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TECHNICAL COMMITTEE
ASHRAE 2.6
SOUND & VIBRATION

Engine Exhaust Noise Control

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JGL ACOUSTICS, INC.

Engine Exhaust Noise Control

- Reactive Mufflers
- Absorptive Silencers
- Reactive/Absorptive Mufflers
- Tail Pipe Design
- Tuned Resonators
- Project Examples

The above are the subjects that we will discuss. Some data will also be presented from field tests: One an example of a project failure and the other a big success.

Engine Exhaust Considerations

The exhaust system of a generator has several inherent design problems that must be considered. These characteristics impose severe limitations on what can be done to silence the engine exhaust noise:

- Very High Noise (100 to 120 dBA @ 1 m)
- High Temperatures (950 to 1050 ^{o}F)
- High Velocities (5,000 to 15,000 fpm)
- Combustion By-Products (soot & corrosion)
- Pipe Thermal Expansion

Performance Characteristics

- Insertion Loss (dB)
  depends on design, size and frequency
- Pressure Drop (inches H_2O or Hg)
  depends on velocity & design
- Self-Generated Noise (dB ref. 1 picowatt)
  depends on velocity & design

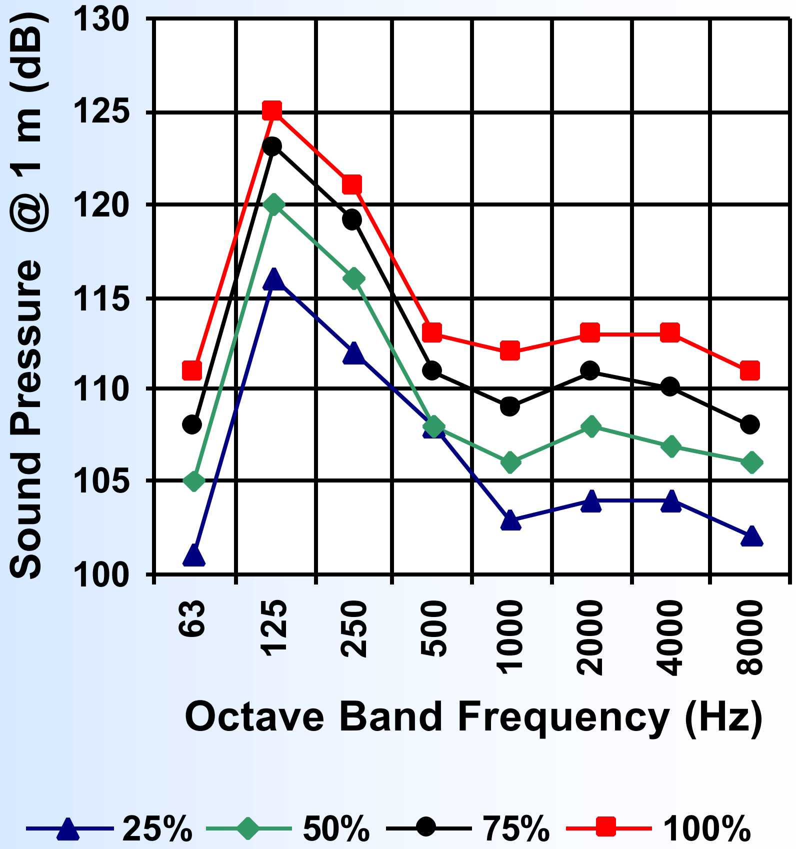
Insertion loss (IL) is defined as the reduction of noise level that occurs when a silencing element is inserted into the system. Because engines generate strong tonal components, the IL of any one muffler will not be the same with different engines, different loads, or different piping configurations. Pressure drop is more predictable, however. Specific data on self noise is generally not available.

Engine exhaust noise varies significantly with loading. Typically the noise level at full load is about 10 dB higher than the no-load condition.   The next slide shows typical engine exhaust sound levels at different loads.

The curves also show that the majority of the engine exhaust noise is at low frequencies.

Unsilenced Exhaust Noise

- Unlike engine block noise, exhaust noise increases significantly with engine load
- Graph at right shows noise level vs. load for a 16-cyl. 2000 KW engine (1800 RPM diesels)



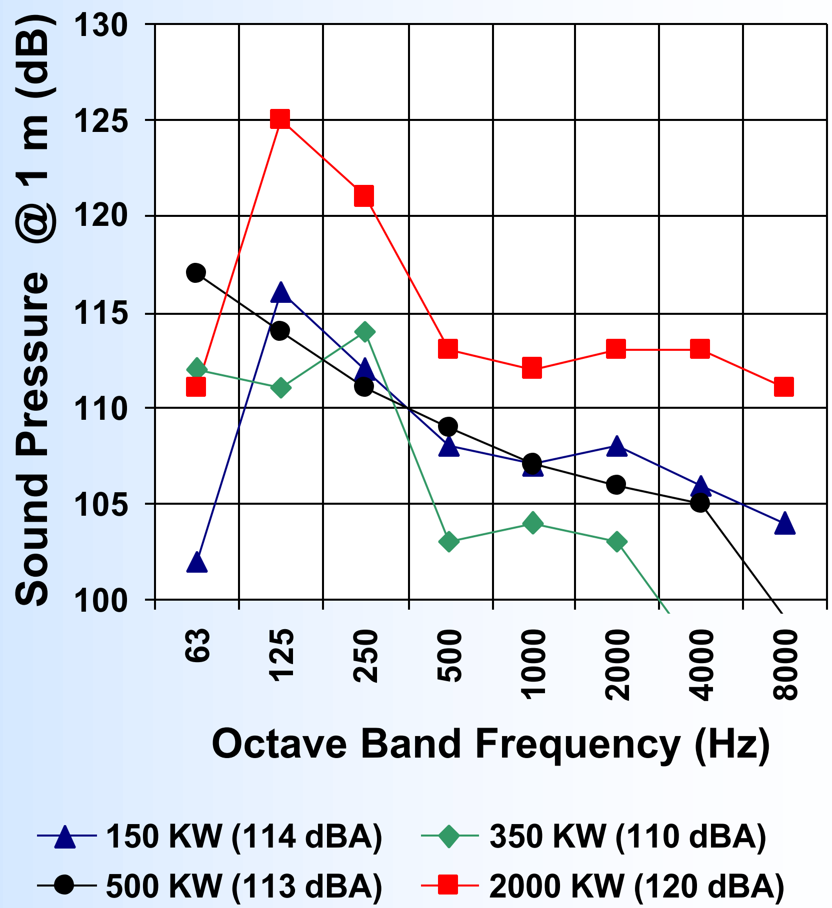
The overall noise level from most unsilenced engine exhaust systems varies from about 110 dBA to 120 dBA, when measured 1 meter from the pipe outlet.

The noise level does not always align with the power rating of the generator as you can see by this next graph.

Exhaust noise can also be affected by engine turbochargers and after-coolers. It is best to obtain exhaust noise data from the engine manufacturer.

Unsilenced Exhaust Noise

- Unsilenced engine exhaust noise is broad-band with highest levels at low frequencies
- Data compares 6-cyl. 150 KW and 500 KW engines with a 16-cyl. 2000 KW engine (all 1800 RPM diesels)



The exhaust noise spectrum will always contain strong tones associated with the rate of cylinder firings. In 4-cycle engines each cylinder fires once *every other revolution* of the drive shaft.

Cylinders fire once every rev in 2-cycle engines. The lowest tone is always the CFR, which is the firing rate for any one cylinder.

The engine firing rate is generally the strongest tone in the exhaust spectrum.

Engine Exhaust Tones

- Cylinder Firing Rate (CFR)

  CFR = RPM/60 for 2-cycle engines

  CFR = RPM/120 for 4-cycle engines

- Engine Firing Rate (EFR)

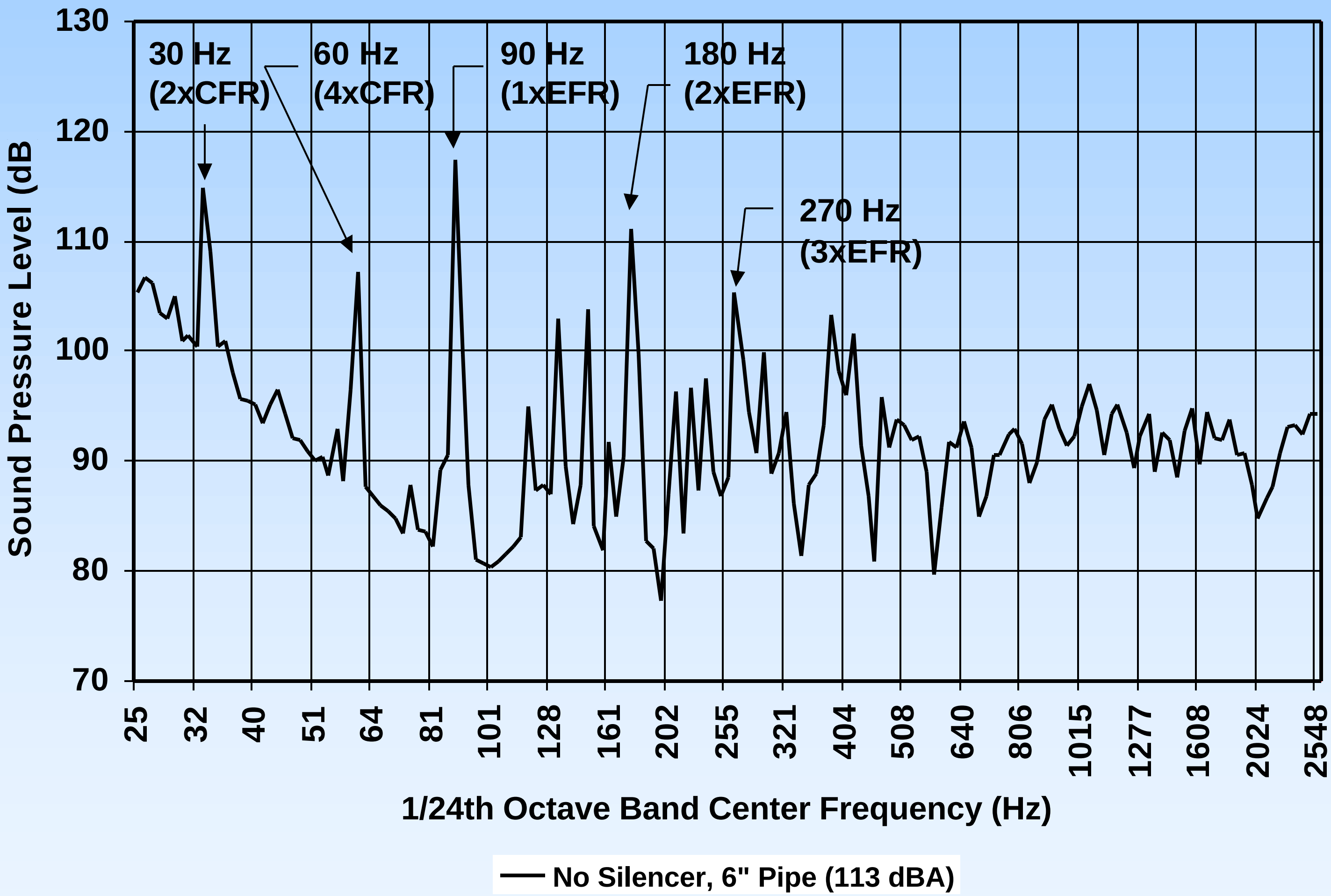
  EFR = N(CFR) where N = # cylinders

- Harmonics of CFR and EFR

This graph shows a narrow band spectrum of the exhaust noise of a 6 cylinder diesel engine running at 1800 RPM in a 500 kW generator. The data was collected with the microphone placed 1 meter from the exhaust outlet with the engine running at full load.

Note the strong tone at 90 Hz, which is the EFR. Note that the second and third harmonics are also prominent in the spectrum.

500 KW Engine Exhaust Tones



The most common element used to silence generator exhausts are reactive mufflers. Reactive mufflers are available in a wide range of cost and performance. The noise is reduced by forcing the exhaust air to pass through a series of tubes and chambers.

Each element in the muffler has sound reduction properties that vary greatly with acoustic frequency, and it is the mixing and matching of these elements that constitutes muffler design.

Reactive Mufflers

- 2, 3 or 4-chamber designs
- All metal construction with no sound absorptive materials
- Maximize ratio of body diameter to pipe diameter & volume

Over the years a series of muffler grades have evolved to describe the approximate insertion loss performance for engine exhaust mufflers. The words do not necessarily imply where the mufflers should be used. Note that better quality (e.g. higher insertion loss) mufflers will be physically larger than lower quality units.

Although size is not the only factor, you cannot get good acoustical performance without it.

Exhaust Muffler Grades

- Industrial/Commercial: IL = 15 to 25 dBA

  Body/Pipe = 2 to 2.5   Length/Pipe = 5 to 6.5

- Residential Grade: IL = 20 to 30 dBA

  Body/Pipe = 2 to 2.5   Length/Pipe = 6 to 10

- Critical Grade: IL = 25 to 35 dBA

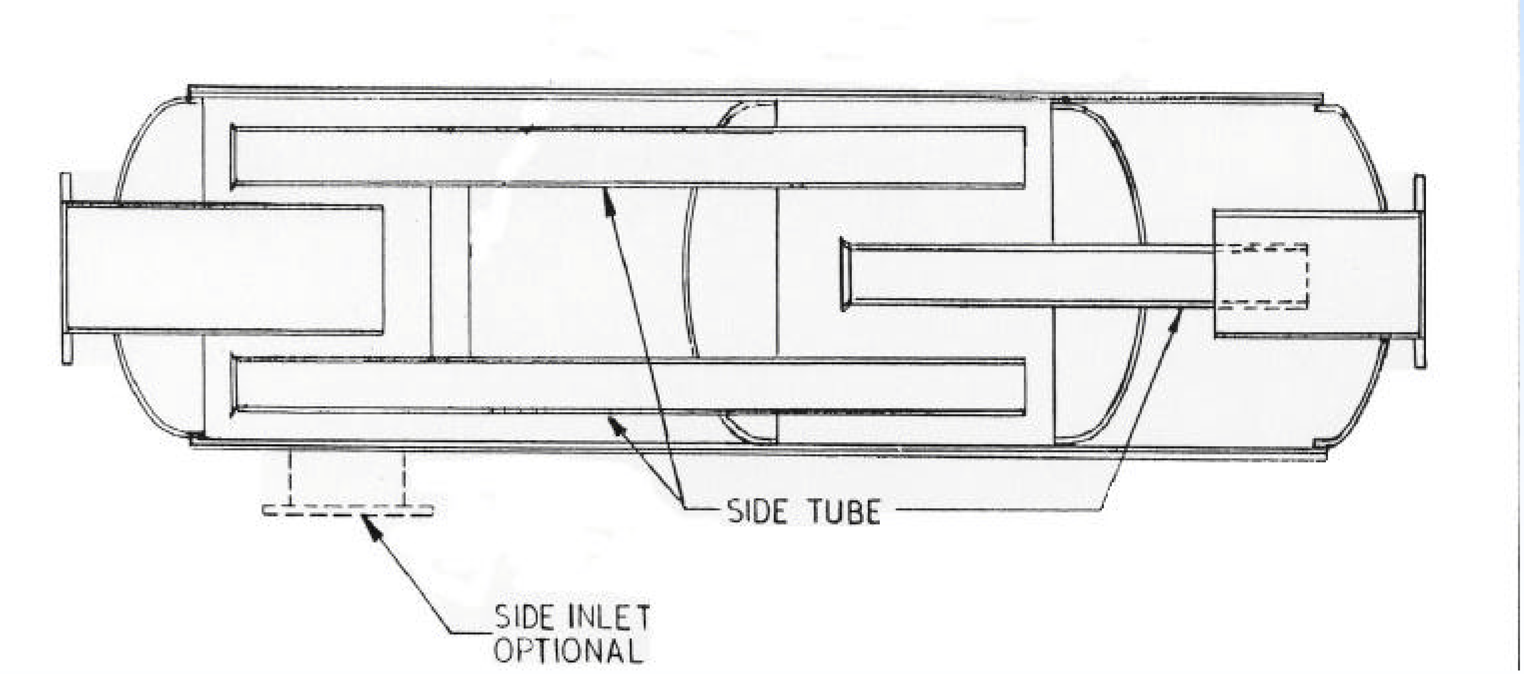
  Body/Pipe = 3   Length/Pipe = 8 to 10

The super-critical grade muffler generally represents the “top of the line” for reactive mufflers. Some manufacturers include an absorptive section to reduce high frequency sound transmission, but that is not the case for the silencer design shown in the next slide.

This drawing shows a 3 chamber critical grade muffler. It achieves its “super-critical” status primarily from its length, as much as 16x pipe diameter.

Exhaust Muffler Grades

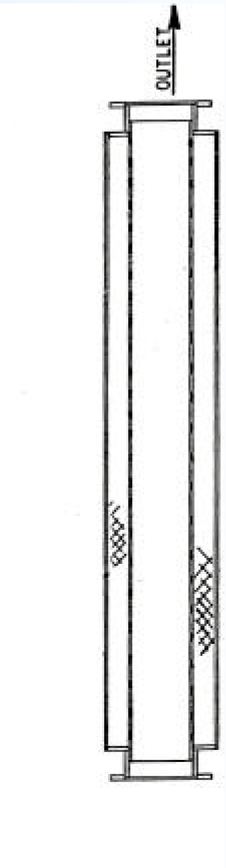
- Super Critical Grade: IL = 35 to 45 dBA
  Body/Pipe = 3 Length/Pipe = 10 to 16



Absorptive silencers use fiberglass or other acoustic fill material to absorb noise without any reactive elements (tubes &chambers). Absorptive silencers provide very little noise reduction at low frequencies, so they should never be used as the only silencer in an engine exhaust system. The straight-through design shown here is very useful for absorbing high frequency self-generated noise created by reactive mufflers.

Absorptive (secondary) Silencers

- Straight through design with fiberglass shielded from the exhaust stream by perforated sheet metal
- Provides mostly high frequency IL with low pressure drop

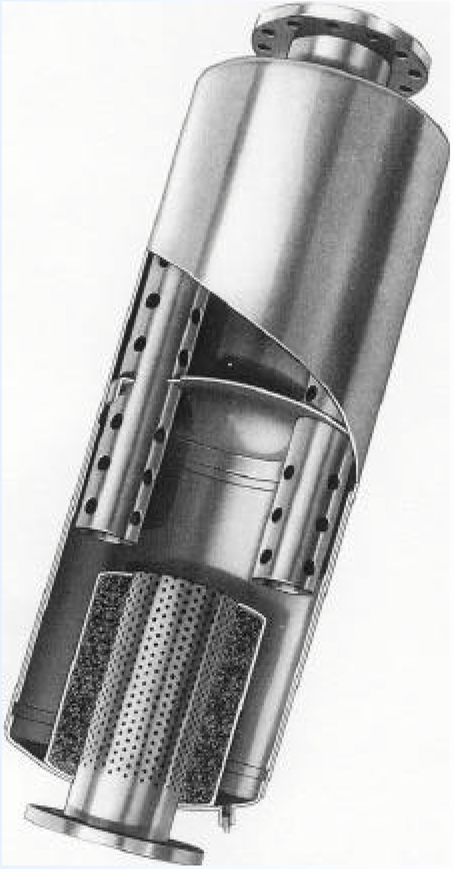


Some manufacturers offer combination reactive/absorptive silencers in a single package unit. Although this sounds like a good idea, you generally will get better overall acoustical performance by using a reactive muffler followed by a separate absorptive silencer.

Of course, a combination silencer may be appropriate for installations where there is not enough length in the exhaust system to fit two separate units.

Reactive/Absorptive Silencers

- These devices contain fiberglass shielded from the exhaust stream by perforated sheet metal
- Provides broad-band noise control

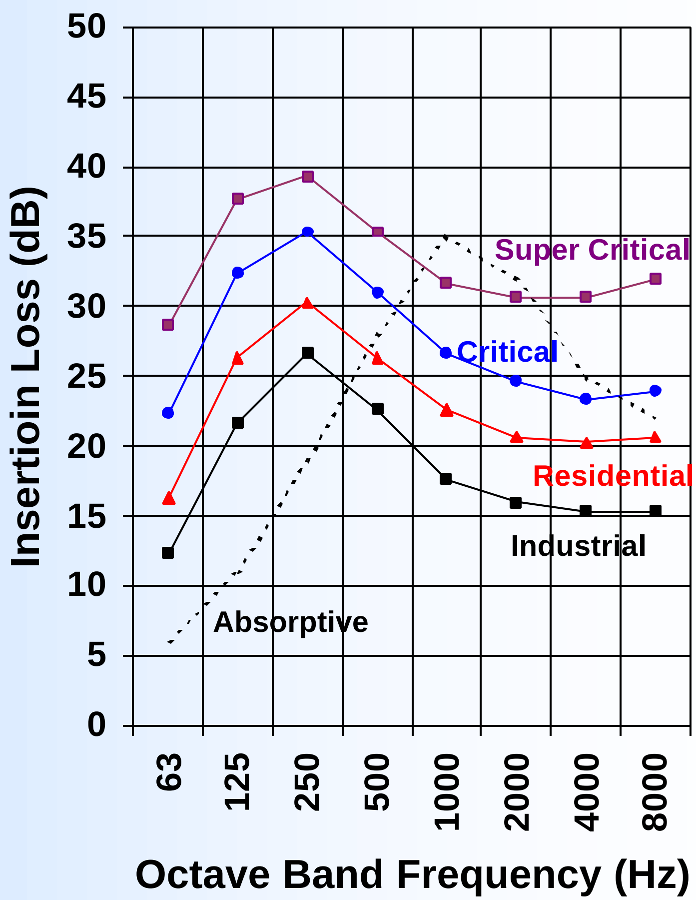


This graph shows the approximate insertion loss as a function of frequency for the various grades of mufflers.

Note that all values are approximate since no muffler has repeatable IL performance from engine to engine. Also note how the IL performance of the absorptive silencer is best in the frequency region where reactive mufflers start to deteriorate.

Muffler Insertion Loss

- Reactive mufflers work best at 125 Hz and 250 Hz
  (IL is reduced at high frequencies by self-noise)
- Absorptive mufflers work best at 1000 Hz and 2000 Hz



The first step in generator exhaust noise control design is to determine if a single muffler (by itself) can meet the project requirements.

Step 1 in this process is to obtain the unsilenced noise level from the engine manufacturer. This is typically given as sound pressure level at 1 meter (or similar distance).

Step 2 is to determine the noise criteria at the receiver. Provide a 5 dBA margin to allow for other sound transmission paths.

How to Select a Muffler

Step 1: Unsilenced Noise Level
(e.g. UNL = 116 dBA @ 1 m)

Step 2: Calculate Exhaust Noise Criteria ENC = RNC - 5 (dBA)

(e.g. to meet a total noise level of 60 dBA, design muffler for 55 dBA)

Step 3 is to calculate the unsilenced exhaust noise at the receiver location. The following equation provides a correction for distance assuming free-field spreading.

Reflections from large objects (e.g. buildings) can cause the actual noise level to be higher than that predicted by this equation.

Conversely, shielding provided by barriers (partial or total) can cause the received noise level to be lower.

How to Select a Muffler

Step 3: Correct UNL to Receiver Distance

$$L_p(x_r) = L_p(x_0) - 20 \log (x_r/x_0)$$

for example:

$$L_p(25\text{ m}) = L_p(1\text{ m}) - 20 \log (25/1)$$

$$L_p(25\text{ m}) = 116 - 28 = 88\text{ dBA}$$

In Step 4 the required insertion loss of the muffler is determined by subtracting the receiver noise criteria from the unsilenced receiver noise level. Note that a 5 dB safety factor is recommended to account for the fact that actual muffler performance often falls short of the manufacturer's claims.

Once a muffler grade is determined, the last step is to size the inlet/outlet pipe for pressure drop.

How to Select a Muffler

Step 4: Required IL = UNL - ENC + 5

IL = 88 dBA - 55 dBA + 5 = 38 dBA
(super critical grade required)

Step 5: Select inlet/pipe size for pressure drop no more than 50% of maximum

Octave band IL data must be used to compute the expected noise level if barriers are involved in the sound transmission path. If barriers are not involved, it is much simpler to use the approximate dBA attenuation figures available from a reputable manufacturer.

Keep in mind that octave band values are approximate because they vary from engine to engine and also with load.

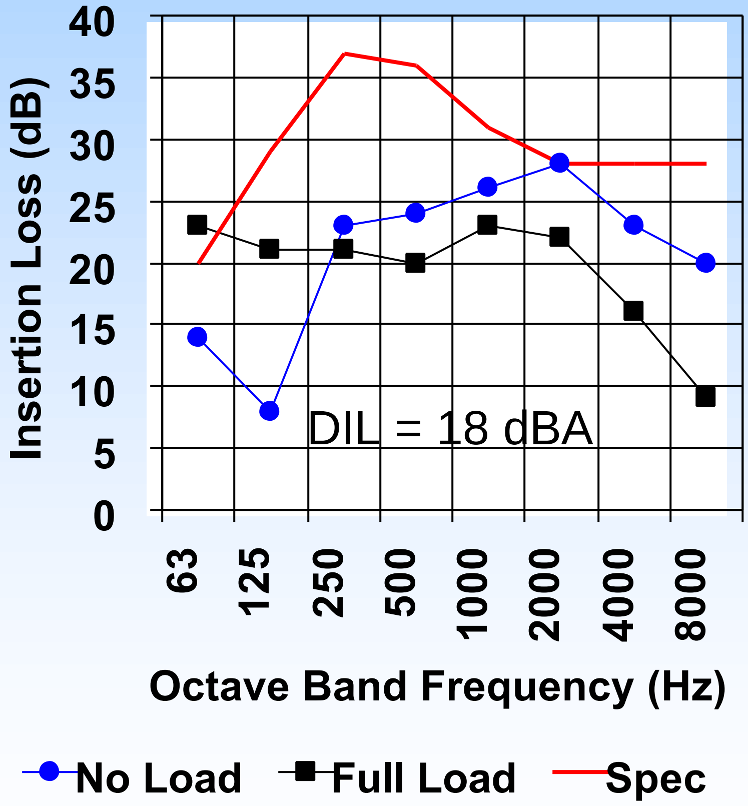
Using Octave Band IL Data

- Octave band IL data must be used to assess effects of barriers
- Accuracy is probably no better than the dBA method (without barriers)
- Manufacturer's octave band data are listed as "typical" because they are inconsistent from engine to engine

This graph presents the results of an insertion loss field test, where the contractor wanted to substitute a less expensive muffler from an "off-brand" manufacturer. Even though the manufacturer "guaranteed" that his muffler would meet the IL of the specified unit, it failed at nearly every octave band. The overall noise reduction was only 18 dBA with the initial test shown here.

Insertion Loss Field Test

- "Off brand" muffler was substituted, but was "guaranteed"
- Muffler failed the field test "repeatedly"
- After 2 years of testing & re-testing the specified muffler was finally installed

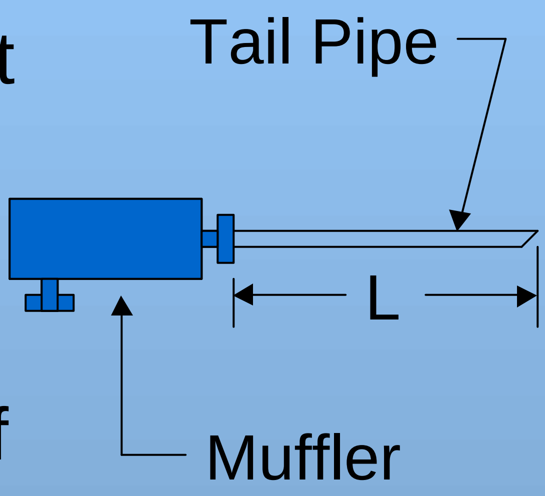


One aspect of the engine exhaust system acoustical design that is often overlooked is the tail pipe. The section of pipe downstream of the final silencer will have acoustic resonances that can amplify engine tones if they match.

Resonances can be avoided simply by keeping the length of the tail pipe less than 1/2 wavelength at the tone frequency. Even better, size the tail pipe to exactly l/4 to cancel the tone. `

Tail Pipe Design

- Exhaust tail pipe will have resonances that can amplify engine tones
- Avoid amplification of tones by using short tail pipe or size L to 1/4 wavelength (λ/4)



The next equation will give you the various resonance frequencies of any exhaust tail pipe. The number n is any positive integer, but usually it is only the low frequencies that are a concern. Note that resonance occurs when L = nl/2, so this tail pipe length should be avoided at all times.

Tail Pipe Resonances

$$f_n = nc/(2L)$$

where:

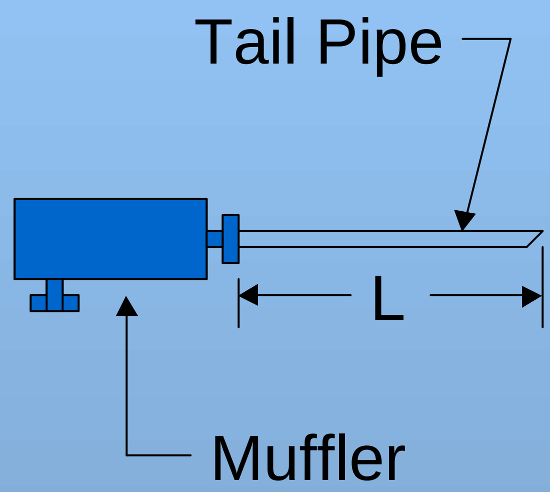
f_n is resonance frequency of pipe

n = 1, 2, 3, …

c is speed of sound

L is length of pipe (ft)

resonance occurs if $L = n\lambda/2$



This example goes through the various steps required to design a tail pipe for a 4-cycle engine. The frequencies to avoid are 15 Hz, 30 Hz, 45 Hz, 60 Hz, 75 Hz, 90 Hz, 105 Hz, etc.

The most important frequency is the 90 Hz EFR. The wavelength at 90 Hz is 20 feet, so we want to avoid a tail pipe length of 10 feet, 20 feet, 30 feet, etc. The best length is exactly 5 feet because this will cancel the 90 Hz tone at the outlet.

Tail Pipe Design Example

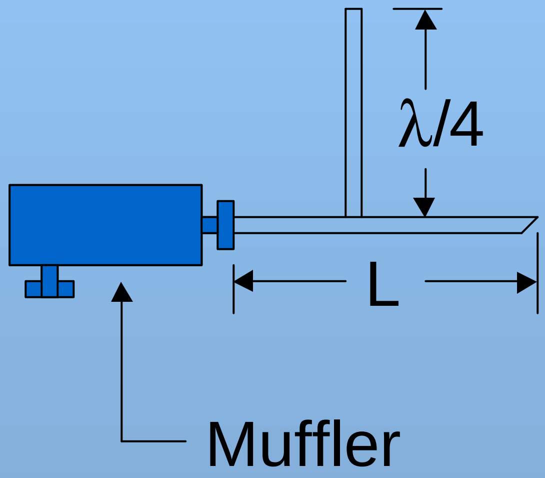
- 6 cylinders @ 1800 RPM (950 ^{o}F)
- CFR = (1800/120) = 15 Hz
- EFR = 6(CFR) = 90 Hz
- $c = 49.03(460+950)^{0.5} = 1841$ ft/sec
- $\lambda_{CFR} = 1841/15 = 122$ ft
- $\lambda_{EFR} = 1841/90 = 20$ ft
- Tail Pipe Length = 20/4 = 5 ft (or 15 ft)

Tuned resonators can be used to attenuate specific frequencies in the exhaust spectrum. There are a lot of different resonator designs, but the simplest and easiest to understand is the side branch resonator, sometimes called the 1/4 wave resonator. A side branch resonator is nothing more than a dead-end section of pipe connected to the main exhaust pipe.

Tuned Resonators

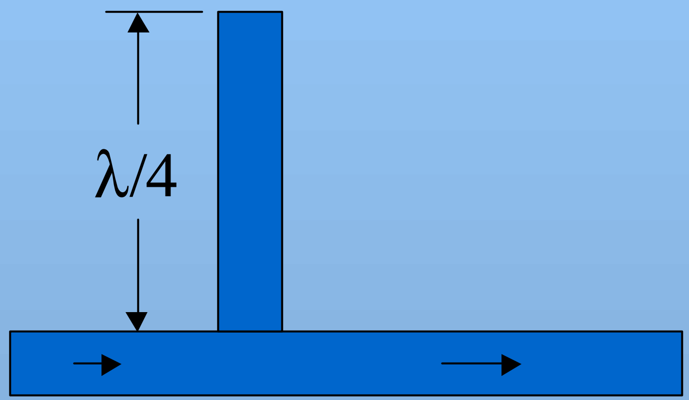
- Resonators can be used to remove tones from the exhaust spectrum

- Sketch shows a side branch resonator tuned to 1/4 wavelength (λ)



The diameter of the side branch should be equal to the diameter of the main pipe. As the acoustic wave from the source reaches the branch, the energy splits equally. The wave travelling down the side branch reflects off the closed end and is reflected back toward the branch. When it arrives back at the branch it is exactly 180 degrees out of phase from the source wave because the branch has a length of l/4.

Side Branch Resonator



- Side branch is dead end pipe (no flow)
- Length of pipe is tuned to $\lambda/4$ or $3\lambda/4$
- Speed of sound increases with temp.

Wavelength, $\lambda = c/f$

Speed of Sound, c

Frequency, f (Hz)

$c = 49.03(T_R)^{0.5}$ (ft/sec)

$T_R = 460 + T_a(^{o}F)$

Side branch resonators are effective only at low frequencies and only in three narrow frequency regions. Side branch resonators are inconsequential at other frequencies.

Problems inherent with the side branch resonator include de-tuning caused by changes in the speed of sound as the engine warms up. In engine exhaust systems, soot buildup and water collection in the side branch can also degrade the attenuation.

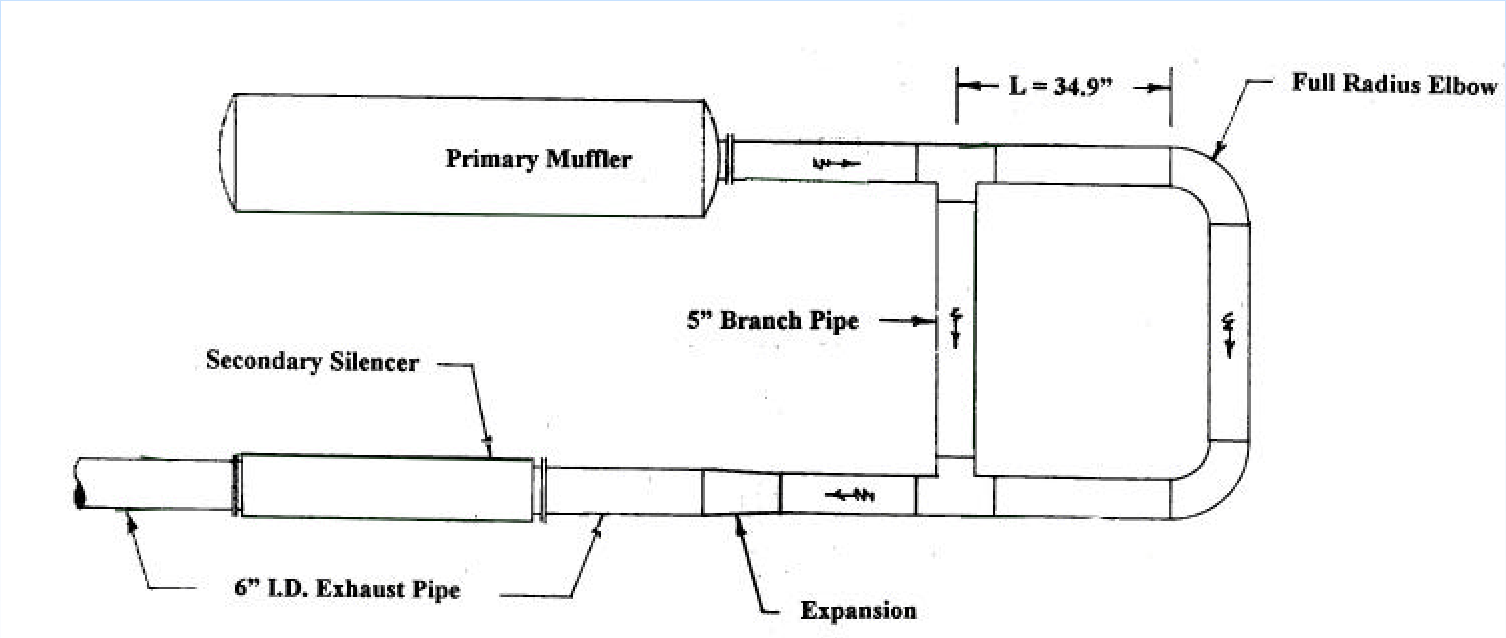
Side Branch Resonator

- Only effective at low frequencies (when λ > 10 times pipe diameter
- Only effective in 3 narrow frequency regions (L = $\lambda/4$, $3\lambda/4$, and $5\lambda/4$)
- Can achieve 20 to 30 dB insertion loss if tuned properly
- May become ineffective if end of pipe does not remain reflective

Another resonator design that is particularly suited for engine exhaust systems is the Herschel-Quincke tube, which I like to call the trombone resonator. Acoustically, it works very much like the side branch resonator - except that it doesn't require a reflection.

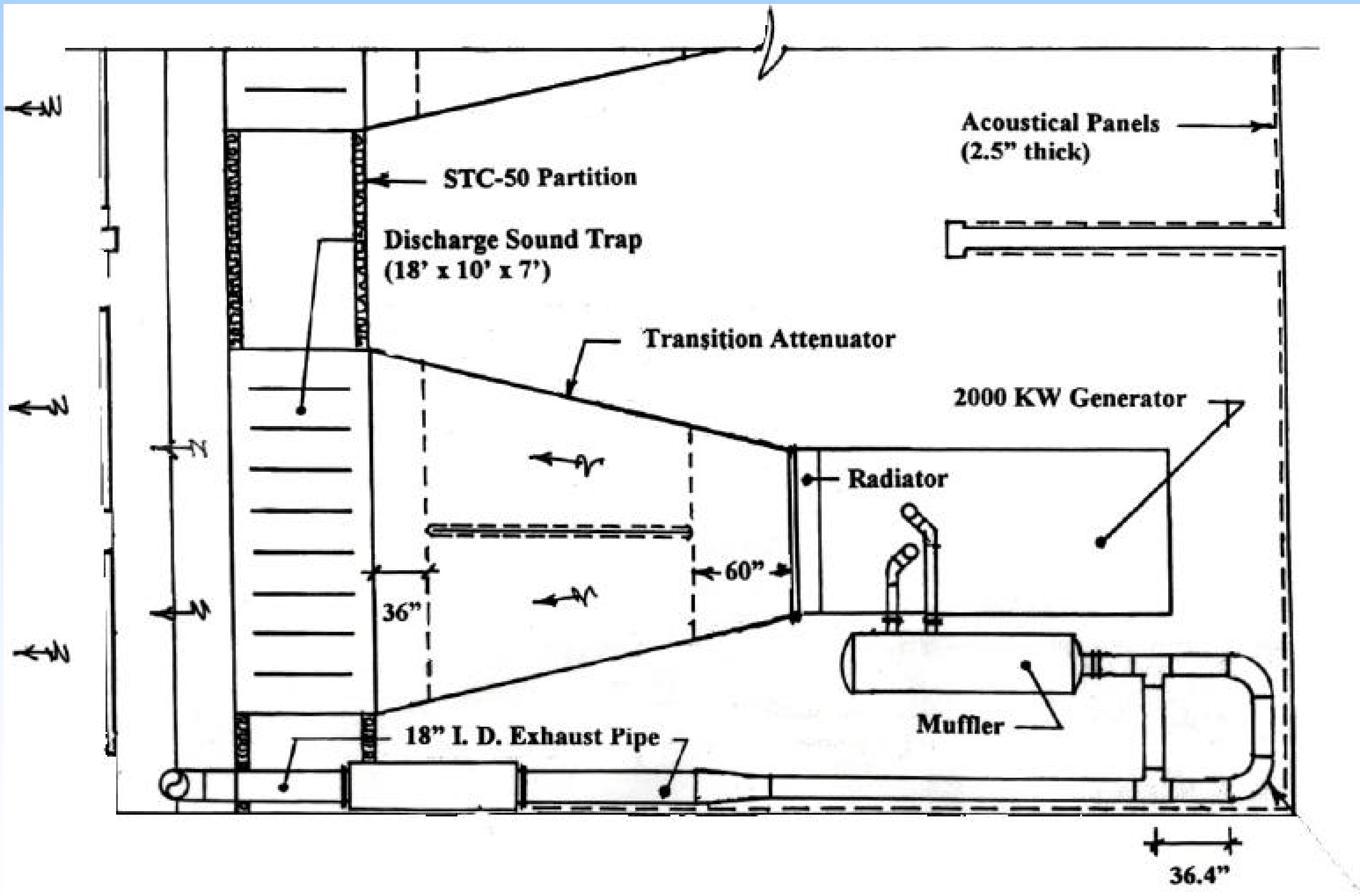
The only difference is that you have to consider the effects of flow velocity on the speed of sound for proper tuning.

Trombone Resonator (Herschel-Quincke Tube)



This drawing shows a floor plan of the generator room in a field application using a trombone resonator in a 2 MW generator installation on the ground floor of an office building. In order to obtain the necessary vertical space, the ground floor slab was depressed 4 feet in the vicinity of the generator. A custom fabricated acoustic transition followed by 7 ft. long duct silencers controlled the radiator and engine noise.

Resonator Field Application



The trombone resonator was designed to eliminate the 240 Hz engine firing rate of the 16-cylinder diesel. The other two resonator frequencies were 80 Hz and 400 Hz.

Trombone Resonator Design

- Tuned for EFR = 240 Hz ($3\lambda/4$)
- Also effective at $\lambda/4$ = 80 Hz and $5\lambda/4$ = 400 Hz
- Gas Flow Rate = 16,745 CFM
- Gas Temperature = 946 ^{o}F
- Speed of Sound = 1,838 ft/sec
- Additional Loop Length = 138 inches

After completion of the acoustical design, the owner decided to incorporate a 1MW load bank between the radiator discharge and the acoustical transition.

This worked very well from an acoustical standpoint because no additional noise control was required for the load bank.

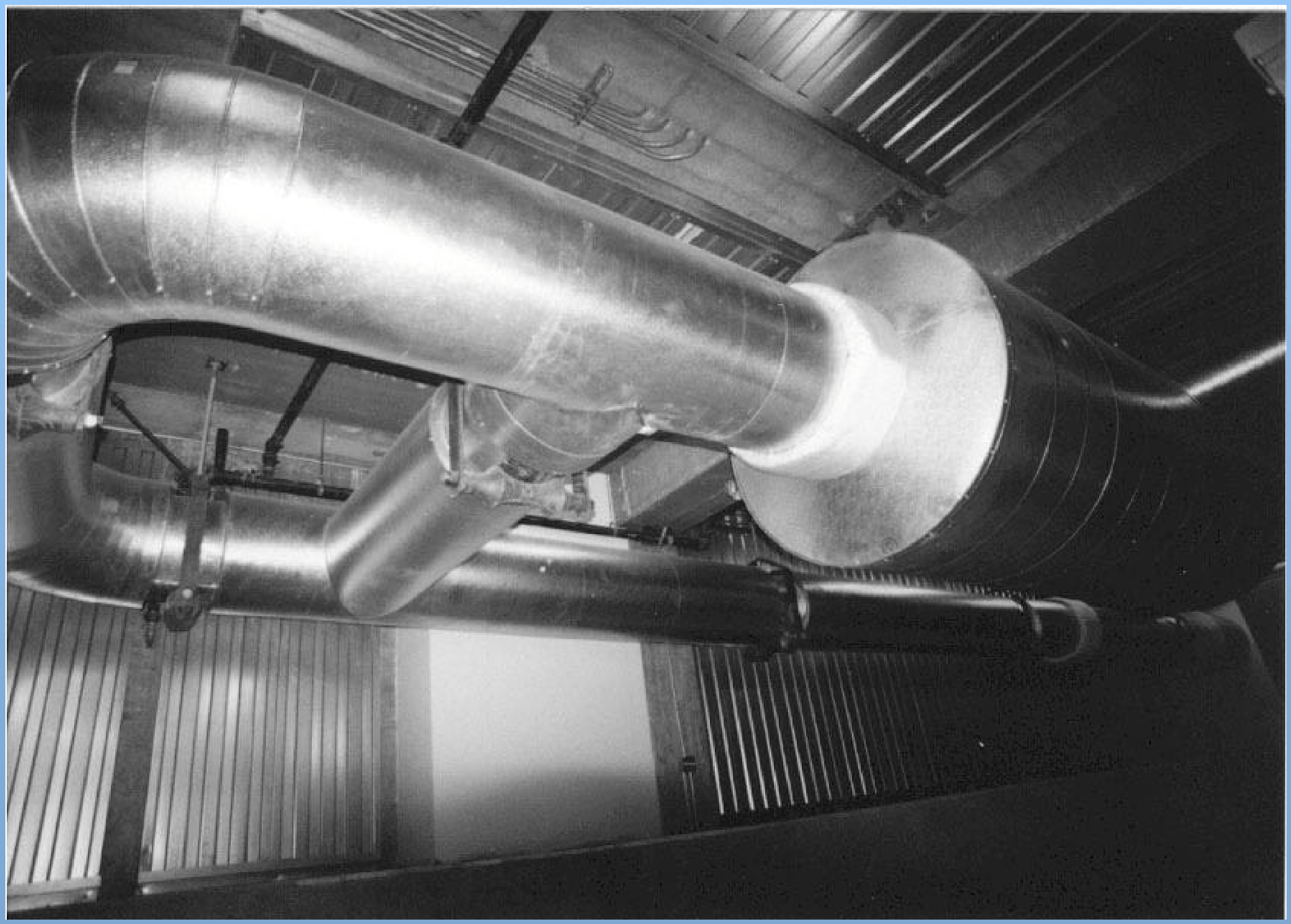
Engine, Radiator & Load Bank

This next slide is a view of the trombone resonator (note the super-critical primary muffler on the left).

The exhaust pipe and muffler are insulated and externally wrapped for thermal purposes.

Acoustical panels with perforated metal facing are also visible on the slab above.

Trombone Resonator

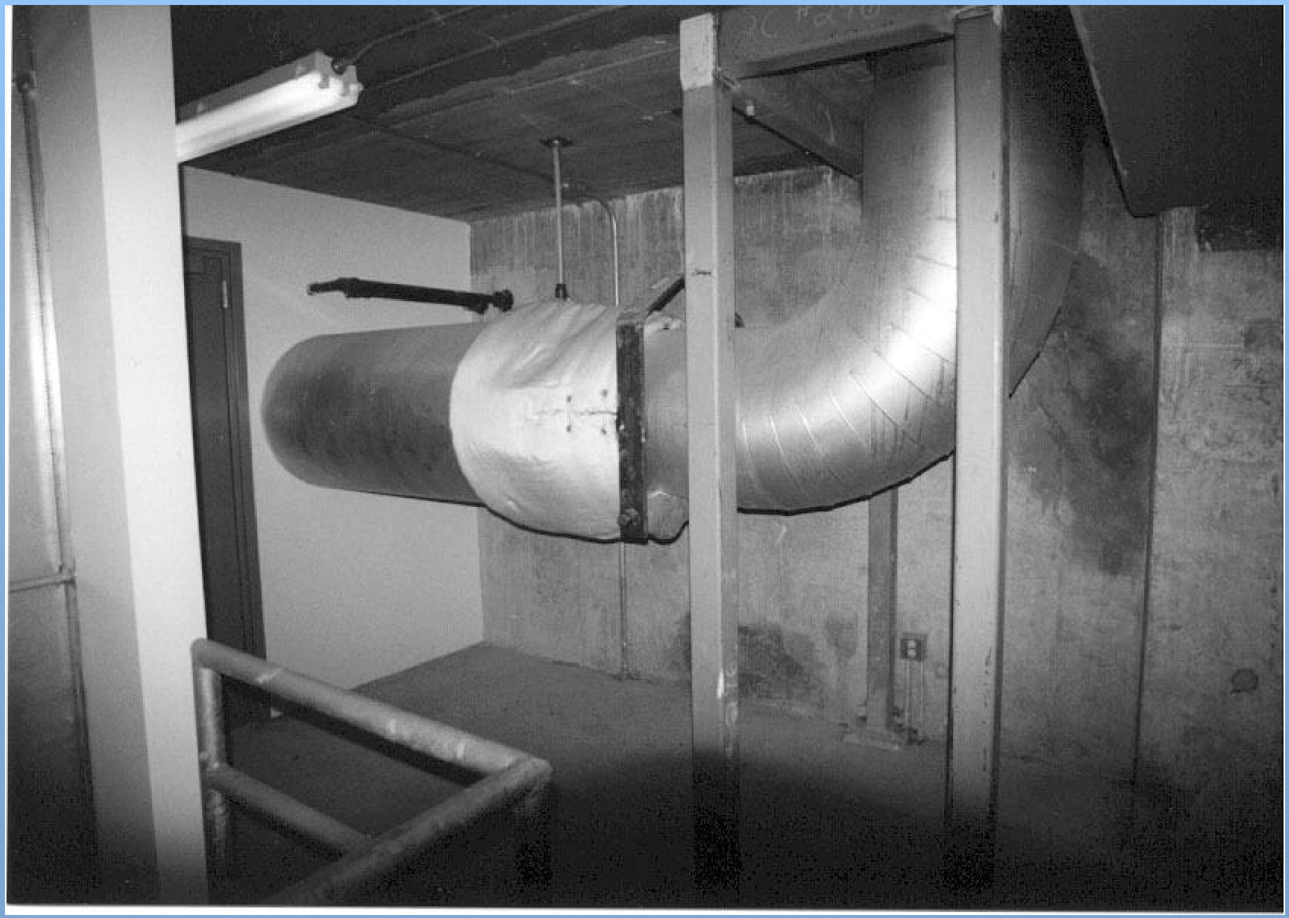


Dual Air Intake & Muffler

View of the dual air intake filters with the primary muffler behind. This particular engine has dual 8” exhaust outlets.

Secondary Silencer & Elbow

View of the secondary silencer as it passes through the generator room wall. The exhaust then makes an elbow up followed by two additional elbows before exiting the discharge plenum.



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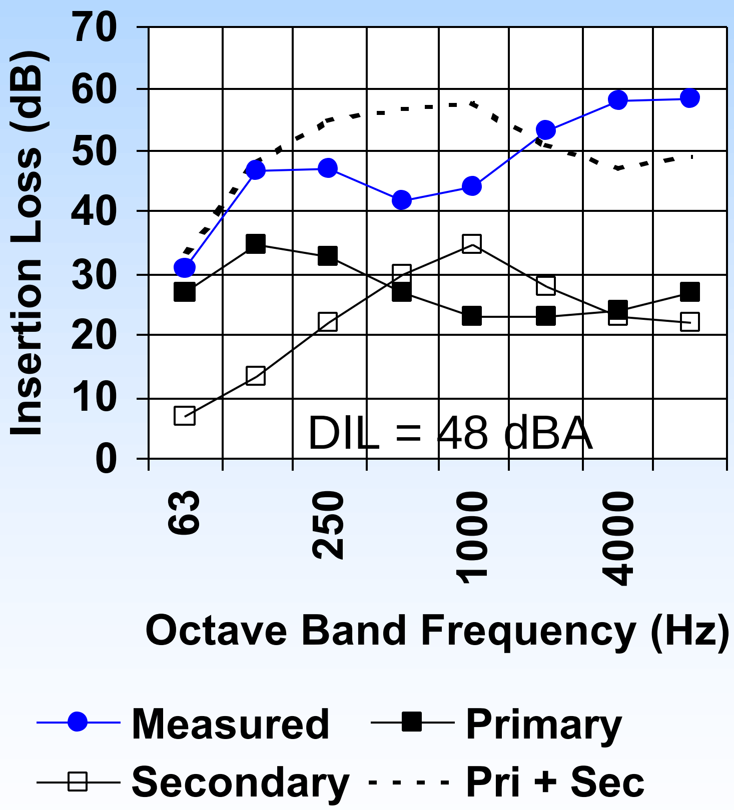
These are views of building exterior showing the ground level radiator outlet with the exhaust outlet above.

This next graph shows the measured exhaust noise levels 1 meter from the exhaust outlet with the generator running at 50% load. Using the unsilenced engine exhaust noise data from the manufacturer, We show the calculated total insertion loss of the exhaust system. Also shown is the manufacturer’s estimated octave band IL data for the primary and secondary silencers.

Field Test Results (50% Load)

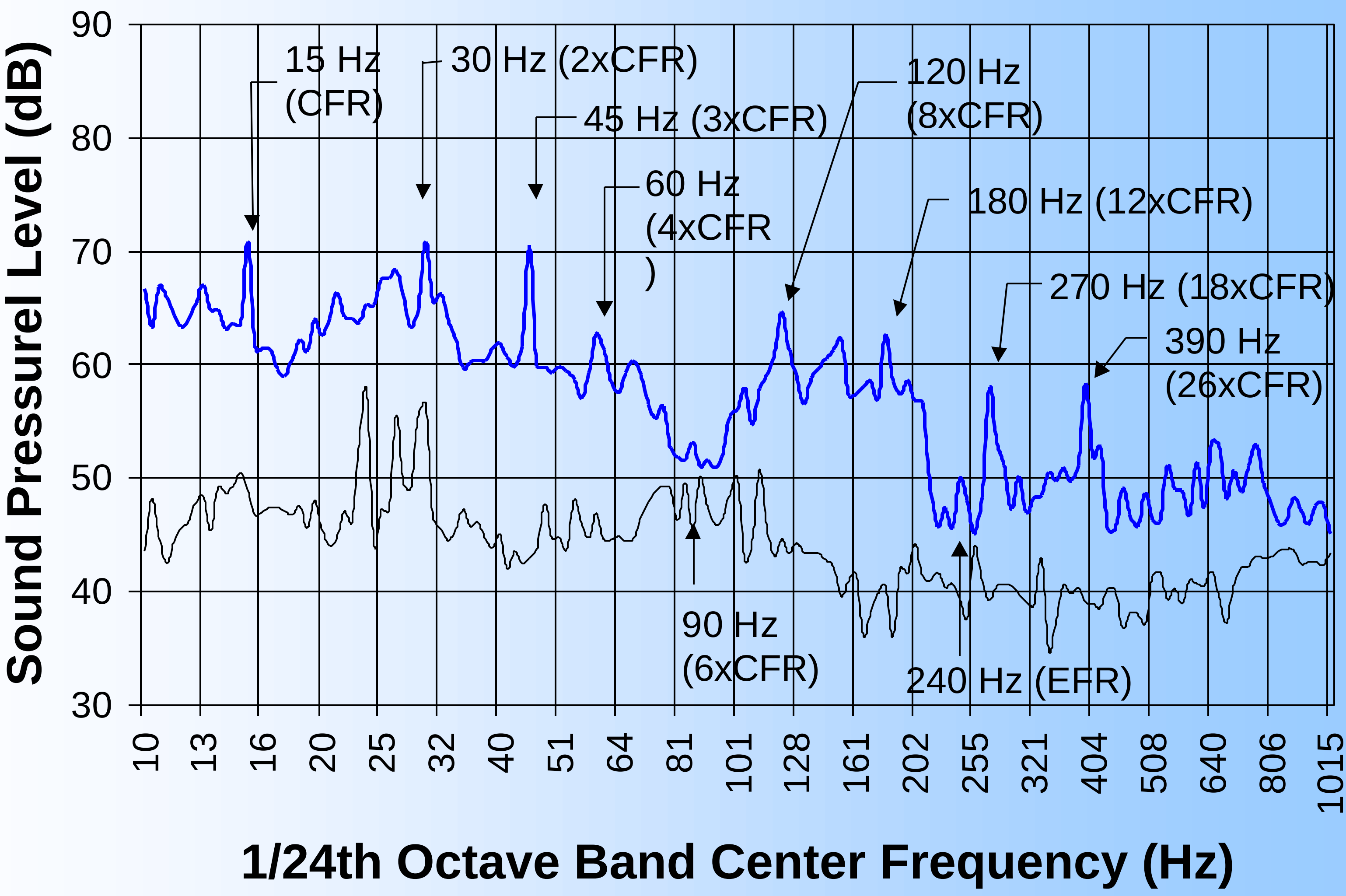
- Exhaust system achieved 48 dBA insertion loss (based on factory unsilenced data)
- Performance was limited by self-noise at mid-frequencies
- 67 dBA at 1 meter



The next slide shows a narrow band spectrum of the octave band data presented in the previous slide and shows the effect of the trombone resonator. Note the dip in the curve in the vicinity of 80 Hz and 240 Hz.

The fact that there is no EFR tone (240 Hz) at all is very impressive.

Measured Spectrum at 1 meter



Summary

- In most cases a reactive muffler is adequate to control exhaust
- In very sensitive installations add a secondary absorptive silencer (sized to 3000 ft/min) with a short tail pipe

Summary

- CAUTION: Do not use two reactive mufflers in series (too much self-noise)
- In extreme cases use super-critical primary muffler with secondary absorptive silencer plus a tuned resonator to eliminate tones

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