spectrum for the analysis of jet noise in frequencies above 2500 Hz. Figures 10 and 11 show the sound power levels plotted for each 1/3 octave band for both TNG and propane at sonic and subsonic flows.
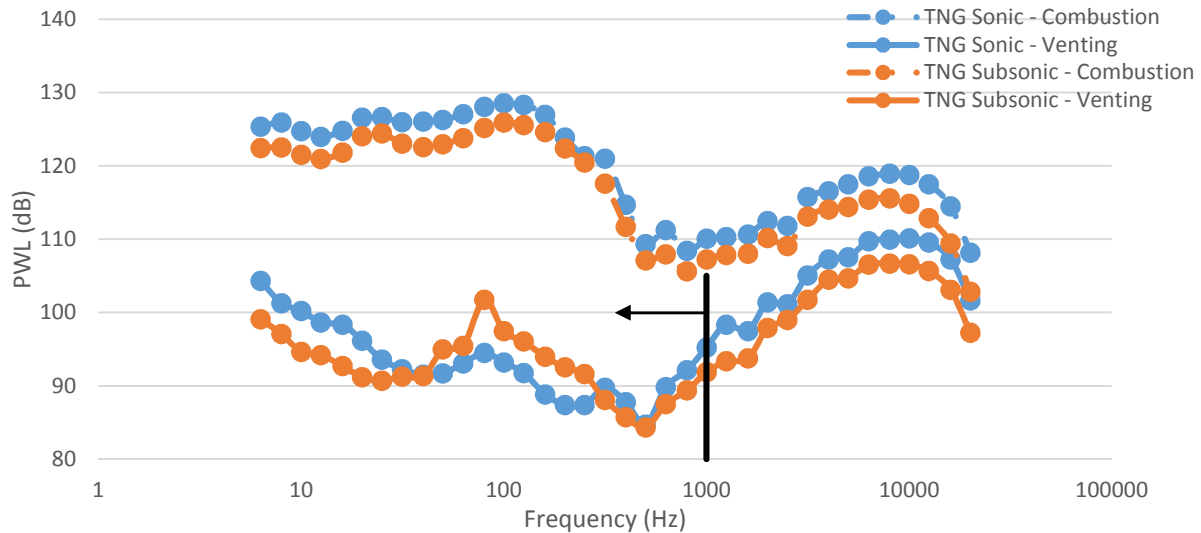
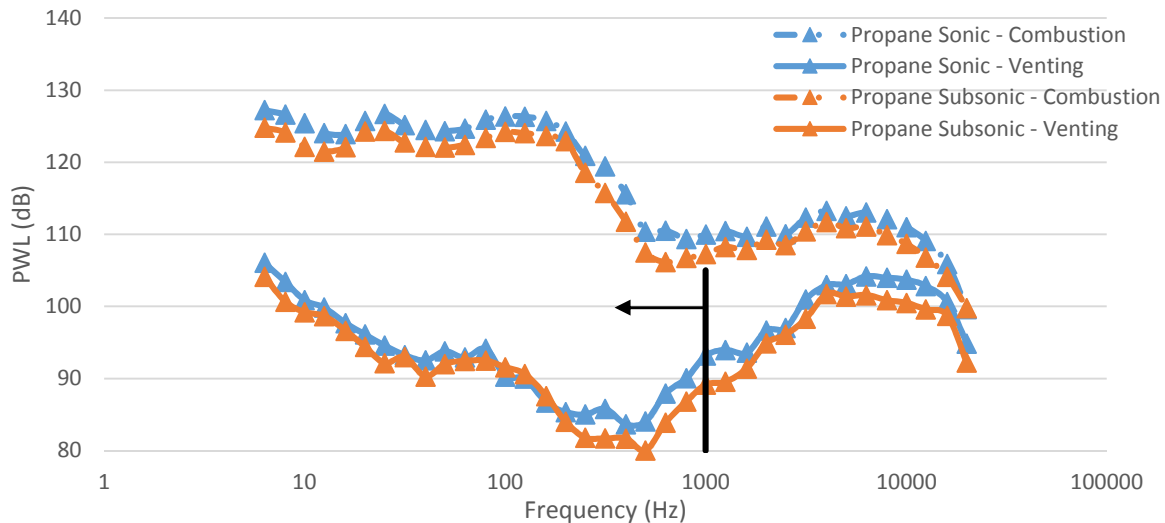**FIGURE 10: SOUND POWER LEVEL (PWL) AS A FUNCTION OF FREQUENCY - TNG**

FIGURE 11: SOUND POWER LEVEL (PWL) AS A FUNCTION OF FREQUENCY - PROPANE

In Figure 12 and Figure 13, the sound power level versus 1/3 octave band frequencies have been plotted for each test point, again note the noise spectrum is dominated by below 500 Hz and above 2500 Hz. Individual test point information in these figures are of less concern. The main observable trend is the sound power level increase for

low (500 Hz and below) and high (2500 Hz and above) frequencies. This trend is observed in both propane and TNG testing.
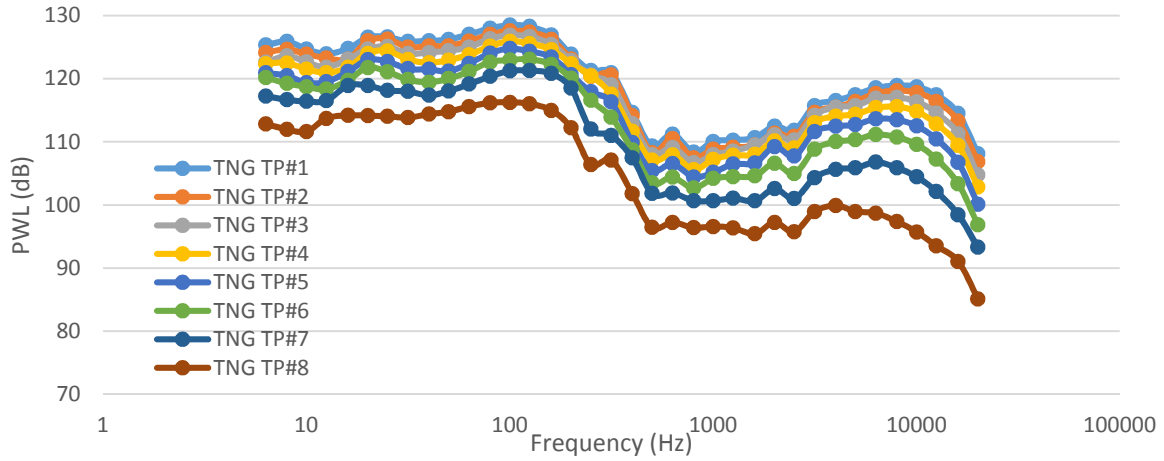

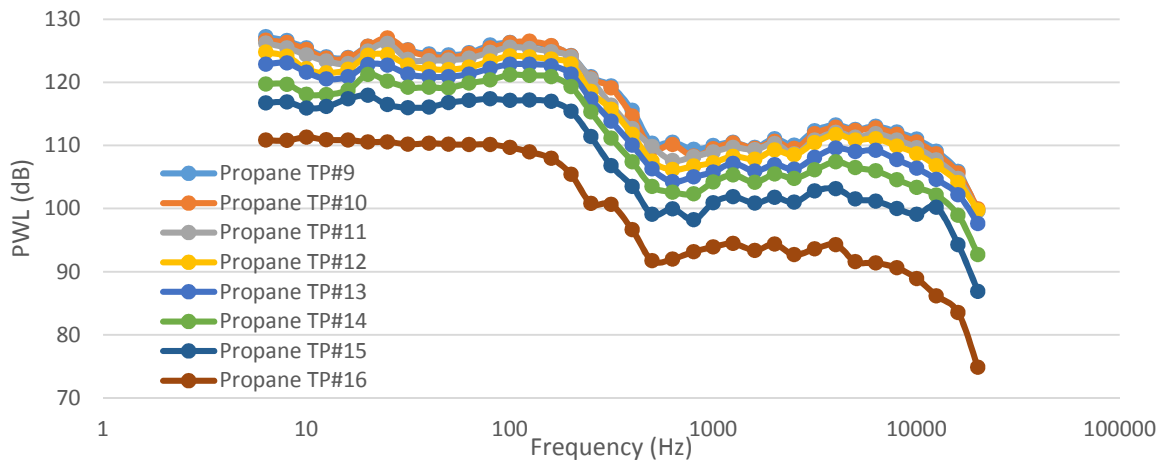**FIGURE 12: SOUND POWER LEVEL (PWL) AS A FUNCTION OF FREQUENCY AND FUEL FLOW RATE – TNG**

FIGURE 13: SOUND POWER LEVEL (PWL) AS A FUNCTION OF FREQUENCY AND FUEL FLOW RATE - PROPANE

Conclusions

10Log vs 20Log Analysis

Previous information debates using a 10Log versus 20Log relationship to calculate the overall PWL. For each case, a reference fuel mass flow rate and corresponding power level is used to determine a sound power level over a range of fuel mass flow rates. In equations 3 and 4, G_0 references the known fuel flow rate corresponding to a known sound power level. G, is the fuel mass flow rate at which a sound power level is to be determined.

$$PWL_{calculated} = PWL_{reference} + 10Log\left(\frac{G}{Go}\right) \qquad \text{EQ. (3) (NARASIMHAN, 1986)}$$

$$PWL_{calculated} = PWL_{reference} + 20Log(\frac{G}{Go}) \qquad \text{EQ. (4) (NARASIMHAN, 1986)}$$

$$PWL_{Calculated} = Sound\ Power\ Level\ at\ Desired\ Flow\ Rate, dB$$

$$PWL_{reference} = Sound\ Power\ Level\ at\ Empirical\ Reference\ Point, dB$$

$$G = Desired\ Fuel\ Flow\ Rate, \frac{lb_{mass}}{hr}$$

$$G_0 = Fuel\ Flow\ Rate\ at\ Empirical\ Reference\ Point, \frac{lb_{mass}}{hr}$$

Figures 14, 15, 16, and 17 show the analysis of the 10Log vs 20Log trends. The actual test data was graphed as well as the data calculated based on G_0 being a low flow point, mid flow point, or a high flow point. These low, mid, and high flow points are all empirical data collected during the testing. The low flow point references the lowest fuel flow point in the data set for that fuel gas, mid flow references a mid-range point, and high flow references the highest fuel flow of the data set for each fuel.
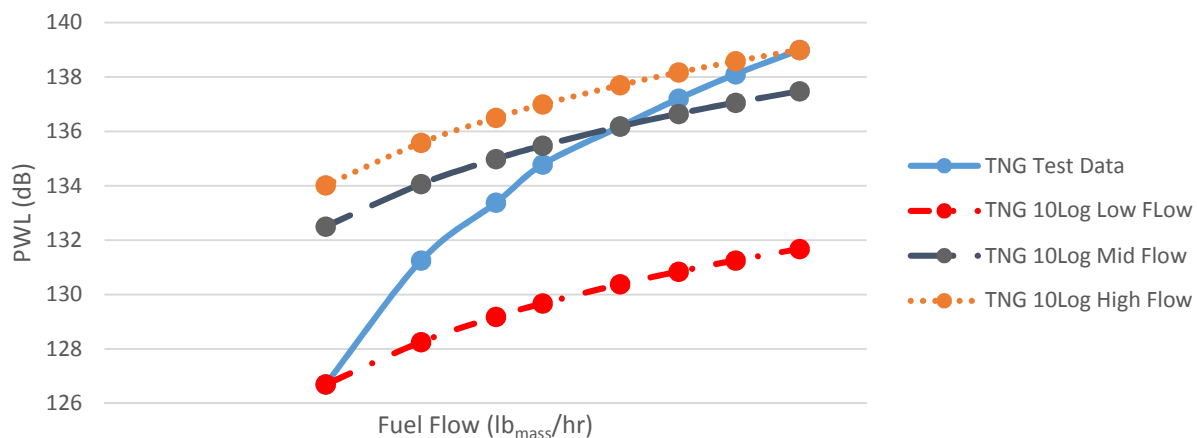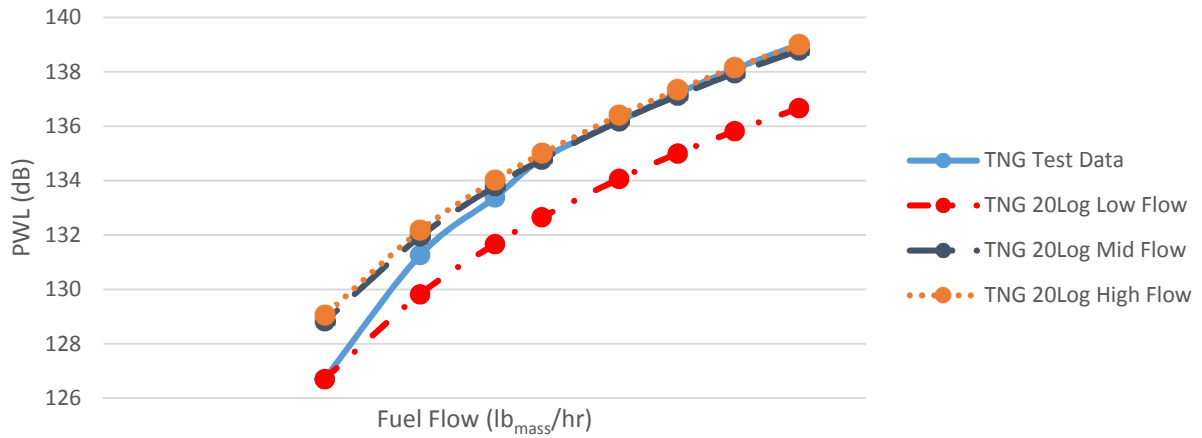

FIGURE 14: 10LOG TREND ANALYSIS - TNG

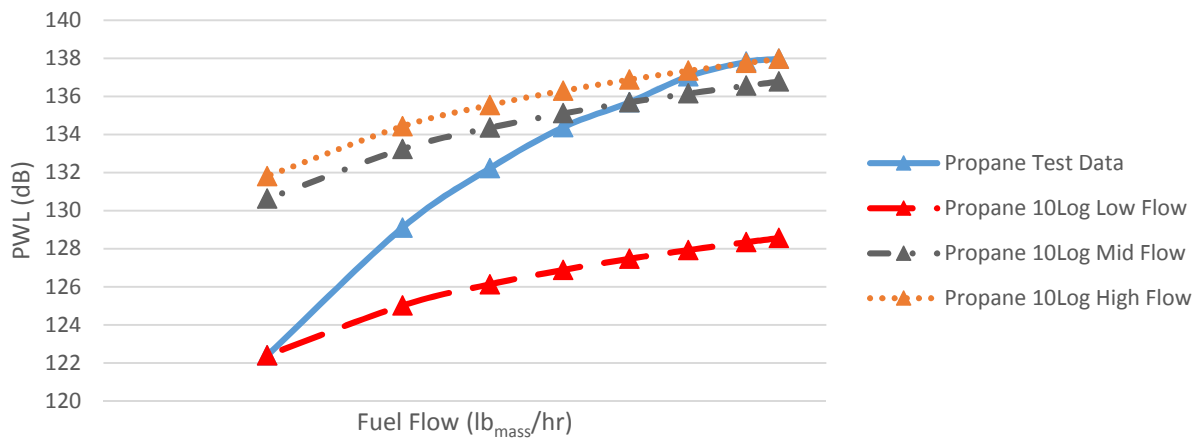**FIGURE 15: 20LOG TREND ANALYSIS – TNG**
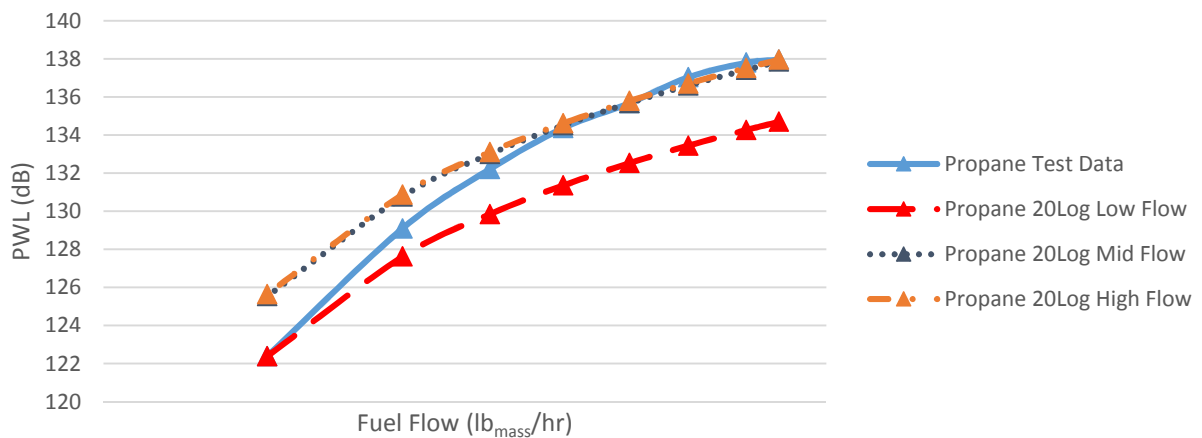

FIGURE 16: 10LOG TREND ANALYSIS – PROPANE

FIGURE 17: 20LOG TREND ANALYSIS - PROPANE

As shown in the figures above, for both propane and TNG, the 20Log trend fit resulted in a smaller percent error. Also observed in the figures above, the referenced empirical data point impacts the percent error. When analyzing a data point corresponding to a smaller mass flow rate, the trend does not accurately represent empirical data.

		Low Flow		Mid Flow		High Flow	
		Avg % Error	Max % Error	Avg % Error	Max % Error	Avg % Error	Max % Error
TNG	10Log	-3.5	-5.3	0.8	4.6	1.9	5.8
	20Log	-1.3	-1.7	0.3	1.7	0.4	1.8
Propane	10Log	-5.0	-6.9	1.2	6.7	2.1	7.7
	20Log	-1.9	-2.6	0.5	2.6	0.6	2.7

TABLE 4: PERCENT ERROR IN 10LOG AND 20LOG TRENDS

As shown in Table 4, the most accurate trend while yielding conservative results, is a 20Log trend based on a data point corresponding to a mid-range mass flow rate. It is important to note that as the calculated sound power level and associated mass flow rate deviate from the referenced point, the percent error increases. This increase is greater at calculated sound power levels associated with low mass flow rates.

Acoustical Efficiency

Multiple publicly available reference articles include discussions on the topic of acoustical efficiencies. Several discrepancies exist between these reference articles as shown in Table 5. The empirical data collected for this testing was investigated for acoustical efficiency trends. Using Eq. (5) and Eq. (6), acoustical efficiencies for each test point were calculated.

$$PWL = 10Log(\frac{W}{W_0}) \qquad \text{EQ. (5)}$$

$$W = e\left(0.293\frac{hr \cdot W}{Btu}\right) G \cdot H_v \qquad \text{EQ. (6)}$$

$$e = Acoustical\ Efficiency$$

$$W = Sound\ Power, Watts$$

$$W_0 = Reference\ Sound\ Power, Watts$$

$$G = Fuel\ Flowrate, \frac{lb}{hr}$$

$$H_v = Heat\ Value, Btu/lb$$

Reference Article	Acoustical Efficiency for a Typical Hydrocarbon
"Predict Flare Noise and Spectrum" (Cunha-Leite, 1988)	$5(10^{-8})$
"Predict Flare Noise" (Narasimhan, 1986)	$1(10^{-6})$
"Noise Generation by Open Turbulent Flames" (Smith, 1963)	$1.23(10^{-8}) - 8.20(10^{-8})$
"Ecological Aspects of Combustion Devices (with Reference to Hydrocarbon Flaring)" (Swithenbank, 1972)	$1(10^{-7}) - 1(10^{-9})$

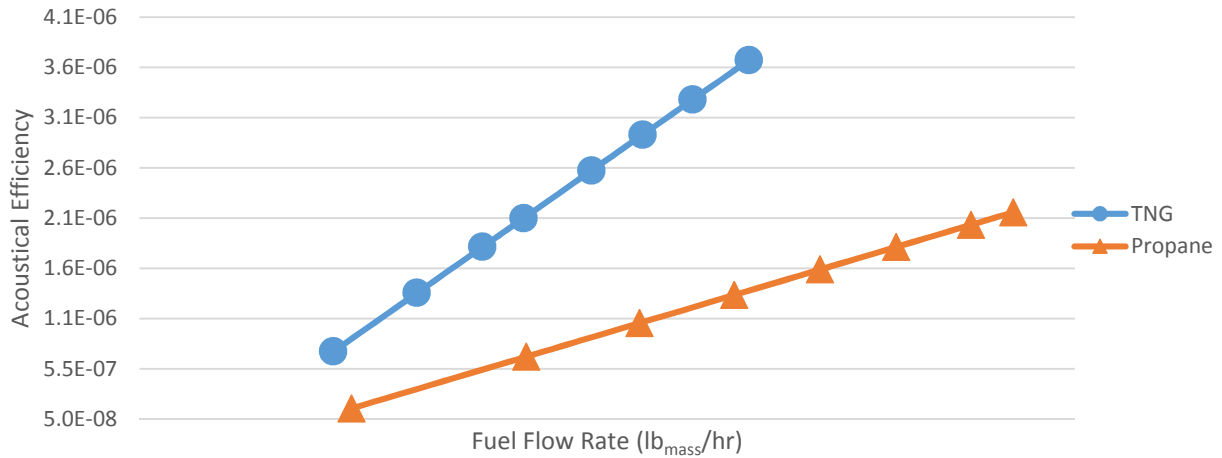**TABLE 5: ACOUSTICAL EFFICIENCIES FOR A TYPICAL HYDROCARBON**

FIGURE 18: ACOUSTICAL EFFICIENCY (E) AS A FUNCTION OF FUEL MASS FLOW RATE

As shown in Figure 18, it was observed that the acoustical efficiency increases with increasing fuel mass flow rate for a constant exit area. Trends of both TNG and Propane were similar with differing rates of change.
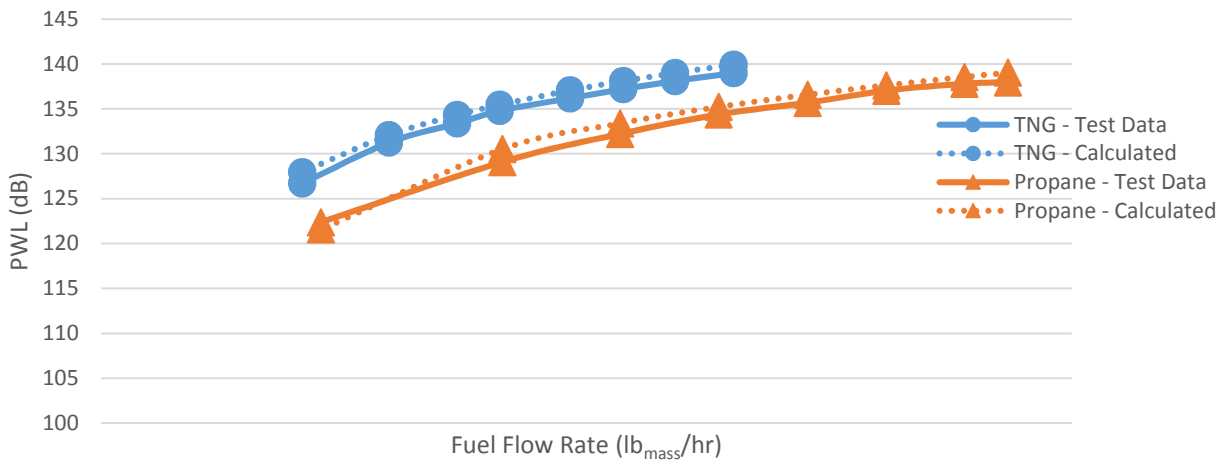

FIGURE 19: SOUND POWER LEVEL (PWL) AS A FUNCTION OF FUEL MASS FLOW RATE

In conclusion, it was observed that as the fuel mass flow rate increased, the acoustical efficiency increased for a constant exit area. When applying the changing acoustical efficiency as a function of fuel composition and flowrate, the prediction model shows a much stronger correlation, as shown in Figure 19. Zeeco is continuing work with Hoover & Keith to determine the impact of these acoustical efficiency trends.

Further Testing

10Log vs 20Log Analysis

While the 10Log vs 20Log analysis shows a more accurate trend correlation when analyzing by means of a 20Log function, testing including higher fuel flow rates would provide a better understanding of the error involved when extrapolating noise values outside of a small range away from the referenced empirical data. A larger range of fuel flow rates would also allow a better understanding of optimal fuel flow rates to use as an empirical reference.

Acoustical Efficiency

With the observance of increasing acoustical efficiencies associated with increasing fuel flow rate for a constant exit area, further testing is required to determine actual causation. Testing of the same format with a multitude of fuel gases would be beneficial. This information would provide more evidence to analyze trends present between fuel gases with different heating values and molecular weights. In addition, fuel blends and inert mixtures would add additional understandings to the phenomena observed. The aforementioned acoustical efficiency testing could potentially yield a more accurate method of predicting multipoint ground flare noise levels.

Combustion vs. Venting

While the combustion versus venting tests provide insight into which frequency ranges are dominated by respective noise mechanisms, it would be beneficial to test a multitude of fuel gases of differing molecular weights and sonic velocities. Adjusting fuel exit areas while maintaining a constant fuel flow rate would yield a better understanding of the driving noise mechanisms of combustion versus venting and would allow a better understanding of the magnitude of impact from combustion noise. This would be facilitated by incrementally decreasing the fuel exit velocity and respective jet noise, while maintaining constant combustion.

References

Breysse, P. N. (2006). Noise. John Hopkins School of Public Health.

Cunha-Leite, O. (1988, December). Predict flare noise and spectrum. *Hydrocarbon Processing*.

Darling, D. (2016). *Noise*. Retrieved from Encyclopedia of Science:
        http://www.daviddarling.info/encyclopedia/N/noise.html

Narasimhan, N. (1986, April). Predict flare noise. *Hydrocarbon Processing*.

Reed, R. J. (2001). *North American Combustion Handbook* (Third ed., Vol. I). Cleveland, OH: North American
        Manufacturing Company.

Smith, T. &. (1963, May). Noise Generation by Open Turbulent Flames. *The Journal of the Acoustical Society of
        America, 35*(5), 715-724.

Swithenbank, J. (1972, May). Ecological Aspects of Combustion Devices (with Reference to Hydrocarbon Flaring).
        AIChE Journal, 18(3), 553-560.