



GUIDE FOR RATING GENERATOR EXHAUST SILENCERS

EGSA 201S-2014

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Electrical Generating Systems Association
1650 South Dixie Highway, 4th Floor
Boca Raton, FL 33432
Phone: (561) 750-5575 • Fax: (561) 395-8557

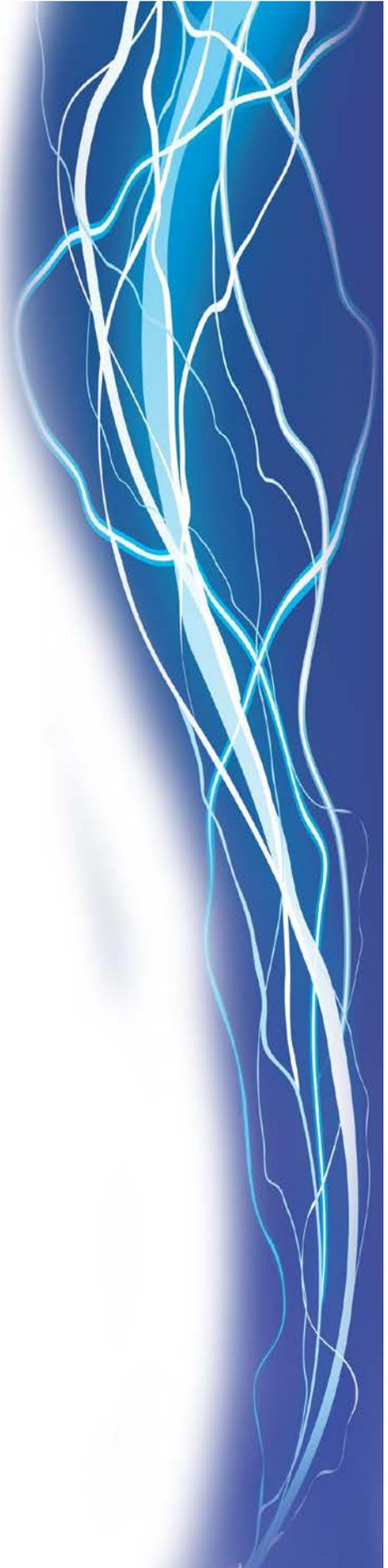


TABLE OF CONTENTS

	Page
1. FOREWORD.....	2
2. INTRODUCTION	2
3. SCOPE.....	3
4. TERMS AND DEFINITIONS.....	3-6
5. INSERTION LOSS.....	6
6. EGSA SILENCER SOUND PERFORMANCE GRADES	7
7. SILENCER GRADE SPECIFICATION CONSIDERATIONS	8-9
8. APPENDIX: UNDERSTANDING INSERTION LOSS DETERMINATION	9-14

1.1 FOREWORD

The Electrical Generating Systems Association (EGSA) is the world's largest organization exclusively dedicated to on-site power generation. The Association is comprised of manufacturers, distributor/dealers, contractors/integrators, manufacturer's representatives, consulting and specifying engineers, service firms, and end users throughout the U.S. and around the world involved in on-site power generation technology and equipment. EGSA encourages the exchange of information, offering education and training for the mutual benefit of the on-site power generation systems industry and end users.

EGSA has members that are leading authorities in the development and monitoring of performance standards for the on-site power industry. One area of performance is that of engine silencers. While there are standards addressing silencers for heating, ventilating, and air-conditioning (HVAC) duct and on-highway engines, there is no industry accepted guideline for silencers used in electrical generating systems. EGSA members recognized this deficiency and expressed a need to develop a more uniform silencer rating criteria. At the request of EGSA past president, Michael Pope, EGSA's Codes and Standards Surveillance Committee created a working group charged with the task of developing an industry guideline that would provide an accepted matrix of silencer ratings for the electrical generating industry.

The Silencer Working Group is a sub-committee formed within EGSA's Codes and Standards Surveillance Committee to establish a meaningful industry guideline for electrical generator exhaust silencers. The group is comprised of EGSA members with industry-leading experience and expertise in the design and manufacture of exhaust silencers and emission products for reciprocating internal combustion engines used in electrical generating systems.

2.1 INTRODUCTION

Historically there were four silencer "grades" that were very non-specific to performance, but simply reflected metro zoning that was common at the time. These were "industrial, commercial, residential, and hospital" grades. While these grades were useful at the time, a more precise criteria to express exhaust silencer performance is needed to meet the demands of today's market. The assumption was that if a manufacturer "labeled" their silencers one of these grades, then the silencer performance would be sufficient to meet a given metropolitan zoning area and provide normally acceptable noise levels. However, there were no quantitative numerical sound reduction criteria.

With no performance standard for reduction criteria, these grades were not necessarily consistent. The amount of noise reduction for a given grade could vary between models and manufacturers.

The *EGSA Guide for Rating Generator Exhaust Silencers* was developed to provide quantitative, consistent silencer ratings that can be used by EGSA members, specification writers, acoustical consultants and facilities engineers with confidence that they get the noise reduction expected from a silencer labeled with a particular grade. This guide provides criteria for the classification of exhaust silencers that are equipped on reciprocating internal combustion engines.

3.1 SCOPE

3.1.1 General. The purpose of this guide is to provide a uniform noise reduction rating system for exhaust silencers used on reciprocating internal combustion engines that are utilized for the purpose of generating electrical power. The guide specifies the ranges of expected dynamic insertion loss (DIL) performance when using different classifications of exhaust silencers. It is intended to provide rating classifications that may be used by manufacturers, specification writers, consultants and end users. Specifying the sound reduction criteria in this guide will help provide consistent and quantitative acoustic performance.

3.1.2 Limits of Applicability. This guide applies to exhaust silencers equipped on reciprocating internal combustion engines that are utilized for the purpose of generating electrical power. This guideline is *not applicable* to any other applications such as on- and off-highway vehicles, HVAC equipment, intake silencers, etc.

Testing, measurement methods, and predicative equations are not within the scope of this guide. The silencer performance prediction is inherently complicated and utilizes multiple variables and equations. Some of these factors are addressed in the appendix for reference.

4.1 TERMS AND DEFINITIONS

Absorptive Silencer: Absorptive or dissipative silencers use sound absorbing materials to attenuate sound waves. Absorptive silencers include lined duct attenuators, packaged cylindrical and rectangular attenuators, acoustic louvers and lined plenum chambers.

Ambient Noise (Background): Ambient noise is the pervasive noise associated with a given environment, usually a composite of sounds from sources both near and distant.

Attenuation: This is a general term that refers to any reduction in the strength of a signal; in this case, sound. The extent of attenuation is usually expressed in units called decibels (dBs).

Decibel (dB): The decibel (dB) is a logarithmic unit that indicates the ratio of a physical quantity (usually power or intensity) relative to a specified or implied reference level. A ratio in decibels is ten times the logarithm to base 10 of the ratio of two power quantities.¹ A decibel is one tenth of a **bel**, a seldom-used unit. The decibel is commonly

used in acoustics to quantify sound levels relative to a 0 dB reference, which has been defined as a sound pressure level of .0002 microbar. The reference level is set at the typical threshold of perception of an average human.

Decibel, A-Weighted (dB-A): This symbol is often used to denote the use of different weighting filters and is used to approximate the human ear's response to sound. Although the measurement is still in dB, it is designated as a *sound level* rather than a *sound pressure level*. These measurements usually refer to noise and its effects on humans, and are in widespread use in the industry with regard to noise control issues, regulations and environmental standards.

Divergence Loss: Divergence loss is sound pressure loss measured at one distance compared to another distance from the source (e.g. end of tailpipe).

Engine Exhaust System: The engine exhaust system uses tubing or duct work to guide waste exhaust gases away from a controlled combustion inside an engine. From the engine to the silencer, the tube is referred to as exhaust pipe; from the silencer to the outlet, the tube is referred to as the tailpipe.

Engine Intake System: This is the subsystem of an **engine** that meters in air from the environment and delivers it to the combustion chamber.

Expansion Ratio: The expansion ratio is the ratio of the cross sectional area of the nominal inlet/outlet diameters to the cross section area of the cylindrical or other cross section shaped shell (silencer body).

Dynamic Insertion Loss DIL is the difference between the sound pressure level measured at the same point *before* and *after* the insertion of the silencer into the engine intake or exhaust system.

Octave: An octave refers to the interval between one frequency and its double or its half. In acoustics, the first nine octave bands are identified by their center frequencies of 31.5, 63, 125, 250, 500, 1,000, 2,000, 4,000, and 8,000 Hertz (Hz). These center frequency values are based on the ISO/ANSI Preferred Numbers and therefore are known as the *preferred octave band center frequencies*. The 31.5 band is also referred to as the band number 0, and 63 Hz is band number 1.

Octave Band Center Frequency (OBCF): Each octave and 1/3 octave bands are identified by a middle frequency (f_o), a lower frequency band, and an upper band. The reference middle frequency in acoustics is 1,000 Hz. Other middle frequencies are computed by successive multiplications or divisions of this reference value by 2 or $2^{1/3}$ for octave and 1/3 octave bands respectively. The upper and lower limits of each octave are Center Frequency multiplied by the square root of 2 (≈ 1.414) and square root of 2 divided by 2 (≈ 0.707). For example, the 1,000 Hz octave extends from 707 Hz to 1,414 Hz.

Reactive Silencer: The primary function of a reactive silencer is to reflect sound waves back to the source and, internally, reduce the amplitude of a wide range of frequencies. Energy is dissipated in the extended flow path resulting from internal reflections and by absorption at the source. Reactive silencers have tuned cavities or membranes and are designed to attenuate a wide frequency range of flow borne noise from machines.

Resonators: This type of silencer is designed to create an "exhaust note" that reduces the noise of a limited and rather narrow specific range of frequencies. The "tuning" of a resonator may be extremely narrow or wide to accommodate changing wavelengths of specific frequencies due to variations in gas temperature.

Silencer: A silencer is a device engineered as an acoustic device designed to reduce the loudness or amplitude of the sound pressure created by the engine. It can be coupled with or incorporate a catalytic converter for the treatment of exhaust gases emissions.

Sound Pressure: Sound pressure, or *acoustic pressure*, is the local pressure deviation from the ambient or local barometric pressure (average, or equilibrium) caused by the pressure variations produced by a sound wave.

Sound Pressure Level (SPL or L_p): The sound pressure level is the force (N) of sound on a surface area (m^2) perpendicular to the direction of the sound. It is measured in decibels (dB) above a standard reference level. The commonly used "zero" reference sound pressure in air is 20 μ Pa RMS, which is usually considered the threshold of human hearing (at 1 kHz).

Sound Level (L_A): This is the term for sound to which a weighting has been applied to reflect the reaction of specific receptors. For example A-weighting reflects the lower sensitivity of normal human hearing response to frequencies below 1,000 Hz and is referred to as A-weighted sound level (*not* sound pressure level) and is noted as L_A . Other sound level weightings exist for special application; however A-weighted sound level is the one most commonly used in regulations for workplace and community noise.

Sound Power: Sound power (w) (or *acoustic power* P_{ac}) is a measure of sonic energy E per time t unit. The rate of emission of acoustical energy from a source is typically expressed in watts (W). Sound power is only a function of the source generated acoustic energy. It does not change with distance or surrounding acoustical environment.

Sound Power Level (PWL or L_w): This is a common way to express the magnitude of sound power produced by the source. The range of sound power is very large (10^{-9} for a whisper to 10^8 for a shuttle launch). By expressing the level as a logarithm of the ratio of the source to a common reference, the range of scale collapses to a more convenient range and is easy to relate to a known source. Sound Power Level is a logarithmic ratio

of the watts of power produced divided by the standard reference of 10^{-12} Watts, and is represented in dB.

$$L_w = 10 \log (w/10^{-12})$$

The relationship between L_w and L_p at a particular distance from the source (on flat pavement, outdoor, free field) is calculated as

$$L_p @ r \text{ ft} = L_w - 20(\log_{10} (r)) + 2.34\text{dB.} \quad \text{Equation 1}$$

For example:

$$\begin{aligned} \text{At 100 ft } L_p &= L_w - 20(\log_{10} (100)) + 2.34\text{dB.} = L_w - 20 (2) + 2.34 \text{ dB or } -40 + 2.34 \\ &= L_w - 37.66 \text{ dB} \end{aligned}$$

Transmission Loss: Transmission loss is the ratio in dB of the amount of sound measured on the source side to the amount of sound measure on the receiver side of a barrier.

Velocity Noise: Also known as “self-noise,” velocity noise is the noise power level in decibels generated by the silencer when inserted in the air flow. The self-noise depends on whether the flow direction is forward or reverse. The sound power (watts) is proportional to Velocity^4 therefore if velocity increases by 20%, the L_w of the self-noise increases by 10 ($\log(1.2)^4$) or 10 ($\log(2.074) = 3.2 \text{ dB}$). If the velocity doubles, the self-noise increases by 12 dB

Wavelength: The wavelength of a sinusoidal wave is the spatial period of the wave (in this case a sound wave) or the distance over which the wave's shape repeats.² It is usually determined by considering the distance between consecutive corresponding points of the same phase, such as crests, troughs, or zero crossings. Wavelength at a given frequency in a gas is proportional to the square root of the absolute temperature of the gas $^{\circ}\text{R} = ^{\circ}\text{F} + 460$. Silencers respond to wavelength; therefore, the DIL of a given silencer at particular frequencies in an intake system is different from that same silencer installed in the exhaust system of the same engine.

5.1 INSERTION LOSS

Dynamic insertion loss (DIL) is the change in sound level at a specific point in space when a silencer is inserted into the exhaust system. It includes the effects of raw engine exhaust noise, exhaust flow, temperature and self-noise. See Figure 1 for a schematic of DIL.

$$\text{DIL} = L_{p1} - L_{p2} \quad \text{Equation 2}$$

DIL is normally measurement in dB at 1/1 or 1/3 octaves beginning with the 31.5 Hz octave band center frequency (OBCF) through the 8,000 Hz OBCF. To provide a convenient single number rating, the measured DIL is converted to an A-weighted

sound level (dBA). A-weighted sound levels correlate well with the human ear and judgment. Outdoor environmental noise standards and local noise ordinances most commonly use dBA sound levels for acceptance criteria. For the purpose of this document, the overall DIL will be expressed in dBA. (See the Appendix for further technical information on determining insertion loss.)

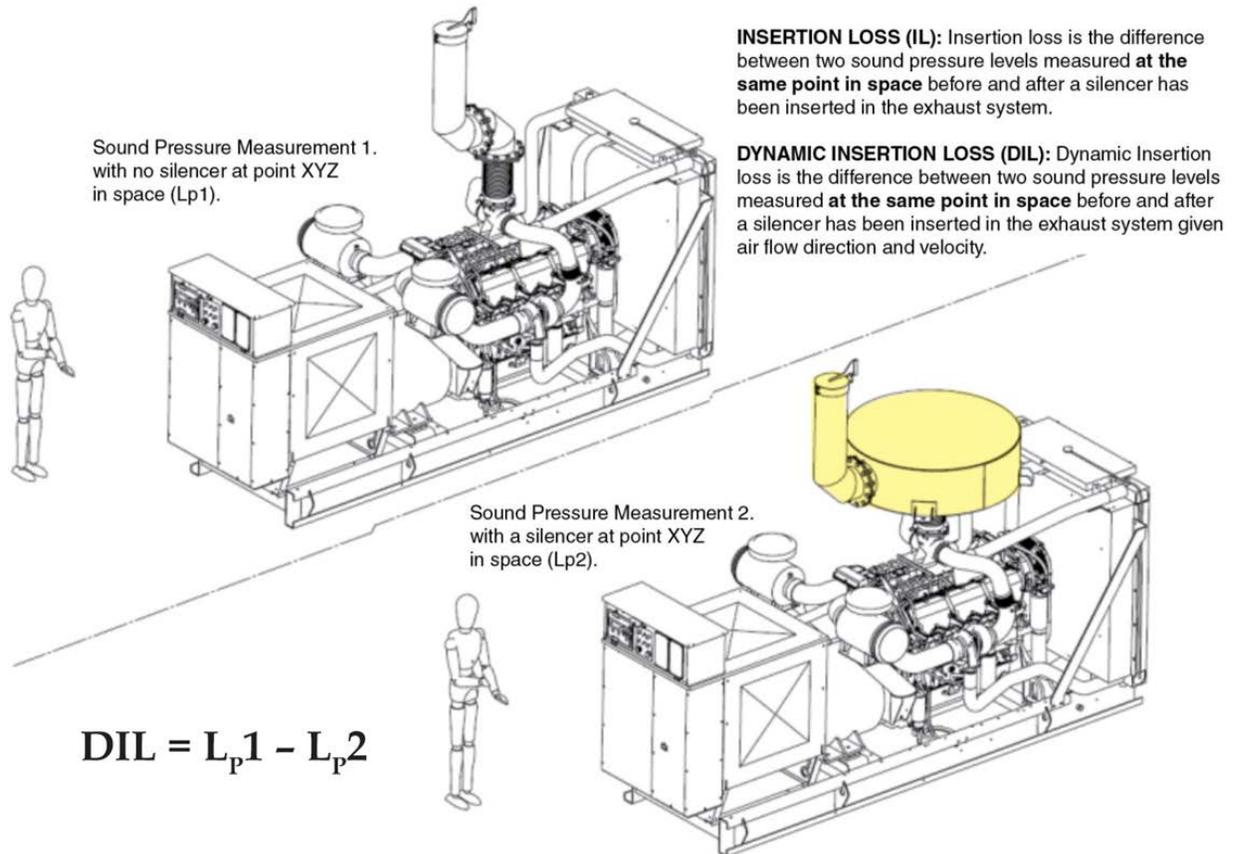


Figure 1 Dynamic Insertion Loss (DIL)

6.1 EGSA SILENCER SOUND PERFORMANCE GRADES

The table below defines the normally expected range of DIL for the EGSA silencer grade classification when installed in the exhaust system of a stationary reciprocating engine. The variation shown from low to high indicates the minimum and the maximum overall A-weighted noise reduction (dB-A) to be expected. These levels of separation are enough to be audibly different to the human ear, offering a distinction in value. Many factors will affect variations in performance. The table should be considered as an indication of anticipated performance of the various silencer models available at a given grade. For example an “EGSA Class 1” silencer will provide a DIL performance between a minimum of 10 dBA and 15 dBA.

Grade	dBA Reduction Range	
	Low	High
EGSA Class 1	10	15
EGSA Class 2	15	20
EGSA Class 3	20	25
EGSA Class 4	25	30
EGSA Class 5	30	35
EGSA Class 6	35	40
EGSA Class 7	40	45
EGSA Class 8	45	50

Table 1 Silencer Sound Performance Grade

These levels are not a guarantee of a specified silenced sound level at a specified location relative to the exhaust system outlet. This depends on multiple in situation factors beyond the scope of this guide. It is anticipated that a professional will use the EGSA Silencer Grade as a consistent ratings method in conjunction with an overall system approach to develop sound reduction that meets project requirements.

Silencer performance beyond EGSA Class 8, or above 50 dBA DIL, is beyond the scope of this guide.

7.1 SILENCER GRADE SPECIFICATION CONSIDERATIONS

It is important to note that the silencer grade does not guarantee a given sound pressure level (SPL) that will be obtained at a given distance or location from the generator set. The design professional is expected to weigh all factors in the sound control system to meet sound pressure levels required for the project. To ensure that the end users' expectation of noise control is met, the silencer grade specification should sufficiently describes the performance anticipated by the design professional so that the silencer manufacturer can design to meet the need. Use of the EGSA Performance Class in Section 6.1 will help provide a consistent guide.

For some projects the sound level criteria is critical. The requirement for low noise can be driven by a number of issues. Health care facilities require low noise to create an atmosphere that promotes recovery and does not disturb the patient. Performance venues require low background noise to create a space that meets acoustical performance requirements. Some local jurisdictions have stringent noise ordinances.

As the need for quiet running generators increases, so does the need to insure that a silencer will comply with the rating it claims. It can be very expensive to fix noise issues in the field, which can result in significant problems and delays in project completion, commissioning, and approval by the local authority. Therefore project engineers, owners and owners' representatives may consider including suggestions contained within this section in their silencer specification.

7.1.1 Silencer Performance. Silencers shall be EGSA Class # (specify desired class based on section 5 and 6) capable of a DIL of at least ## dBA (specify dBA required by the class in Section 6 of this guide).

7.1.2 Approved Manufacturers. The silencer manufacturer should be an established and recognized manufacturer regularly engaged in design, fabrication and testing of silencers in compliance with EGSA silencer performance grades. The silencer manufacturer should demonstrate a minimum five (5) years' experience in design of silencers that meet the DIL performance requirements.

7.1.3 Quality Assurance. It is the responsibility of the silencer manufacturer to ensure that the EGSA silencer performance grade is met for that stated application. Silencer manufacturers should be able to provide, upon request, a silencer performance chart with supporting calculations that includes an overall insertion loss value (dBA) and predicted back pressure for a specific application. This would also include the EGSA class rating and any limitations to the application of the silencer.

8.1 APPENDIX: UNDERSTANDING INSERTION LOSS DETERMINATION

Silencer performance prediction is inherently complicated and utilizes multiple variables and equations. Engine parameters provided by the engine manufacturer, such as raw engine exhaust noise (1/1 OBCF or 1/3rd OBCF), maximum allowable back pressure, engine displacement, revolutions per minute (rpm), flow rate, and temperature, provided by the engine manufacturer, are used to calculate and predict acoustical performance. Internal acoustic elements are chosen based on the raw or unsilenced engine noise spectrum and are tune selected to reduce the noise to the required levels.

System Effects

Dynamic insertion loss (DIL) is the change in sound level at a specific point in space when a silencer is inserted into the system and includes the effects of flow and temperature, which impact self-noise. Insertion loss is normally expressed in 1/1 or 1/3 octaves beginning with the 31.5 Hz Octave Band Center Frequency (OBCF) through the 8,000 Hz OBCF. Insertion loss (IL or DIL) of the silencer is affected by the entire system and all connecting exhaust pipe.

The values for a given silencer configuration will be different when the device is inserted into an engine intake system than when inserted into an engine exhaust system. These differences are due to several factors. Among them are:

1. Flow velocity
2. Flow direction
3. Flow temperature
4. Unsilenced sound pressure level

The first three (flow velocity, direction, and temperature) have a direct impact on wavelength, (λ), of a given frequency.

$$\lambda = C / F \quad (A1)$$

where C = The Speed of sound C (ft/second)

F = The sound frequency (cycles/second or Hz)

The speed of sound in air or typical exhaust gasses is determined at a given temperature by the equation

$$C = 49.03 \times \sqrt{T} \quad (A2)$$

where T is the air temp (degrees Rankin)

Direction of flow impacts the effective wavelength by adding to or subtracting from the speed of sound; thereby affecting the time period for a given frequency sound to move from point "A" to point "B". This is referred to as the Doppler effect and is experienced by the sudden apparent change in frequency of noise emitted by a fast moving vehicle as it passes a given point and is suddenly moving away rather than approaching a receptor at that point.

The observed impact of these factors are demonstrated in the following example:

1. As the gas temperature increases, the wavelength of a given frequency increases. When comparing an engine exhaust application at 900°F (1360°R) to an intake system application on the same engine at 70°F (530°R), the wavelength of a given frequency increases. In this example, the change in wavelength is proportional to the change in C ft/sec.

$$C_{900} / C_{70} = \sqrt{1360^{\circ}R / 560^{\circ}R} = 1.6$$

Therefore the DIL curve of a silencer at 900°F based on measurements at 70°F will shift to the right approximately 2/3rds of an octave. i.e. A value in the 125Hz 1/3 OBCF at 70°, will "move up" to the 200Hz 1/3 OBCF; thus becoming a contributor to the 250Hz 1/1 OBCF rather than the 125Hz 1/1 OBCF.

2. Exhaust gas moving toward the outlet of the system at 900°F and 200ft/sec will see a sonic velocity as follows:

$$C_{EXIT} = 49.03 \times \sqrt{1360^\circ R} + 200 \text{ (ft/sec)}$$

$$= 1808 \text{ ft/sec} + 200 \text{ ft/sec} = 2008 \text{ ft/sec.}$$

3. Intake air moving from the inlet of the system at 70°F and 150 ft/sec will see a sonic velocity as indicated below:

$$C_{INLET} = 49.03 \times \sqrt{530^\circ R} - 150 \text{ (ft/sec)}$$

$$= 1129 \text{ ft/sec} - 150 \text{ ft/sec} = 979 \text{ ft/sec.}$$

Therefore, based on these variables and with a given silencer, the DIL performance will be impacted as

- $\text{shift} = (2008 \text{ ft/sec}) / (979 \text{ ft/sec}) = 2.05$

A value in the 125Hz 1/3 OBCF at 70°, will "move up" to the 250Hz 1/3 OBCF; thus becoming a contributor to the 250Hz 1/1 OBCF rather than the 125Hz 1/1 OBCF.

4. Unsilenced sound power impacts DIL performance, primarily, in two ways. (1) All silencer devices "react" to the level of sound power to which they are applied. The most obvious and extreme example is with a given unsilenced level of 40 dB or dBA, it would not be able to achieve 41 dB or dBA DIL. (2) All silencer devices and the systems in which they are installed create a "secondary" noise level, commonly referred to as self-noise or velocity noise. The impact is that DIL measured with a high unsilenced level, may not be achieved when the unsilenced level is lower due to the limitation of the level of self or velocity noise. In effect it establishes a minimum silenced level that can be reached. Generally, the sound power (Watts) of self noise is proportional to the velocity raised to the fourth power. For example, as velocity doubles from 100 to 200, the impact is that sound power, dBA, of Self Noise (SN) increases as follows:

$$SN_{200\text{ft/sec}} = SN_{100\text{ft/sec}} + 10 \log_{10} ((200/100)^4) \text{ dB}$$

$$= SN_{100\text{ft/sec}} + 10 \log_{10} (16) \text{ dB}$$

$$= SN_{100\text{ft/sec}} + 10 \times 1.2 \text{ dB} = SN_{100\text{ft/sec}} + 12 \text{ dB}$$

As may be seen, a "typical" exhaust system "routinely" limited to 200 ft/sec or 12,000 ft/min velocity will have a self-noise sound Level 12 dB or dBA louder than the same system limited to 100 ft/sec or 6,000 ft/min.

8.1.1 Silencer Types. Generally silencers are one of or a combination of three types of devices:

1. Reactive silencers, often referred to as "chamber" silencers, generally have their peak DIL in the 63 or 125 Hz OBCF
2. Absorptive silencers, often referred to as "packed" silencers, generally are most effective in the 250 Hz through 8 KHz OBCFs.
3. Resonators are generally specifically designed to have an effective DIL over a very narrow range, usually no more than a single octave.

While we generally present typical insertion loss in terms of IL relative to frequency. All of these silencer types actually respond to wave length rather than frequency. The DIL curves for these are generally based on a "typical" temperature for the most common application of these. When applied to an application with a different temperature, their performance curves must be adjusted accordingly. Reactive Silencers are thought of as Exhaust Silencers and their performance is usually based on a "typical" Exhaust Gas Temperature (EGT) value. Generally Absorptive Silencers are applied as intake silencers to best control the high frequency content of modern high speed turbocharged engines. When absorptive are applied in combination with a reactive silencer, as is becoming more common with higher speed multi-cylinder engines and requirements for noise reduction as an A-Weighted value are becoming more demanding, the performance of these must be adjusted for size and the longer wavelengths for specific frequencies in the exhaust system. Generally a Resonator is designed for a specific requirement.

Determination of DIL of any silencer is a combination of reviewing empirical data and then making "educated adjustments" based on guidelines. Due to the number and complexity of factors which affect DIL, pure analytical evaluation rarely, if ever, produces reliable results for prediction of performance. Empirical data obtained without flow and temperature considerations invariably yields overstated and unreliable performance.

8.1.2 Silencer Performance. Some guidelines for "adjusting" and estimating performance based on known empirical data are as follows:

1. Reactive silencers generally perform as follows:
 - "Basic" or lower performance silencers generally utilize two chambers, which should be adjusted, by baffle position, for lengths having ratios of prime numbers.
 - Broader performance that is more nearly consistent across the audible spectrum is generally achieved by including three or four chambers with baffles spacing according to prime number ratios.

- Greater DIL is generally achieved by increasing the diameter of the body in order to increase the "expansion ratio." The expansion ratio is defined as the ratio of the cross section area of the nominal inlet / outlet size and the cross section of the cylindrical shell. It is also affected by reducing the cross section area of the choke tubes connecting the chambers and extending these further into each chamber. Moving peak performance toward a lower frequency range is generally achieved by increasing the length of the body while preserving the individual chamber length ratios. For example, in order for a trombone to reach a lower note, the slide is extended to make the "tuned" path longer. This example illustrates that doubling the length will cause a full octave shift in the performance curve.
2. Absorptive silencer performance is generally a function of the following:
 - Flow passage diameter (or radius in the case of cylindrical absorptive elements, or flow passage width in the case of parallel panel absorptive elements) impacts the peak wavelength reduction which may be defined as peak frequency for a given flow temperature.
 - Flow passage length generally impacts the amount of noise reduction achievable. (The longer the absorptive path, the greater the amount of energy absorbed.)
 - The absorptive element thickness relative to flow passage width or radius impacts the broadness of the insertion loss. Thicker elements result in a lower "fall off" of performance on either side of the peak.
 3. Resonator silencers are generally directed toward a specific frequency and therefore a specific wavelength. Performance is a function of the volume of the cavity relative to the resistance of the conduit between the flow tube and the cavity. As the volume and/or resistance increases, the wavelength and frequency are shifted to a longer wavelength or lower frequency.

Generally for any system with a silencer, the amount of achievable DIL is limited to approximately 50dB due to flanking of noise through the metal piping and silencer bodies.

8.1.3 Determination of DIL. Accurate determination of DIL by measurement in the field and on engines is usually not possible due to a number of factors:

- Inability to remove the silencer(s) from the system to allow measurement of the unsilenced noise levels at the position(s) being investigated.
- Inability to accurately determine intake or exhaust flow and therefore establish velocity.
- Remember self-noise is a function of velocity to the 4th power.
- Inability to effectively isolate all sources of noise other than the one of interest.
- Issues with ambient noise levels from nearby unrelated sources.

Accurate determination of DIL should be in "lab" situations with flow at anticipated temperature. Without flow or representative temperature the measured DIL is never reliable. Invariably the performance is overstated in the absence of flow, and the measured performance is often not "adjusted" for a shift in wavelength due to temperature difference.

REFERENCES

- 1 <http://en.wikipedia.org/wiki/Decibel>
- 2 <http://en.wikipedia.org/wiki/Wavelength>