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Engine Test Cell Noise Emission Design With Performance Validation Results

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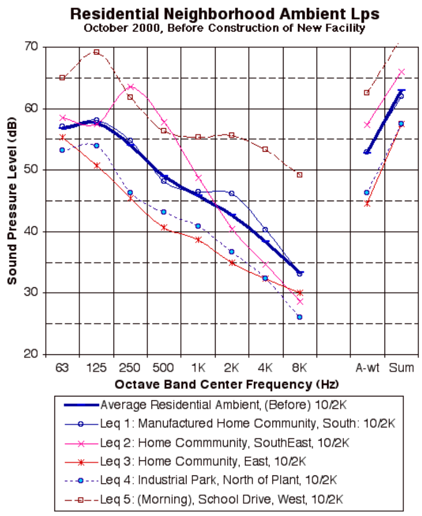
Abstract: An existing industrial test facility was proposed to be relocated from a plant site in a high ambient noise environment to a community with low ambient noise. The existing facility contained engine test cells and support equipment with loud noise emissions. The original location was in an industrial park, adjacent to a high-speed multi-lane divided highway, but residential communities were nearby. Few noise complaints had been received at the existing location. The proposed future site was in a semi-rural area, near a two lane, moderate speed roadway. Although some moderate environmental noise emissions existed from an industrial installation on the existing site, the potential was recognized for community noise disturbance from introduction of a new noise source. JEAcoustics was retained to assess the ambient noise environments and noise emission characteristics for the purpose of determining attenuation requirements for the new facility. A consultant's confidentiality agreement with the owner prevents disclosure of the facility name, plant locations, discussion of plant processes or revelation of other proprietary information. This case study presents the findings of that effort and the noise criteria that were established. Noise control designs and product applications are discussed with results of post-construction noise validation measurements.

Noise Control Design Issues

For business reasons, it became necessary to relocate an industrial test facility to another existing plant location. The proposed relocation site is a semi-rural community with moderate ambient noise. Community acceptance of the facility required its environmental impact be minimal. Among other issues, the noise contribution to the environment could not be allowed to cause annoyance to residents in the area. In addition, compliance with the building code was required, including land use compatibility and noise regulations. To achieve these requirements, acoustical design criteria were required to satisfy all parameters.



Allowable Noise Criteria

Noise measurements were conducted during late evening and morning hours in the community surrounding the proposed relocation site, for the purpose of establishing acceptable noise levels. Measured ambient sound levels included contributions from the existing plant facility. Noise reinforcing effects due to weather[1] were taken into consideration. The findings were compared with the building code to determine a single noise criterion that would satisfy all requirements.

Reference	Day	Night	Factor	Allowable
SBCCI Standard for Sound Control[2] SSTD 8-87, Table 303, Residential (R1)	60 dBA	-5 dBA	*Tonality* -5 dBA	50 dBA
Average Measured Community Ambient Noise, Evening (assume = nighttime)	- - -	53 dBA	*Weather* -3 dBA	50 dBA
DESIGN CRITERION: Property Boundary (night)		**50 dBA** (55 dBA if non tonal)		

Noise Sources to be Mitigated

The noise sources to be relocated included test cell exhaust discharges from diesel engines that might vary in size from 500 to 2000 horsepower, and depending on the testing requirements, might operate continuously at a constant speed, or operate over a range of rpm's. Other test cells contain apparata that discharge hot compressed gas (can not describe in detail due to confidentiality agreement). A group of (very tonal) helical screw air compressors provided process air for the test facility. A fabrication and support machine shop inside the building could produce transient impact and machine noise. Anticipated sources also included building air handling and exhaust fans, which were to be roof mounted.

The nighttime permissible noise criterion for tonal sources of 50 dBA controls at the facility property boundaries, which are at least 60 m in any direction from the proposed site. At least 27 dB of distance loss could be expected, if the sound is not reinforced by large reflecting surfaces or atmospheric conditions. The existing building at the relocation site is larger and taller than the proposed test facility, and consequently, acts as a barrier[3] to noise propagation in one direction. To be conservative, 25 dB of distance loss was assumed at worst case. *Given a 50 dBA allowable at the property boundary, attenuation is required for noise sources on the site in excess of 75 dBA to assure compliance with the building code and the design criterion.*

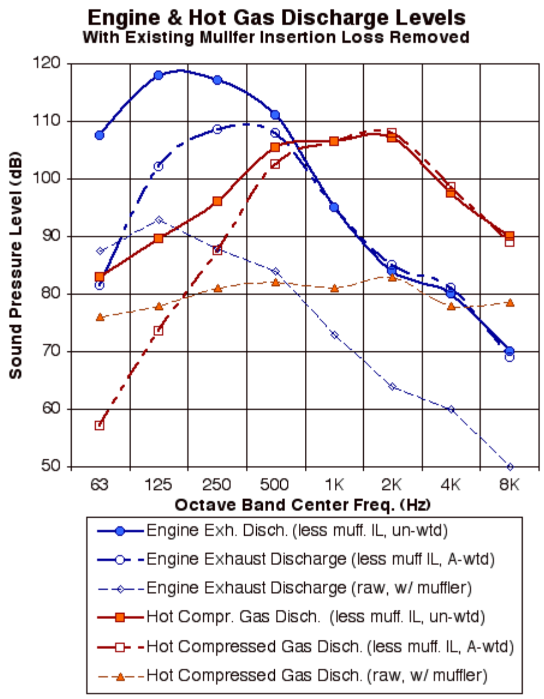
Sound Levels at Original Installation

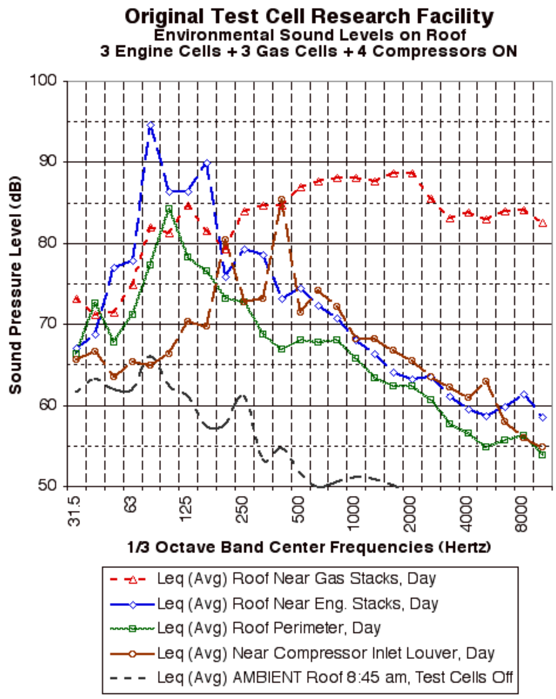
Noise measurements were conducted at the original facility to determine source levels and spectra. A Larson-Davis 2900 two channel real-time FFT spectrum analyzer with precision microphone and pre-amp (ANSI Type I, ± 1 dB)[4] was used to acquire and analyze data. Outdoor measurements were made with a windscreen. Measurements were conducted within the building, on the roof, near test cell exhaust discharges, and adjacent to the compressor room air inlet. Since the facilities were to be replicated at the new site, these measurement results were considered very reliable indicators of future conditions. The engine and hot gas test cell exhaust pipes incorporated mufflers, whose insertion losses would have to be factored out of the raw data for analysis to determine the true source levels. Sound level measurements were normalized to 3m (10') from the sound sources (exhaust terminations and inlet air louvers). Data was acquired in 1/3 octave bands over short durations, 30 – 60 seconds for continuous sources, and up to 3 minutes for varying level sources. The 1/3 octave spectra were saved for equivalent level or integrated average, Leq, the minimum, Lmin, and maximum, Lmax, levels during the sampled period. In general the Leq values were utilized as the reference source levels, with Lmin to Lmax values used to determine deviation from the integrated averages.

Noise Source, r=3m (10')	LAmin	**LAeq**	LAmax	ΔL	**Dominant A-wt. Octave**
Diesel **Engine** Test Cell*	83	**84**	86	3	250 – 500 Hz
Hot Compr. **Gas** Cell*	82	**88**	92	10	500 – 2000 Hz
Screw Air **Compressors**	71	**76**	78	9	Tones @ 200 & 400 Hz
Avg. on Roof Perimeter: **3** Eng + **3** GS + **4** Compr	69	**76**	83	14	500 – 2000 Hz
Ambient: Roof ~ 9 am	58	**61**	65	7	250 - 500 Hz

* Measurements of Engine and Hot Gas discharges included attenuation from existing mufflers, estimated ≥ 30 dBA.

The noise spectra for various sources were analyzed for sound level, balanced spectrum, variability (difference between Lmin and Lmax), and tonality. Sideband differentials of 6 dB or more between 1/3 octaves are considered tonal[5]. In addition, the A-weighted octave spectra were studied to determine principal contributing frequencies to overall A-weighted level. In other





words, the octave levels, decreased by A-weighting factors, were plotted on level versus frequency charts to determine which frequencies contributed the most to dBA levels or audibility. For example, the engine noise, above, is greatest in the 125 Hz octave, but with A-weighting, the 250 – 500 Hz frequency span contributes the most to the A-weighted sum. The 1/3 octave spectra were then reviewed for tonality (large sideband differentials) and peak frequencies, such as the 200 Hz and 400 Hz helical screw compressor tones in the chart above.

Noise Attenuation Design Concepts

A multifaceted design approach was developed to address the various types of noise sources, and to achieve low noise levels with smooth, balanced spectra. Each type of noise source had distinct spectral, temporal and directional characteristics. Design concepts were developed to match attenuation frequency responses to noise source spectra, and to reduce tonal and intermittent (temporal) sources below the ambient levels at sensitive receivers.

Beginning within the building, absorption was specified to reduce build-up of reverberant sound within test cells and support equipment spaces. Wall, door, window and roof assemblies were designed to contain sound within the building, including vibration isolation and decoupling of elements to reduce exterior surface radiated noise. Silencers were selected for air inlets, engine exhausts and hot compressed gas discharges. Based on known locations of residential, commercial, and light industrial zoning, the direction of least sensitivity was determined, so that exhaust pipe terminations could be pointed that way. A roof parapet wall was designed to surround the other three more sensitive sides of the loudest noise sources. With all of these concepts combined, in addition to the estimated 25 dBA of distance noise reduction, the design approach included: (a) room acoustics attenuation, (b) barrier attenuation, (c) building noise containment, and (d) inlet/exhaust silencing.

For each noise source group, the following attenuation measures were recommended:

Engine Test Cells: Diesel engines produce broadband noise. With A-weighting applied, dominant octaves are in the 250 - 500 Hz octave bands. Attenuation requirement: > 40 dBA.

Room Acoustics: Perforated metal panels with acoustically absorptive fiber fill (encased in vinyl) on walls and ceilings of cells. Estimated reverberant reduction: 4 - 7 dBA.

Noise Containment: CMU Walls enclosing test cells within building walls. Concrete deck and support equipment mezzanine above. Sound rated doors and windows. Internal duct liner or silencers below exhaust fan and air handler roof penetrations.

Barrier Attenuation: Exhaust pipe terminations on roof point in the direction of least sensitivity (towards fewer, more distant homes). Parapet wall taller than exhaust pipe terminations on the three, more sensitive sides of roof exhaust discharges.

Silencers: Straight perforated pipe silencer (with acoustically absorptive fiber filler in body), within test cell, in series with 3-chamber reactive muffler located in mezzanine above. Combined insertion loss is greatest over 250 - 1000 Hz frequency span, matching maximum A-weighted engine exhaust octaves (see "Test Cell Muffler Concepts" below).

Hot Gas Cells: Hot compressed gas discharge produces a broad tonal noise. Dominant A-weighted octaves are in the 500 - 2000 Hz bands. Attenuation requirement: > 43 dBA.

Room Acoustics: Perforated metal panels with acoustically absorptive fiberfill on walls and ceilings of cells. Estimated reverberant build-up reduction: 4 - 7 dBA.

Noise Containment: CMU Walls enclosing test cells within building walls. Concrete deck and support equipment mezzanine above. Sound rated doors and windows.

Barrier Attenuation: Exhaust pipe terminations and parapet wall enclosure as above.

Silencers: Straight perforated pipe silencer (with acoustically absorptive filler in body), within test cell, in series with larger absorptive muffler with "bullet" insert, located in mezzanine above. Combined insertion loss is greatest over 1000 - 2000 Hz frequency span, matching maximum A-weighted hot gas exhaust octaves (see " Test Cell Muffler Concepts " below).

Air Compressor Room: Helical screw compressors produce strong tones. For this installation, peak tones are at 200 and 400 Hz octave bands. Attenuation requirement: Minimum > 1 dBA overall, but to assure tonality is reduced below ambient, > 6 dBA.

Room Acoustics: Slotted concrete masonry units (CMU), selected for maximum absorption in 250 Hz octave plus vinyl covered, exposed insulation below corrugated metal roof deck. Estimated reverberant build-up reduction: 4 - 7 dBA.

Noise Containment: CMU Walls enclosing compressor room. Concrete on corrugated metal roof deck. Sound gasketed doors.

Silencers: Acoustical louver in exterior wall air inlet, selected for $\geq$ 7 dB at 500 Hz.

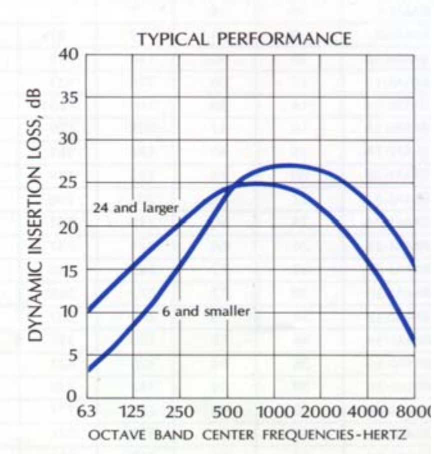
Roof Mounted Air Handler and Exhaust Fans: Radiated noise levels at perimeter of roof were estimated to be less than 75 dBA, and therefore required no additional attenuation. Internal duct liner and/or duct silencers were specified below roof penetration for test cell noise (see "Test Cells Noise Containment", above).

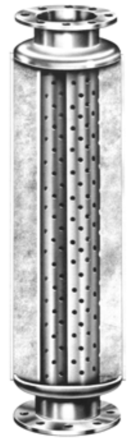
Test Cell Exhaust Terminations on Roof (Engine Test Cell and Hot Gas Cell Barriers, above): Exhaust pipes were designed to terminate in a "goose-neck," partially to prevent rain capture. To benefit from directionality of mid- to high-frequency noise (which has greater affect on A-weighted overall level), terminations point in the direction of least sensitivity (fewer, more distant homes). A parapet wall, designed to be slightly higher than pipe terminations enclosed the exhaust terminations on the other three, more sensitive directions (the open, less sensitive side provides a fume dilation draft).

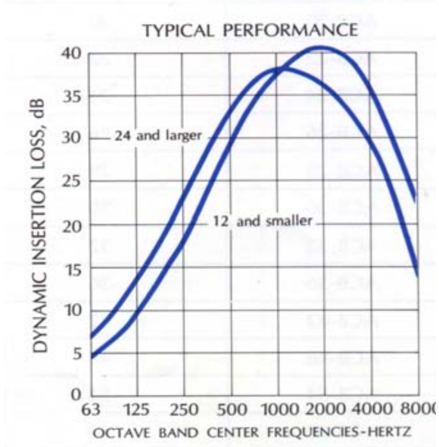
Test Cell Muffler Concepts
Dissipative versus Reactive Mufflers

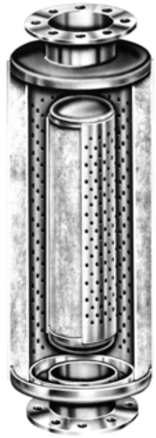
A silencer design approach was selected to match attenuation spectrum with source spectrum, i.e., maximum silencer insertion loss in the maximum A-weighted noise source octave. In the cases where a single silencer could not achieve compliance with the allowable noise criterion, two silencers were applied in series. In those cases, the silencer types were selected based on composite insertion loss spectrum. Two primary types of silencers are common for engine exhaust, dissipative (absorptive), and reactive. It is not the intent of this paper to discuss the "how" and "why" of silencer physics, but instead, to discus the applications.

Dissipative silencers are double wall vessels with perforated inner walls. The annular space is usually filled with acoustically absorptive fibers. Some attenuation occurs from Helmholtz resonance, but most of the broadband attenuation is from the acoustic filler. The most simple designs have a straight perforated pipe as the inner wall, and have virtually no pressure drop.



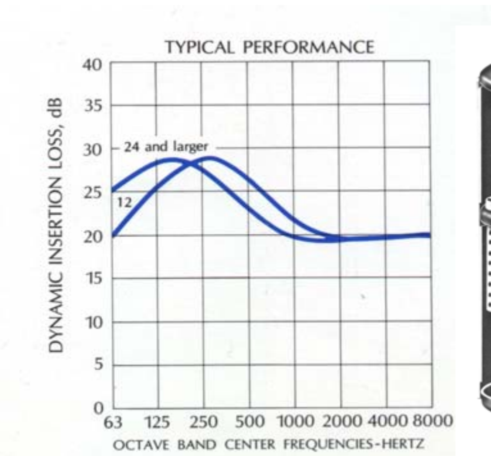


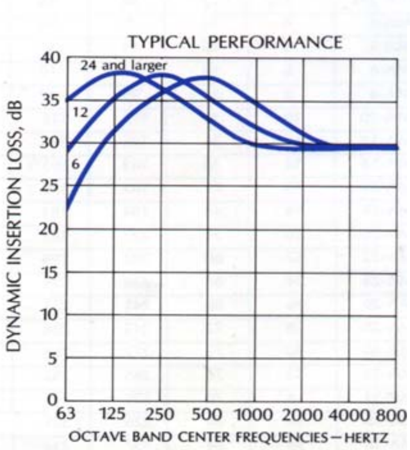




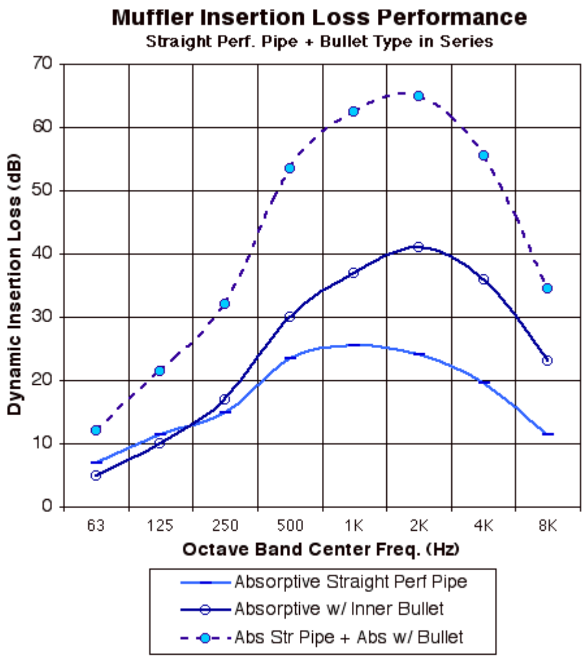
Others have a greater diameter inner wall, with a perforated "bullet" insert inside the pipe. These can have somewhat greater attenuation, but at the cost of slightly greater pressure drop. Both variations have good mid- to high-frequency attenuation, but poor low frequency attenuation. (Illustrations courtesy of Burgess Manning[6])

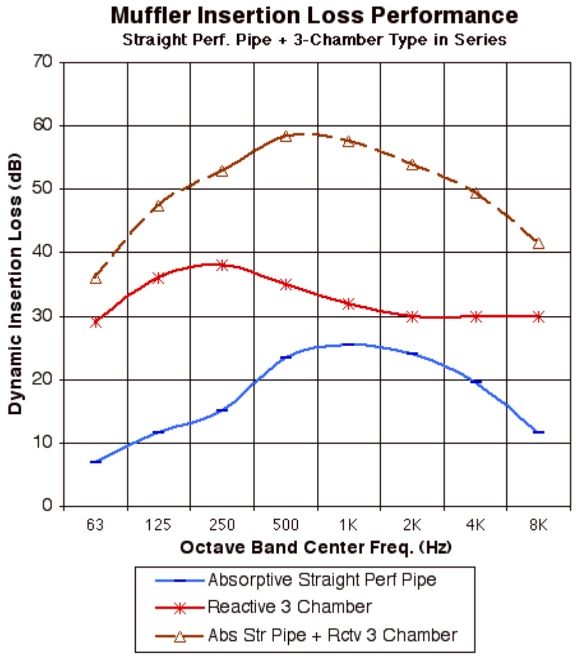
Reactive silencers are vessels that attenuate noise by the expansion chamber principle[7]. Reactive mufflers generally have at least two chambers, connected by small pipes. The pipes may be perforated to diffuse airflow. The frequency response and amount of attenuation is proportional to the volume and number of chambers. Reactive mufflers have good low frequency attenuation (peak frequency depending on length and diameter), but typically have much greater pressure drop than dissipative silencers.





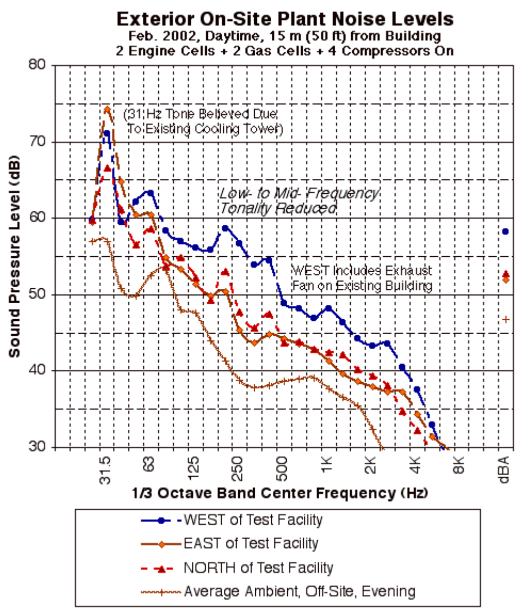
For this project's extraordinary attenuation requirements, two mufflers in series were recommended for hot gas exhausts and for test cell exhaust discharges, but the pressure drop implications had to be considered. The hot compressed gas discharge could not accommodate much pressure drop, so pairs of absorptive silencers were selected for moderate pressure drop; one straight pipe and one bullet insert type, which produced an insertion loss frequency span with peak insertion loss near the center of the audible spectrum. The engine exhausts could tolerate moderately high-pressure drop, so reactive mufflers were specified in concert with straight pipe absorptive types, which produced broadband insertion loss, with good low frequency attenuation. In both cases, specified dual silencer performance was matched to source noise spectra.





Design Implementation

The architect and engineers implemented the primary noise control recommendations for room acoustics, sound containment, air inlet and exhaust pipe silencers and roof parapet. The building noise containment designs, including interior test cell acoustical measures perform as planned. Inlet attenuation for the air compressors and exhaust attenuation for the engine and hot gas test cells exceed expectations. Environmental noise emissions have relatively smooth spectrum shapes, and low noise levels compared to surrounding environment. The results provide improved working conditions for technicians in the support shop and operators at the test cell control consoles, with interior sound levels 6 - 9 dBA less than the levels at the older facility. Exterior sound levels from building wall radiation, compressor inlet air louver, and the various test cell exhaust discharges are very moderate. Actual performance validation measurement results are shown below.



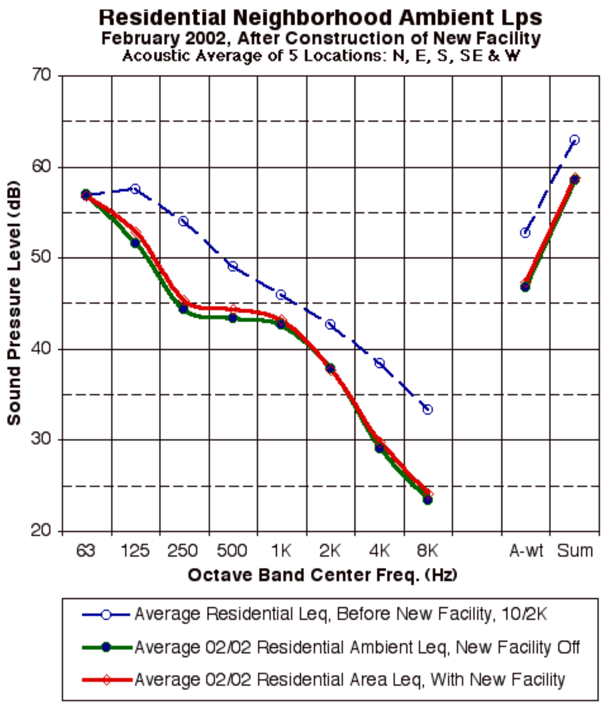
Validation Measurement Results

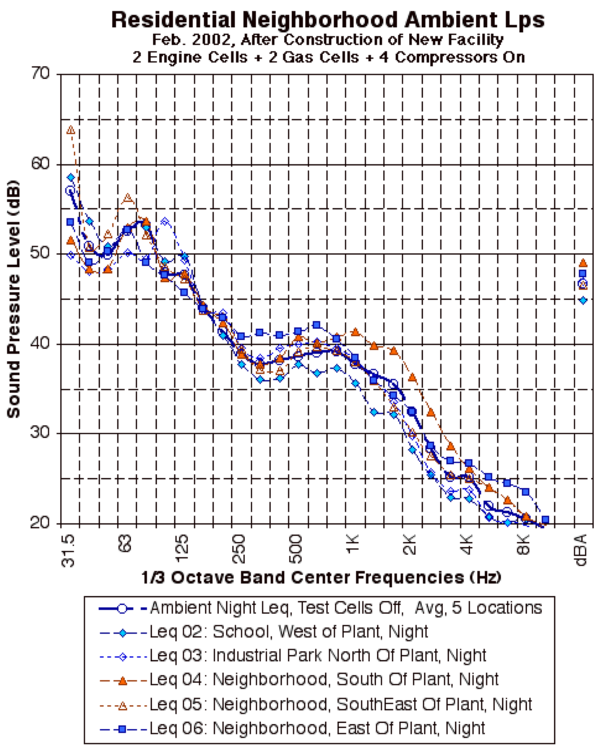
JEAcoustics returned to the new plant facility in February 2002, to conduct performance validation measurements. Sound levels and spectra were measured within the compressor room, representative operational test cells, control console areas adjacent to test cells, support mezzanine, on the roof, and around the perimeter of the building. All sound levels due to test cell operations, including the screw air compressors, met or exceed design projections.

Source: **2** Eng + **2** GS + **4** Compr Measured: r = 15 m (50 ft) Projected: r > 60 m (200 ft)	**LAeq**	Projected To Prop. Line
North of Building	**53**	$\leq$ 40 dBA
East of Building	**55**	$\leq$ 42 dBA
West of Building	**58**	$\leq$ 45 dBA
South (Existing Plant Bldg. acts as noise barrier)	**N/A**	N/A
Allowable Lp @ Prop. Line	**- - -**	50 dBA

On-site measurements showed a tonal peak on the site in the 31 Hz 1/3 octave band (see chart above), which is believed to be from a cooling tower or another industrial source. Neither noise source measurements at the original installation, nor measurements near the exhaust terminations at the new facility exhibited the same tone. On the west side of the new facility, broadband sound levels were somewhat greater than on north and east sides, but by observation, exhaust fan noise from the existing building on the relocation site contributed to sound levels. With those exceptions, the outdoor noise levels and spectra on site were neither loud nor tonal. Equivalent levels (Leq) measured 15 m (50 ft) from the new test facility varied from 53 – 58 dBA on the north, east and west sides of the facility (the existing building south of the test facility does not permit a nearby measurement in that direction). When the 15 m (50 ft) measurements are projected out at least 60 m (200 ft) in any direction to property boundaries, sound levels due to test facility operations are only 40 – 45 dBA.

Nighttime ambient sound levels in surrounding neighborhoods average 47 dBA (energy average of A-weighted levels at five locations). The Southern Building Code permissible nighttime sound level at the property boundary, after accounting for tonality is 50 dBA (55 dBA if not tonal) in residential areas. The (projected) 40 – 45 dBA noise emissions at the property boundary could increase the 47 dBA ambient 1 – 2 dB (by addition). Those levels are within the project design criteria and comply with the building code.





Sound levels measured in neighborhoods in the vicinity of the test facility show a 1 – 2 dB increase in the 125 – 500 Hz octave bands, when compared with ambients (both are energy averages of Leqs at five locations surrounding the facility). Individual 1/3 octave spectra from the five community locations surrounding the plant show very little tonality (re: side band differentials $\geq$ 6 dB), and have spectrum shapes very similar to the average ambient 1/3 octave community spectrum.

Conclusion

It is possible to design and construct an industrial test facility within a semi-rural community with very quiet ambient noise environment with very little noise impact. The design approach of matching attenuation spectrum to noise spectrum proved successful at reducing environmental noise emissions to acceptable levels and preventing community annoyance due to perceptible tonality. The project complied with the Southern Building Code Standard for Sound Control and met all acoustical design criteria.

Acknowledgements

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References

[1] Harris, Cyril M., *Handbook of Acoustical Measurements and Noise Control*, McGraw-Hill Publishing Company, New York, 3.10 (1991)

[2] SSTD 8-87, Standard for Sound Control, *Southern Building Code*, SBCCI, pg 9, Table 303, Birmingham, (1987)

[3] Wilson, C.E., *Noise Control*. Harper and Row Publishers, New York, 77, (1989)

[4] *ANSI S1.4-1983, American National Standard Specification for Sound Level Meters*, American National Standards Institute, New York (R1990)

[5] Harris, Cyril M., *Handbook of Acoustical Measurements and Noise Control*, McGraw-Hill Publishing Company, New York, 47.15 (1991)

[6] *Burgess Manning Industrial Silencing Internal Combustion Engines*, Burgess Manning Industries Company, Dallas, 10-18 (1978)

[7] Foreman, John E.K. *Sound Analysis and Noise Control*, Van Nostrand Reinhold, New York, 126-130, (1990)