AIR FILTRATION AND SOUND CONTROL SYSTEMS FOR GAS TURBINES — THE STATE OF THE ART

by

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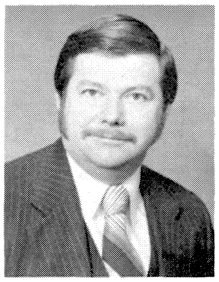

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ABSTRACT

This paper discusses some of the latest design concepts and materials currently being utilized in the design and manufacture of noise control equipment for gas turbine engines. Some related areas which are also discussed include inlet air filtration and low frequency noise. Consideration is also given to some of the various environments such as arctic, desert, offshore, etc. Several reference tables and charts are included such as NEMA and ISO NR standards, addition of sound pressure levels, and comparison of sound pressure levels to common environmental sounds. There is also other reference information such as a list of fundamental definitions frequently encountered. Consideration is given to the fact that most people are not "acousticians" and for this reason theoretical concepts are not discussed. The basic intent of the paper is to familiarize the reader with gas turbine air filtration and sound control systems.

INTRODUCTION

Since the introduction of the gas turbine engine, increasing performance demands have been made of the turbine. There has been a steady progressive upgrading of gas turbine technology. Newer and more flexible applications have continued to be developed. Today we find gas turbines being used for electrical generation; marine propulsion drives; mechanical drives for oil and gas pumping, gas gathering and compression, reinjection, and waterflood; plus countless others. They are found in onshore and offshore environments ranging from arctic to desert conditions.

Exhaust temperatures and engine sound power levels have increased substantially. Consequently, both of these items have had a considerable effect on the "state of the art" of noise control. Another factor that has exercised a major impact on noise control is the public attitude toward noise in general. Today we are all concerned about the effect of noise in the environment. Regulatory commissions and groups have been established on the corporate, local, state and federal levels. Noise is constantly being monitored by each of us in some way, especially since we understand its adverse effects much more clearly than we did years ago. Thus the "state of the art" has been compelled to change due to engine upgrading and the resultant higher exhaust temperatures, due to the increased sound power levels, and due to greater public interest and legislation.

Increased exhaust temperatures demand that improved and better grades of materials be developed. Design techniques have changed to meet the challenge of higher temperatures, lower pressure drops, higher stresses, greater mass flows, and larger systems in general. Increased sound power levels require greater amounts of silencing, as well as improved acoustical design concepts. Public interest and legislation has made a significant impact regarding the amount of noise and the type of noise that the environment will tolerate.

AIR FILTRATION AND SILENCING SYSTEM

Typically, a gas turbine silencing system is modularized into the following components: 1) Inlet System (consisting of the inlet silencer and inlet plenum); 2) Turbine Enclosure; 3) Secondary Cooling System; 4) Exhaust System; and 5) Compressor/Generator Enclosure. Another component the gas turbine sound control manufacturer frequently provides is the Inlet Air Filtration System (see Figure 1). Each of these components produces a significant contribution to the overall performance of the total system.

The Inlet Air Filtration System

The primary purpose of the inlet air filtration system is to keep unwanted dirt from entering the gas turbine engine. A good filtration system will provide acceptably clean air delivery to the engine. Much remains to be learned about filtration as is evidenced by the considerable controversy which continues to exist regarding the right filter for the right application. It is not the intent of this paper to resolve this problem. The purpose is to develop an awareness of some of the types of filters available, their efficiencies, and in general, how they are used. One of the areas to be understood immediately is "filter efficiency." Some clarification of the term "efficiency" must be made since filter efficiency can be reported in any of three ways. These are by weight (arrestance), by particle count, and by area. Efficiency by weight (arrestance) refers to the amount of dirt by weight retained by the filter. Efficiency by particle count refers to the actual number of dirt particles retained by the filter. Efficiency by area considers particles that will stain since visible stain is a function of the projected area of dust particles. Generally when applied to gas turbines, concern is only for the

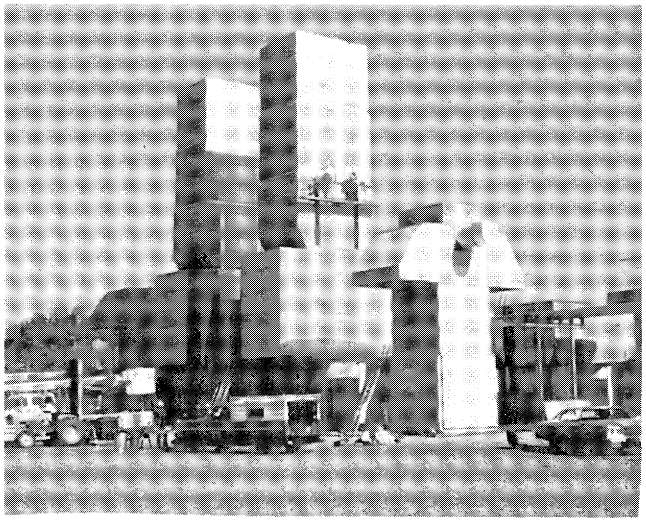


Figure 1. Gas Turbine System Consisting of Air Filtration System, Inlet System, Inlet Plenum, Turbine Enclosure, Secondary Cooling System, Exhaust System, and Generator Enclosure.

first two ratings — by weight (arrestance) and by particle count. The latter method of rating by area is more relevant to building maintenance since staining directly affects the amount of cleaning and maintenance required. An example which might help explain the efficiency question follows. The equation for efficiency is (DIRT RETAINED/ DIRT UPSTREAM OF FILTER) × 100. Assume there are 101 dirt particles of the same density upstream of the filter consisting of one 10-micron particle and 100 one-micron particles. If the 100 one-micron particles pass through the filter and the single 10-micron particle is retained, then the three efficiencies can be rated in the following manner:

1. Efficiency by weight (Ew) - each particle's weight is proportional to its diameter cubed.
   Therefore:

$$\frac{D_R}{D_U} \times 100 = \% \text{ efficiency} \tag{1}$$

Where:
D_R = Dirt Retained
D_U = Dirt Upstream

Then:

$$Ew = \frac{10^3}{10^3 + (100 \times 1^3)} \times 100 \tag{2}$$

$$= \frac{1000}{1000 + 100} \times 100 \tag{3}$$

$$= 90.9\% \text{ Efficient by Weight} \tag{4}$$

2. Efficiency by Area (E_A) - staining ability is proportional to the size of the particle diameter squared.

$$E_A = \frac{D_R}{D_U} \times 100 \tag{5}$$

$$= \frac{10^2}{10^2 + (100 \times 1^2)} \times 100 \tag{6}$$

$$= \frac{100}{100 + 100} \times 100 \tag{7}$$

$$= 50\% \text{ Efficient by Area} \tag{8}$$

3. Efficiency by Particle Count (Ec) - based on the actual number of particles in the system.

$$Ec = \frac{D_R}{D_U} \times 100 \tag{9}$$

$$= \frac{1}{1 + 100} \times 100 \tag{10}$$

$$= 0.99\% \text{ Efficient by Particle Count} \tag{11}$$

We can conclude that efficiency by weight is more meaningful with large, heavy particles. Efficiency by count is more meaningful for small, light particles. Efficiency by area relates to the amount of stain removal ability of the filter.

When evaluating the filter system performance, the type of efficiency must be considered. Additionally the actual test standards and materials used should be noted since they vary widely. The test standards and materials will not be discussed in depth here but some of the test codes used are ASHRAE 52-76, DOP test and SAE J726B. Some of the test dusts used are AC coarse, AC fine, MIL-E-5007C, B.S. 1701, OTTAWA SAND, and ASHRAE dust. Specifications for AC fine and AC coarse are shown in Appendix 1. A final point to bear in mind regarding efficiencies is that a filter rated at 90% will allow 10% of the dirt to pass through and a filter rated at 80% will allow 20% of the dirt to pass through — making the 90% filter twice as efficient.

There are many types of filters, most of which can be divided into the following groups:

1. Inertial — There are two basic types of inertial filters: the vane or pocket inertial configuration and the centrifugal spin tube inertial configuration. These are essentially permanently affixed prefilters and require little or no maintenance. Their purpose is to remove larger particulates from the intake air.
2. Prefilters — These are generally regarded as medium efficiency filters and are usually made from either cotton fabrics or spun-glass fibers. They are used to extend the life of a high efficiency, more costly, filter further downstream. They are relatively inexpensive and are intended to be replaced at more frequent intervals than other medias.
3. Coalescers — These filters are used to agglomerate mist in order to remove moisture from the inlet air system. They are generally constructed using wire or thin gauge metal for the agglomerater.
4. Vanes or Louvers — These are normally used as a first stage filter in conjunction with a coalescer filter to remove large water droplets from the air stream.
5. High Efficiency Media — The purpose of the high efficiency media filter is to remove smaller particles of dirt from the air stream. The efficiency rating is normally very high. They are most frequently available as barrier types and as bag types.

6. Marine or Demister — These filters are used in very humid or marine environments where it is necessary to remove moisture and salt. This type of filter is usually rated in salt removal in ppm.
7. Self-Cleaning — Self-cleaning filters are relatively new in the market and essentially consist of a large number of high efficiency media filters with a very large surface area. Air is drawn through the media material at very low velocities and upon a predetermined pressure drop across the system, a reverse blast of air removes built up dirt from the filter and reduces the pressure drop. These are comparatively expensive, require limited maintenance and are very efficient. The full range of applications is still unknown, but they have shown promise in almost all environments.
8. Specialty Filters — There are many other types of filters designed to perform various jobs. These include roll-type media, oil bath, carbon filters, electronic air filters, plus numerous others.

The selection of a filtration system depends largely on the site and operating conditions as suggested by Figure 2. Whether or not a filtration system is justified is a debatable subject since there have been numerous studies with findings both pro and con.

TYPE OF ENVIRONMENT	TYPICAL TEMP. RANGE °F	TYPICAL CONCENTRATION GRAINS/1000FT^3	EFFECT ON GAS TURBINE	SUGGESTED FILTRATION
RURAL COUNTRY	-10 TO +90	0.004 TO 0.04	MINIMAL	NONE OR HIGH EFFICIENCY MEDIA FILTERS
URBAN / INDUSTRAIL	- 5 TO +95	0.030 TO 0.30	FOULING SOMETIMES CORROSION	INERTIAL + HIGH EFFICIENCY MEDIA
DESERT	+20 TO + 120	0.04 TO 300	EROSION CORROSION	INERTIAL + MEDIA ELEVATED INLET AT LEAST 20′ FROM GRADE
TROPICAL	+40 TO +110	0.004 TO 0.10	FOULING	INERTIAL + MEDIA INSERT SCREEN RAIN HOOD
ARTIC	-40 TO +40	0.004 TO 0.040	INTAKE ICING	HIGH EFF. MEDIA ANTI-ICING PACKAGE SNOW HOOD
OFF SHORE	0 TO +70	0.0004 TO 0.040 NA CL	CORROSION	DEMISTERS
MOBILE	-20 TO +110	0.04 TO 300	FOULING EROSION CORROSION	SELF CLEANING OR INERTIAL + MEDIA (FOR INTERMITENT USE)

Figure 2. General Guide to Filter Selection.

In general, filters serve two basic functions. First, and most importantly, they help extend the life of the gas turbine components by reducing contaminants which contribute to corrosion, erosion, and fouling (see Figures 3 and 4). Secondly, filters add an element of physical protection to the gas turbine engine at varying expense (Figure 5). For these reasons the incorporation of some type of filtration system with the gas turbine package is to be encouraged.

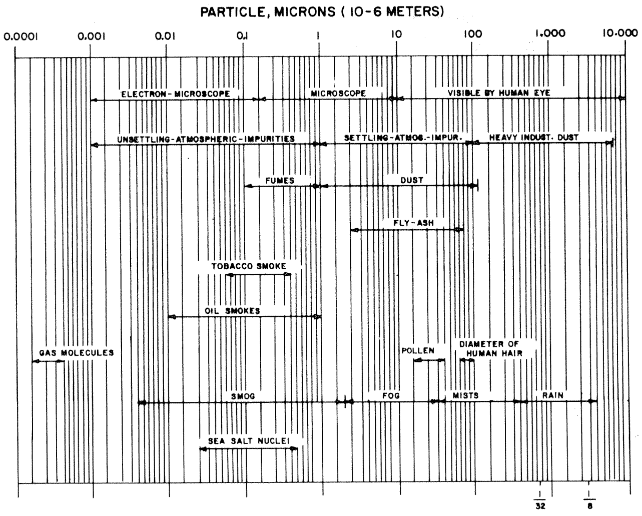


Figure 3. Relative Size Chart of Common Air Contaminants.

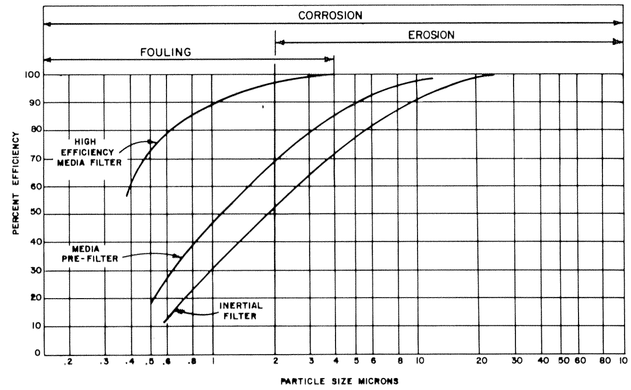


Figure 4. Approximate Efficiencies of Filters on Various Particle Sizes.

TYPE OF FILTER	INITIAL COST	MAINTENANCE COST	FILTRATION EFFICIENCY
INERTIAL	MEDIUM	OCCASIONAL CLEANING	85 %
INTERNAL+HIGH EFFICIENCY MEDIA	MEDIUM TO HIGH	LOW	99.9%
MEDIA PRE-FILTER+ HIGH EFFICIENCY MEDIA	LOW	HIGH	99.9%
LOUVER+COALESCER +HIGH EFFICIENCY MEDIA	MEADIUM	HIGH	99.9%
THREE STAGE MIST ELIMINATOR	HIGH	LOW	99 %
SELF CLEANING	VERY HIGH	VERY LOW	99 %

Figure 5. Typical Cost Comparison of Various Filter Systems.

Inlet System

The inlet system consists of two major components: the inlet silencer and the inlet plenum. Inlet noise is generally the first area which should be considered for silencing because the largest amount of sound power is normally produced by the gas turbine inlet. The inlet system is designed to silence all frequencies; however, special consideration must be given to high frequency noise. The inlet is the primary source of high frequency noise which is the loudest and most disturbing noise source to the ear since it is in the high frequencies where the ear is the most sensitive (see Figure 6). General background information is given in Appendices 2, 3, and 4.

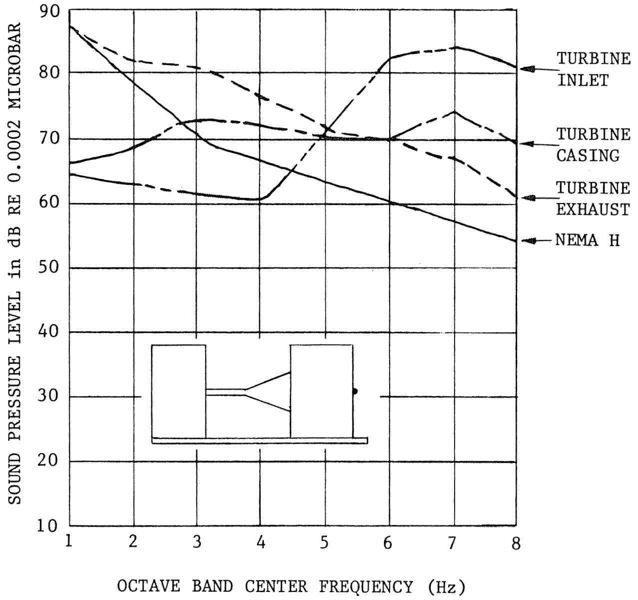


Figure 6. Unsilenced Turbine Intake, Exhaust, and Casing SPL's at 400 ft. as Compared to NEMA H Criteria.

There are several approaches which can be used to help reduce inlet noise. It should be recognized that these are basic methods which serve as a starting point in silencing the gas turbine inlet. Each gas turbine engine has its own performance characteristics, and each job has its own design specifications, and each must be carefully analyzed in order to prepare the final inlet silencing system design. Inlet noise is loudest directly in front of the inlet opening. If noise were measured at points along a circle perpendicular to the plane of the inlet, there typically would be approximately a 15 dB reduction at 90° on either side of the inlet. At 180° from the inlet there would be approximately a further 8 dB reduction. This noise reduction is due to directivity, and this directional characteristic of noise can be effectively used to reduce the inlet noise. Directivity can be applied by utilizing a 90° elbow in the inlet system so the noise is directed upward, resulting in a 15 dB noise reduction. Secondly, if an elbow/plenum is utilized and the walls are acoustically treated, then an additional 10-15 dB noise reduction can be obtained in the primary frequencies where the inlet noise is most objectionable. Additional noise reduction can be achieved by incorporating an inlet silencer which contains various configurations and lengths of acoustical treatment, depending upon the requirements.

The inlet silencer will help "fine tune" the inlet system. As the amount of inlet treatment (length and/or thickness of treatment) is increased, the additional noise reduction becomes marginally less. Other attentuation features which are frequently used include undercoating on the inner plenum walls and perhaps even thicker or double walls to achieve greater noise reduction through the silencer shell.

An inlet silencing system may also be oriented horizontally and at ground level as opposed to the vertical system described above. Ordinarily, preference is for the vertical configuration because of the advantages of the directivity feature. It should also be noted that the vertical inlet concept also elevates the inlet above ground level and provides more protection from debris which is frequently found at ground level.

In addition to considering the noise reduction provided by the inlet, there must also be concern regarding how much pressure loss the inlet adds to the system. Obviously, it is desirable to keep pressure loss as low as possible in order to maintain maximum power and the lowest possible fuel consumption. Pressure loss can be minimized by proper sizing of the inlet silencer, particularly the ratio of open area between the panels and the passages. Pressure loss can be further reduced by using aerodynamically configured leading and trailing edges on the silencing panels, by proper silencer cross section and/or by using turning vanes. Air distortion at the engine bellmouth is vitally important because poor air distribution can cause irregular compressor blade loading and subsequent compressor stalls and/or blade failures. Intake air distortion can be satisfactorily controlled by providing adequate plenum area in which the airflow can uniformly distribute prior to engine entry. Turning vanes and panel orientation may also be used effectively to reduce distortion.

Turbine Enclosure

The turbine enclosure houses the gas turbine engine. Its primary purpose is to contain the casing noise produced by the gas generator and power turbine. Additionally, the turbine enclosure is required to reduce noise radiated by the exhaust shroud and, sometimes, noise being transmitted through the skid. The noise generated by these sources is generally the second most objectionable. This is an interesting point because the noise generated from the exhaust contains more energy while the casing normally generates more noise in the frequency range where the ear is more sensitive. Methods of determining the effective sound levels are shown in Appendices 5 and 6.

Casing noise can be reduced effectively by enclosing the engine within an acoustical enclosure. The amount of acoustical treatment will depend upon the power level of the casing. It is possible that the enclosure walls may vary from bare steel plate to perhaps a double acoustical wall, or even walls with a gunnited covering on the enclosure. As with the inlet system, the amount of noise reduction required for the turbine enclosure will depend upon the engine performance specifications and the actual acoustical performance criteria for the site.

It is helpful to totally isolate the turbine enclosure from the skid in some situations to reduce noise transmission through the walls. If the enclosure is skid mounted, an isolation pad between the skid and the enclosure will reduce the noise transmitted considerably. Casing noise may also be reduced by using isolation pads between the engine and the skid.

Secondary Cooling System

The purpose of the secondary cooling system is to provide cooling air and evacuate heat from the engine casing and exhaust shroud out of the turbine enclosure. The secondary cooling system normally consists of either an electric or hydraulic motor driving either an axial or vane axial fan, intake and exhaust ducting, intake filters, and intake and exhaust silencers. The silencers are primarily required to reduce the emission of noise from the engine casing to the environment. Since the inlet and exhaust openings are exposed to the outside environment, a direct noise leakage path exists which must be silenced. Additionally, depending upon the model and size of the fan and motor, silencing may be required for the fan as a result of the fan blade tip speed.

Filtered intake air is often desirable because the airflow is directly into the enclosure and over the engine. The filtered air can be pulled from either the primary intake filtration system or through a separate filter.

Sizing of the secondary cooling system depends on the volume of air necessary to maintain the desired temperature in the turbine enclosure. Attenuation requirements of the silencers will depend upon the noise levels of the engine casing and the desired performance criteria of the site.

Exhaust System

Exhaust systems are normally designed in one of two different basic configurations. The first option is to make the engine exhaust horizontal. In this case the exhaust silencing system generally consists of an expansion joint, exhaust plenum, exhaust silencer, exhaust extension, and support steel as required. The second type utilizes a vertical engine exhaust. In this case the exhaust silencing system generally consists of an expansion joint, transition exhaust silencer, exhaust extension, and support steel as required.

In both configurations discussed above the hot exhaust gases are normally discharged vertically. The vertical discharge provides the benefit of directivity, which contributes significantly to the noise reduction of the exhaust system. The principles involved here are much the same as discussed regarding the inlet system. In addition to directivity, further noise reduction can be obtained with the addition of an exhaust silencer. This silencer will provide additional attenuation based on the various configurations, lengths, and thicknesses of treatment. Frequently a technique referred to as "blocked-line-of-sight" is used, where panels are staggered or configured in such a manner that the exhaust gases must change their flow path prior to discharge. This technique is particularly effective in providing high frequency noise reduction and is shown in Figure 7. The exhaust stack extension can be used to raise the actual noise discharge height from the ground which will provide better directivity and further reduce the noise level at the criteria location.

If there is substantial noise, which can be radiated through the walls of the exhaust system components, then the walls can be lined with acoustical panels. This acoustical lining also possesses thermal absorptive properties which reduce the temperature of the outer shell surfaces. The gas turbine exhaust is the primary source of low frequency noise. Traditionally, the design criteria provided for silencing turbines has been for frequencies as low as the first octave (63 Hz). It has only been during the past several years that design specifications have incorporated requirements for lower frequencies, particularly 31.5 Hz. Low frequency noise will be discussed later in this paper because it is a particular problem which has been attracting much public attention.

During the design of the exhaust, concern must also be directed to minimization of backpressure. Basically, the same techniques are employed in the exhaust as in the inlet. The ratio between passage area and panel thickness must be carefully selected in order to provide optimum silencing and acceptable backpressure. This normally requires the cross section of the exhaust to be somewhat larger than the intake to accommodate the greater exhaust volume flow. In the vertical discharge, the slope of the transition is carefully controlled and in the horizontal discharge turning vanes are frequently used. Proper panel orientation is important and must be incorporated in such a manner to insure good flow distribution. Poor distribution can cause added backpressure which can contribute to a decrease in silencer life. Exhaust stack extensions can also be effectively used to reduce backpressure.

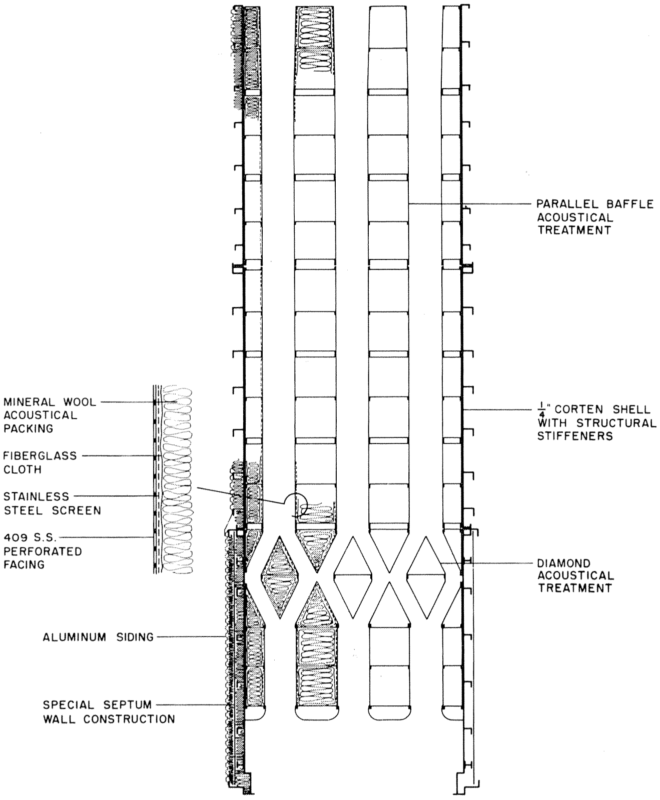


Figure 7. Original Exhaust Silencer Cross Section Showing Diamond Acoustical Treatment.

Aerodynamically configured noses and tails on the panels can also be utilized.

Regenerated noise is often a potential problem depending upon specific criteria and can be effectively controlled by keeping the average exhaust gas velocity through the panels as low as possible. Depending upon the specific acoustic criteria, velocities would normally range from 150 fps to 180 fps.

A major problem with exhaust stack design is the high temperature of the exhaust gases, normally in the range of 800°F to 1100°F. Special design considerations must be incorporated to minimize the resulting high thermal stresses. An early design philosophy was to fabricate a strong fully welded silencer where the shell plates were a heavier grade of steel and the treatment panels were welded into the shell. Today the "floating panel concept" is widely used (see Figure 8). The treatment panels are maintained separate from the shell and are normally retained in place by a ledge angle upon which the panels can rest. The individual panels are separated from one another by pass liners or panel retainers. This permits the panels and the shell to react independently of one another and expand or contract without restraining one another. This simple but effective feature has contributed to longer equipment life and less maintenance as a result of failed welds.

Panel construction and design have also improved. Normally a high density mineral wool is used which is wrapped in fiberglass cloth and then stapled to form a closed pillow. It has been the practice at Environmental Elements to test each shipment of mineral wool to insure that it will perform acceptably at the elevated temperatures and that it will not devitrify or exhibit excessive shrinkage. The mineral wool pillows are packed under compression to minimize settling of the wool

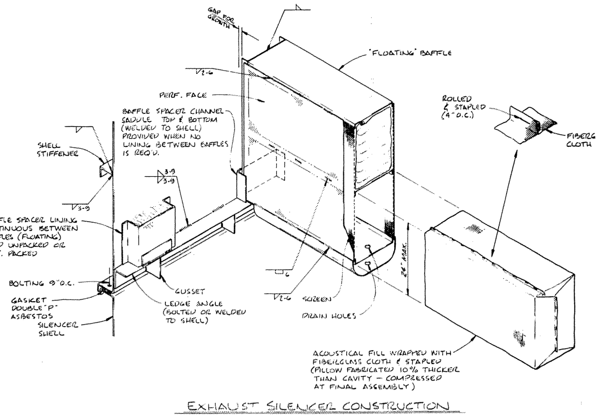


Figure 8. Exhaust Silencer Construction.

during operation. The pillow is positioned between the panel frames and separators and further protected by covering with a fine mesh stainless steel screen. The stainless steel screen is retained between the panel frame and the perforated face sheet. The perforated face sheets are stitch welded to the panel frames in order to prevent "zippering" of the welds. Rivets are unacceptable for fastening the perforated face sheets to the panel frames. Rivets are subject to fatigue and subsequent failure due to the lack of quality control which can be used to insure whether or not a good bite has occurred.

The fiberglass wrapping and the stainless steel screen is used to prevent leaching of the mineral wool through the perforated holes due to the high exhaust gas velocity.

Compressor/Generator Enclosures

The final and least offensive noise source is the compressor or generator driven by the gas turbine. Normally the noise level from this equipment is sufficiently low. In cases where they may be noisier or where site criteria specifications are more stringent an enclosure may be required. Typically, the enclosure would be a bare steel shell without acoustical lining. Actual noise reduction is accomplished simply by the transmission loss through the steel plate. In other cases where more noise reduction is required, the same techniques and principles applicable to the turbine enclosure would apply, including the ventilation system.

LOW FREQUENCY NOISE

In recent years the problems associated with low frequency noise have become more apparent; consequently, public awareness and concern have increased considerably. There have been several papers and articles written relating to low frequency noise. Most of these papers and articles have discussed recent field experiences. Low frequency noise, 31.5 Hz in particular, did not become a problem overnight. Years ago engine sound power levels (PWL) were lower, installations were more remote and there may have been a greater individual tolerance for noise of this type. Obviously, there was a great lack of understanding of low frequency noise. There was little reference to the 31.5 Hz band in manufacturers' specifications, in published reports, and in test codes. At the time, most gas turbine noise specs referenced the NEMA noise curves which gave noise standards for the eight octave bands beginning with 63 Hz as shown by Figure 9. More recently other specifications are being more widely used, such as the ISO NR sound curves which include 31.5 Hz and are shown by Figure 10.

Octave Band Center Frequency (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
Nema A		59	45	38	33	29	25	22	19
Nema B		62	50	42	37	34	31	28	24
Nema C		67	55	48	42	39	36	34	31
Nema D		71	60	53	47	44	41	38	36
Nema E		75	65	58	53	49	46	43	40
Nema F		79	70	62	58	54	51	48	45
Nema G		83	74	68	63	59	56	53	49
Nema H		87	79	72	68	64	61	58	54

Figure 9. NEMA Criteria.

Octave Band Center Frequency (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
ISO/NR 20	69.0	51.3	39.4	30.6	24.3	20.0	16.8	14.4	12.6
ISO/NR 25	72.4	55.2	43.7	35.2	29.2	25.0	21.9	19.5	17.7
ISO/NR 30	75.8	59.2	48.1	39.9	34.0	30.0	26.9	24.7	22.9
ISO/NR 35	79.2	63.1	52.4	44.5	38.9	35.0	32.0	29.8	28.0
ISO/NR 40	82.6	67.1	56.8	49.2	43.8	40.0	37.1	34.9	33.2
ISO/NR 45	86.0	71.0	61.1	53.6	48.6	45.0	42.2	40.0	38.3
ISO/NR 50	89.4	75.0	65.5	58.5	53.5	50.0	47.2	45.2	43.5
ISO/NR 55	92.9	78.9	69.8	63.1	58.4	55.0	52.3	50.3	48.6
ISO/NR 60	96.3	82.9	74.2	67.8	63.2	60.0	57.4	55.4	53.8
ISO/NR 65	99.7	86.8	78.5	72.4	68.1	65.0	62.5	60.5	58.9
ISO/NR 70	103.1	90.8	82.9	77.1	73.0	70.0	67.5	65.7	64.1
ISO/NR 75	106.5	94.7	87.2	81.7	77.9	75.0	72.6	70.8	69.2
ISO/NR 80	109.9	98.7	91.6	86.4	82.7	80.0	77.7	75.9	74.4
ISO/NR 85	113.3	102.6	95.9	91.0	87.6	85.0	82.8	81.0	79.5
ISO/NR 90	116.7	106.0	100.3	95.7	92.5	90.0	87.8	86.2	84.7
ISO/NR 95	120.1	110.5	104.6	100.3	97.3	95.0	92.9	91.3	89.8
ISO/NR 100	123.5	114.5	109.0	105.0	102.2	100.0	98.0	96.4	95.0

Figure 10. International Standards Organization (ISO) Criteria.

31.5 Hz noise is most often generated by the turbine exhaust and is barely below the frequency range of hearing for most adults. Although this frequency may be inaudible or slightly audible, it nevertheless possesses large amounts of energy which just by the very nature of sound creates a detectable pressure change. The sound wave length (or noise wave length) at this frequency is approximately 36′ long at 70°F ambient and approximately 60′ long at 1000°F. These wave lengths are typical of what we would expect in the inlet and exhaust systems, respectively (see Appendix 7). The nominal wave length at this frequency is exceptionally difficult to silence because of its great length. Obviously, the 31.5 Hz noise generated by the exhaust is considerably more difficult than the 31.5 Hz noise generated by the inlet due to its greater length. Most success has been obtained silencing the low frequency noise of the gas turbine exhaust by increasing the thickness of the panels and extending their length, as can be seen by the field retrofit shown in Figures 11 and 12. Needless to say, this requires the addition of large amounts of material at considerable expense. An example of the retrofit for this installation is shown in Figure 13. This type of system is referred to as an absorptive silencer, and although other techniques such as "wave cancellation" and reactive silencers have been theorized and installed with limited success, the absorptive type low frequency silencer has been installed and successfully tested at various sites.

MATERIAL SELECTION

Thus far, the discussion has considered only the silencing system. Materials have become a very important factor.

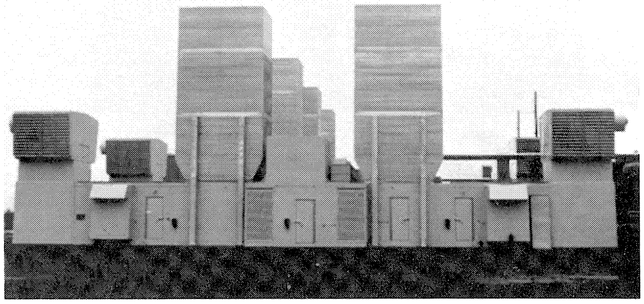


Figure 11. TP&M FT-4C-1 Twin Pac Designed to Meet NEMA D Criteria at 400 ft.

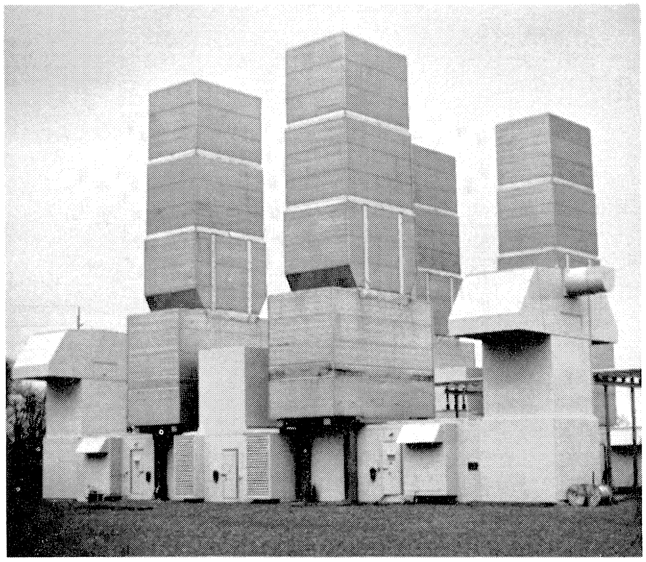


Figure 12. TP&M FT-4C-1 Twin Pac Shown with Field Retrofitted Low Frequency Silencing.

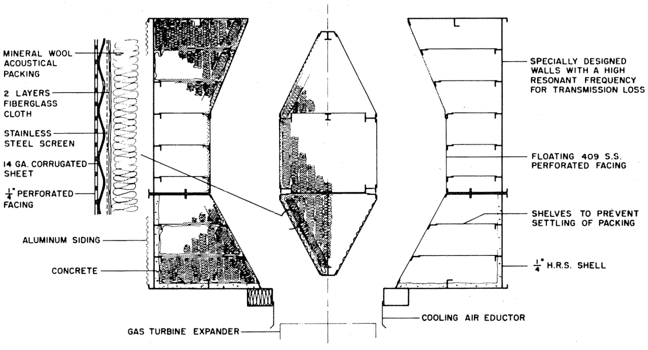


Figure 13. Cross Section of 31.5 Hz Low Frequency Silencer.

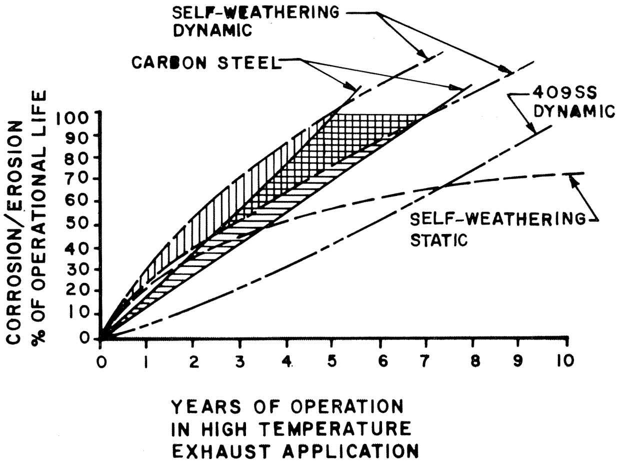
Environmental conditions require a broader range of tolerable materials. They must operate in ambient temperatures as low as −70°F, and in some exhaust stacks the turbine discharge gases are in excess of 1100°F. Equipment must operate in chemically corrosive environments with concentrations such as H_2S, chlorine, salt, salt water, sulfuric acid, and many others. Exhaust systems are subjected to a wide range of fuels, which contain a variety of corrosive contaminants. Additionally, the equipment may be located offshore, on the coast, in the desert, and many other locations. Obviously, materials selection is important and should be carefully evaluated in light of the surrounding environment and turbine operating characteristics (see Figure 14).

	Rural	General Industrial	Desert	Tropical	Heavy Industrial Petro-Chemical	Coastal/ Marine	Arctic
I. Inlet System, Turbine Enclosure Secondary Ventilation							
A. Shell	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	Normalized Stl ASTM A-203
B. Perf	Galvanized	Galvanized	Galvanized	Galvanized	316L SS	304 SS	304 SS
C. Frames & Separators	Galvanized	Galvanized	Galvanized	Glavanized	316L SS	304 SS	304 SS
D. Solid	Galvanized	Galvanized	Galvanized	Galvanized	316L SS	304 SS	304 SS
E. Paint/Shell, etc.	Zinc-Chro & Epoxy Top	Zinc Chro & Epoxy Top	Zinc Chro & Epoxy Top	Zinc Chro & Epoxy Top	Zinc Chro & Epoxy Top	Inorg Zinc Prim & Acrylic Top	Zinc Chro & Epoxy Top
F. Paint/Perf	None	None	None	None	None	None	None
II. Exhaust System							
A. Support Steel	A36 Str Stl	A36 Str Stl	A36 Str Stl	A36 Str Stl	A36 Str Stl	A36 Str Stl	A36 Str Stl
B. Less than 1000°							
1. Transition	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36/A203
2. Shell	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36	ASTM-A36/A203
3. Perf	409 SS	409 SS	409 SS	409 SS	316L SS	304L SS	409 SS
4. Frames & Separators	409 SS	409 SS	409 SS	409 SS	316L SS	304L SS	409 SS
5. Solid	409 SS	409 SS	409 SS	409 SS	316L SS	304L SS	409 SS
6. Paint/Shell, etc.	Hi-Temp Alum.	Hi-Temp Alum.	Hi-Temp Alum.	Hi-Temp Alum.	Hi-Temp Alum.	None	Hi-Temp Alum.
7. Paint/Perf	None	None	None	None	None	None	None
D. Greater than 1000° F							
1. Transition	Cr-Mo Stl	Cr-Mo Stl	Cr-Mo Stl	Cr-Mo Stl	Cr-Mo Stl	Cr-Mo Stl	304 SS
2. Shell	Cr-Mo Stl	Cr-Mo Stl	Cr-Mo Stl	Cr-Mo Stl	Cr-Mo Stl	Cr-Mo Stl	304 SS
3. Perf	409 SS	409 SS	409 SS	409 SS	316L SS	304L SS	409 SS
4. Frames & Separators	409 SS	409 SS	409 SS	409 SS	316L SS	304L SS	409 SS
5. Solid	409 SS	409 SS	409 SS	409 SS	316L SS	304L SS	409 SS
6. Paint/Shell, etc.	Inorg Zinc Prim & Silicone Top Coat	Inorg Zinc Prim & Silicone Top Coat	Inorg Zinc Prim & Silicone Top Coat	Inorg Zinc Prim & Silicone Top Coat	Inorg Zinc Prim & Silicone Top Coat	Inorg Zinc Prim & Silicone Top Coat	None
7. Paint/Perf	None	None	None	None	None	None	None

Figure 14. Basic Materials of Construction.

Prior to 1965, most gas turbine exhaust silencers were fabricated utilizing carbon steel with 10 gauge or heavier perforated face sheets. The intake silencers were normally light gauge galvanized steel. Around 1965 there was a tremendous surge of support throughout the industry, especially by the original equipment manufacturer, for the use of weathering steel. It was felt that longer life could be obtained due to the improved corrosion resistance properties. Additionally, it appeared that the material could be reduced in thickness due to its greater strength and significantly offset the high cost of the weathering steel. This was based on data published by the steel industry regarding the improved corrosion properties and the accompanying superior strength properties relative to carbon steel. Most of the weathering steel materials were used for gas turbine exhausts; however, there were several cases where they were used in the inlet system.

Generally, weathering steel was thought to be the solution to all corrosion and erosion problems. Although the actual life of the steel was never guaranteed, it was widely believed that a great improvement would be experienced. Unfortunately, it has been found that the weathering steels perform about the same as carbon steel in the exhaust, as shown by Figure 15. In some cases life was better and in some cases it was worse. Although weathering steel did work in the inlet, galvanized steel is more widely preferred in the inlet air stream due to the formation of large corrosion flakes typical of the weathering steels and their subsequent ingestion into the engine. Carbon steel and galvanized steel tend to form a powdery oxide rather than the large flakes typical of weathering steels. It appears that the singular reason for the ineffectiveness of the weathering steels in the exhaust gas path was their inability to form and maintain a dense protective, tenacious oxide coating. This was due to the high velocity of the exhaust gas flow wiping the



NOTE: MANY ITEMS EFFECT THE OPERATIONAL LIFE OF MATERIALS IN AN EXHAUST STACK. THE CURVES NOTED ARE BASED ON A TYPICAL GAS TURBINE PEAKING UNIT LOCATED IN AN INDUSTRIAL ENVIRONMENT AND OPERATING ON #2 FUEL

Figure 15. Curve Comparing Years of Operation to Percent of Operational Life.

oxides from the surfaces and by continuous thermal cycling. Thus, by the very nature of the weathering steels, corrosion and erosion always occurred at an accelerated rate. In a static situation corrosion/erosion becomes relatively arrested after 3-4 years.

In the late 1960's and early 1970's, the industry began using 409 SS in the exhaust system. It has demonstrated long life, high strength, and, because the thickness can be reduced, moderate cost increases. Occasionally aluminum, 409 SS, or various grades of 300 series stainless steels are used in intake systems. However, today most systems are manufactured using galvanized steel for the intake systems and turbine enclosures and 409 SS or carbon steel for the exhaust system.

In addition to the frequent use of galvanized steel, carbon steel, and 409 SS, other materials are used for the specialized installations. For offshore applications success has been experienced with several grades of stainless steels such as 304 SS, 304L SS, 316 SS, 316L SS, and aluminum. In low temperature applications structural quality carbon steel is effective as low as −40°F. In general a fine grain steel is preferred for temperatures as low as −80°F. In a chemically corrosive environment, more so than others, the steels must be carefully selected, and generally the 300 series stainless steels are best; for example, 316L SS in H_2S and 409 SS in chlorine.

Material selection depends upon a large number of factors which affect the operating life of the equipment (see Figure 16). Each installation should be evaluated separately, based on these factors. Additionally there must be a consideration of cost vs. estimated operating life (see Figure 17).

FACTORS	LIFE BEST	 WORST
FUEL	NATURAL GAS	#6 CRUDE
MATERIAL	409 S.S.	SELF WEATHERING
MOISTURE	DRY	WET
MODE	CONTINUOUS	PEAKING
PEAKING DUTY	DESERT	COASTAL
SITE	RURAL	HEAVY INDUSTRIAL (CHEMICAL)
ENVIRONMENT	BASE	MAX PEAK
TEMPERATURE	AMBIENT	HIGH

Figure 16. Factors Affecting the Operational Life of a Gas Turbine Air Filtration and Silencing System.

MATERIAL	ESTIMATED LIFE	COST FACTOR	APPROXIMATE $/#
GALVANIZED STL	5-8 Yrs.	1.07	.32
CARBON STEEL	5-7 Yrs.	1.00	.30
SELF WEATHERING	5-7 Yrs.	1.50	.45
409 S.S.	10 Yrs.	2.83	.85
304 S.S.	10+ Yrs.	5.63	1.69
304 S.S.	10+ Yrs.	5.93	1.78
316 S.S.	10+ Yrs.	8.63	2.59
316 S.S.	10+ Yrs.	9.30	2.79

Figure 17. Estimated Life vs. Cost of Frequently Used Materials Based on 1979-1980 Prices.

Material Coatings

Closely related to the materials are coatings. Depending upon the application, there are many coatings which are available. Paints are available for chemical environments, for marine environments, and for high temperature applications. Exhaust stacks have always presented a problem relative to paint maintenance. Now there are specialized paints which can be applied, after the proper surface preparation, that will air dry and then properly cure during operation. Some of these paints can operate at temperatures in excess of 1200°F. Obviously, they are costly, and consideration should be given to an external appearance lagging as an alternative.

Coatings for marine environments are as important as the selection of the proper materials. Certain paint systems have been used successfully. In part, an economic decision must be made regarding material vs. paint. Upgraded materials for a marine environment are certainly more costly in the initial stage; however, any coating system will require continual maintenance in order to prevent deterioration of the base material. The same considerations must be made for equipment operating in a chemical environment. Upgraded materials should be strongly considered. Due to the nature of this type equipment, there are many surfaces which cannot be painted. Some of these surfaces are in the airstream where there is always the potential risk of deteriorated material tearing loose and being ingested by the engine. Coatings can be used effectively on many ancillary items where upgraded steels are not available.

CONCLUSION

The noise created by a gas turbine engine is considerable and to such a degree that it must be reduced in order to eliminate community noise complaints. Perhaps of more significance, the gas turbine engine noise must be reduced to protect plant personnel.

There are concerns other than silencing. Economics are important and, obviously, as the materials, coatings, and performance specifications become more exotic, costs will increase greatly. Proper design and material selection is necessary to insure long operating life. As mentioned, each of these areas must be considered separately in order to provide the right equipment for the right application. We have tried to create an awareness of these factors. Many of these are topics in themselves.

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APPENDIX 1

SPECIFICATIONS OF AIR CLEANER TEST DUSTS

PARTICLE SIZE DISTRIBUTION BY WEIGHT, PER CENT

PARTICAL SIZE	FINE GRADE	COARSE GRADE
0-5	39 ± 2	12 ± 2
5-10	18 ± 3	12 ± 3
10-20	16 ± 3	14 ± 3
20-40	18 ± 3	23 ± 3
40-80	9 ± 3	30 ± 3
80-200	—	9 ± 3

CHEMICAL ANALYSIS OF TEST DUST

CHEMICAL	% BY WEIGHT
SIO_2	67 TO 69
Fe_2O_2	3 TO 5
AL_2O_3	15 TO 17
CaO	2 TO 4
MgO	0.5 TO 1.5
TOTAL ALKALIS	3 TO 5
IGNITION LOSS	2 TO 3

SPECIFIC GRAVITY OF A.C. FINE AND COARSE DUST-2.54

ESTIMATED NUMBER OF PARTICLES PER GRAM OF

A.C. FINE DUST	7,570,500,000
A.C. COARSE DUST	2,548,300,000

APPENDIX 2

GLOSSARY OF FREQUENTLY USED DEFINITIONS

A-Weighted Sound Level (dBA) — A number in decibels (dB) which is read from a sound meter when the meter is adjusted to its weighted scale noted "A." The number approximately measures the relative noisiness or annoyance level of many common sounds as they would most closely be detected by the ear. The human ear is less efficient at low and high frequencies than at the medium or speech range frequencies. In order to obtain a single number from a wide range of frequencies, in a manner which represents the ear's response, it is necessary to reduce or weigh the effects of the low and high frequencies with respect to medium frequencies. The resultant sound level is said to be A-weighted.

Acoustics — The study of sound including its generation, transmission and effect.

Attenuation — The decrease in the magnitude of sound in transmission from one point to another. The loss of sound power or sound pressure traveling through a medium. The attenuation is variable due to the medium of transmission.

Audible Spectrum — 16 to 20,000 Hertz. The human ear is most sensitive at 4000 Hz.

Criterion — A value(s) specifying the desired sound(s) of a silencing system. This is usually expressed as a sound pressure level (SPL) for a single value or as a specific set of octave band values and is measured at a definite distance from the sound source.

Cycles per Second — (Hertz) — The number of oscillations per second of a sine-wave of sound.

Decibel (dB) — A logarithmic unit used to measure the relative loudness of sounds. The zero (0 dB) on the scale is the lowest sound level that the healthy ear can detect. A ten unit increase in decibels (70 dB to 80 dB) corresponds to a ten fold increase in the sound energy and a doubling in perceived loudness. Thus, a noise of 80 dB has ten times the sound energy as 70 dB and sounds twice as loud.

Directivity — The directional character of the sound source.

Directivity Index — In a given direction from the sound source, the difference in decibels between the SPL produced by the source in that direction and the space-average SPL of that source measured at the same distance.

Divergence — The reduction of a sound pressure level (SPL) as a function of distance from the sound source. This reduction is accomplished by spreading the sound energy over a greater area. The Sound Power Level (PWL) of a given source is constant. As the sound power source is converted to sound pressure level (SPL), it will decrease as the distance from the sound source increases. (See Inverse-Square Law)

Far Field — A region at a sufficient distance from the sound source where the sound pressure level (SPL) obeys the inverse-square law and the velocity of the sound particle is in phase with the sound pressure. Generally, the far field begins at a distance approximately equal to four times (4x) the largest dimension of the source envelope.

Free Field — A sound field in which the effect of obstacles or boundaries on the sound propagated in that field are negligible. A region in which no significant reflections of sound can occur.

Frequency — The number of complete cycles per sound. Usually expressed as either cycles per second (CPS) or Hertz (Hz).

Hearing Loss — At a specified frequency, an amount expressed in decibels, by which a person's hearing is worse than some selected norm. This norm is generally the threshold established at some earlier time for him, or the threshold which is determined to be the average threshold for the population.

Infrasound — Inaudible sounds which are normally less than 16-25 Hz.

Insertion Loss (IL) — The numerical difference, expressed in decibels (dB), between two sound pressure levels (SPL) measured at the same point prior to and after the addition of an acoustic silencer between the point of measurement and noise source.

Inverse-Square Law — States that there is a decrease in the sound pressure level of 6 dB for each doubling of the distance from the sound source. The converse would also apply.

Near Field — Regions which are close to the source where the two conditions which consititute the far field are not met. The near field is normally within a distance of four times (4x) the largest dimension of the source envelope.

NEMA Curves — A series of curves which were established by the National Electrical Manufacturers Association (NEMA) to satisfy neighborhood requirements relative to gas turbine installations. The NEMA values are expressed in dBC.

Noise — Any unwanted sound.

Noise Rating (NR) Curves — A series of curves recommended by the International Standardization Organization (ISO). These are similar to the NC curves except they cover a greater range of applications from noise in the home to noise in factories. The NR (ISO) values are expressed in dBC.

Noise Reduction (NR) — A numerical difference, expressed in decibels (dB), between the average sound pressure levels (SPL) of two or more areas.

Octave — Two sounds, whose ratio of frequencies is exactly two, are separated by an octave.

Presbyrusis — The decline in hearing which normally occurs as a person grows older.

Pressure Drop — The net difference between total upstream and downstream pressures and is expressed as inches of water.

Sociocusis — A condition where the nerve endings (cilia) of the inner ear are destroyed as a result of noise.

Sound — Sound is what we hear. A wave motion reaching the ear which is caused when an object moves back and forth; or vibrates; and causes adjacent air particles to move back and forth, and so on, producing a variation in normal atmospheric pressure.

Sound Absorption — The change of sound energy into some other form of energy, which is normally heat, by passing through a medium or striking a surface.

Sound Power Level (PWL) — This is the level of sound power (energy) generated at the source. It is not a directly measurable quantity and must be calculated from the sound pressure level (SPL). The PWL is preferred for system evaluation since it is constant for a given source and is not affected by the acoustic environment. The most frequent reference is 10^{-12} watts.

Space Average — The SPL averaged overall directions and at the same distance.

Speed (Velocity) of Sound — In air, sound moves at a speed of approximately 1130 FPS at 70°F and 14.7 PSI. The speed of sound will vary in different mediums.

Threshold of Audibility — The minimum sound pressure level (SPL) at which a person can hear a sound of a given frequency.

Threshold of Pain — The minimum sound pressure level of a sound of a given frequency at which a person will experience physical pain or feeling in the ear.

Tinnitus — An irritating ringing in the head.

Transmission Loss (TL) — The ratio, expressed in decibels, (dB), between the acoustic energy incident upon structure. TL is very similar to but not the same as Noise Reduction (NR); the primary difference being that TL relates directly to the structure and is independent upon the environment, whereas, NR is affected by the environment.

Ultrasound — Inaudible sounds which are normally 20,000 Hz and above.

Wavelength — The distance a sound wave travels in one cycle. The wavelength is longer at lower frequencies. It is calculated by dividing the speed of sound for a specific medium by the frequency.

APPENDIX 3

SOUND FACTS

A. Decibels are units of sound measurement based on a logarithmic scale. A ten unit increase in decibels (70 dB to 80 dB) corresponds to a ten fold increase (10x) in sound energy and a doubling (2x) in perceived loudness. Thus, a noise of 80 dB has ten times the sound energy as 70 dB and sounds twice as loud.

B. There is a 6 dB decrease in the sound pressure level (SPL) for each doubling of the distance from the source — the converse applies.

C.

Change in Sound Pressure Level (SPL)	Effect Upon Listener
3 dB	Barely Noticeable
5 dB	Distinctly Noticeable
10 dB	Twice as Loud
20 dB	Considerably Louder

D. 80 dB is about as loud as a sound can get without making most people uncomfortable. Any rating above 80 dB produces physiological effects. Long exposures at much above 100 dB threaten permanent impairment of hearing.

E. Walsh-Healy permits 90 dBA for 8 hours per day continual exposure. In no case should a worker be exposed to more than 115 dBA and not to impact noise in excess of 140 dBC.

F. At 90 dBA — 14-16% risk of noise induced hearing loss.
At 85 dBA — 5.7% risk of noise induced hearing loss.
At 80 dBA — 0% risk of noise induced hearing loss.

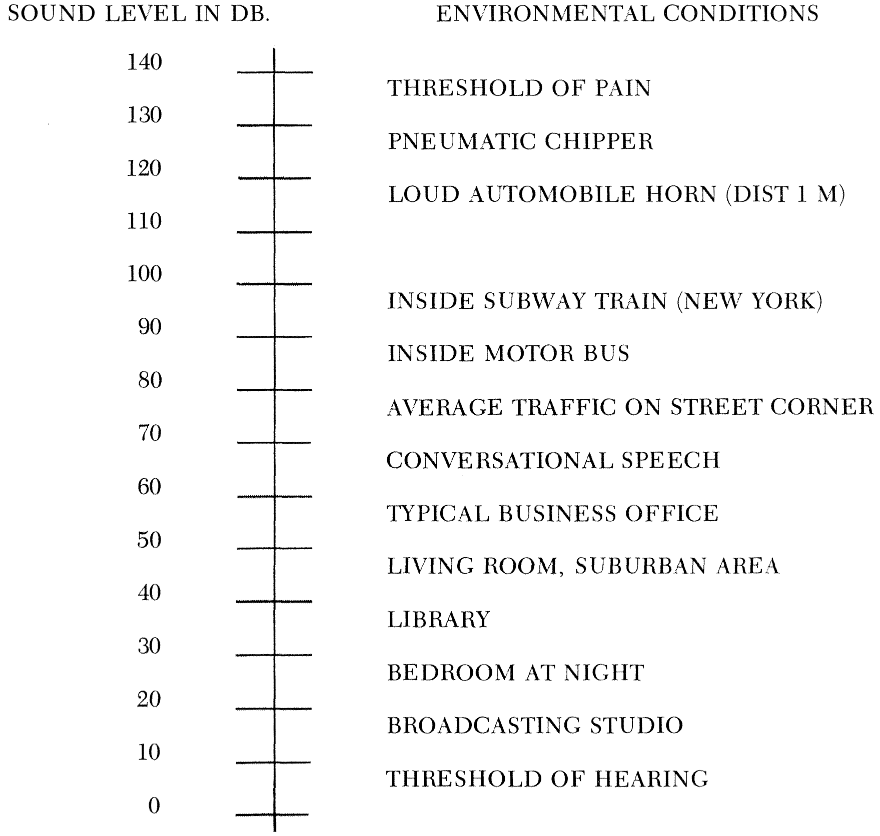
G. Levels of 35-40 dB disturb sleep;
50-60 dB makes conversation difficult

H. Allowable Noise Exposure Per OSHA of Accumulative Exposure per Day

Exposure	Sound Level dB (A)
8 Hours	90
6 Hours	92
4 Hours	95
3 Hours	97
2 Hours	100
1½ Hours	102

1 Hour	105
½ Hour	110
¼ Hour	115

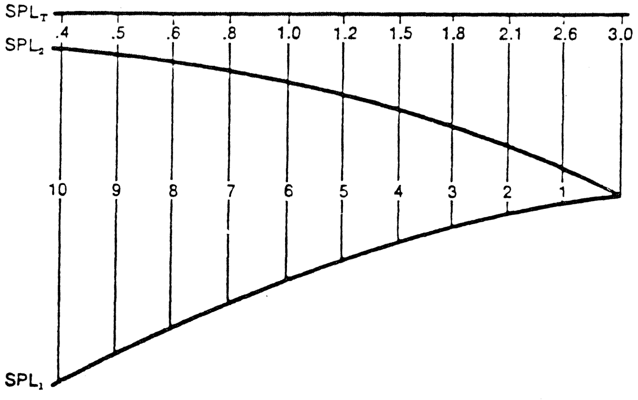
APPENDIX 4
COMMONLY ENCOUNTERED SOUND PRESSURE LEVELS



$$\text{SOUND PRESSURE LEVEL} = 10 \text{ LOG } \frac{P^2}{Po^2}$$

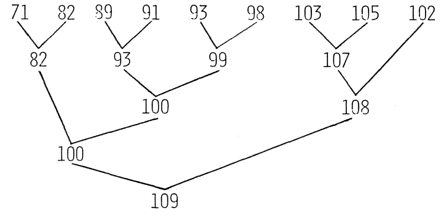
$$\text{REF } P_O = 2 \times 10^{-5} \text{ N/M}^2$$

APPENDIX 5
ADDITION OF SOUND PRESSURE LEVELS



APPENDIX 6
DETERMINING dBA VALUES FROM OCTAVE BAND VALUES

HZ	31.5	63	125	250	500	1000	2000	4000	8000
OCTAVE BAND VALUES	110	108	105	100	96	98	102	104	103
"A" WEIGHTING FACTORS	-39	-26	-16	-9	-3	0	+1	+1	-1
"A" WEIGHTED OCTAVE BAND VALUES	71	82	89	91	93	98	103	105	102



SUM THE "A" WEIGHT VALUES TO OBTAIN DBA

109 DBA OVERALL LEVEL

APPENDIX 7

APPROXIMATE SOUND WAVE LENGTHS IN AIR AT INTAKE AND EXHAUST OPERATING CONDITIONS

$$\text{WAVE LENGTH} = \frac{\text{VELOCITY OF SOUND}}{\text{FREQUENCY}}$$

VELOCITY OF SOUND IN AIR @ 70°F = 1130 FPS

VELOCITY OF SOUND IN AIR @ 1000°F = 1890 FPS

Octave Band Center Frequency (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
Wave Length in Air @ 70°F	35′-10″	17′-11″	9′-0″	4′-6″	2′-3″	1′-1″	0′-7″	0′-3″	0′-1½″
Wave Length in Air @ 1000°F	60′-0″	30′-0″	15′-1″	7′-7″	3′-9″	1′-10″	0′-11″	0′-6″	0′-3″