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NOISE CONTROL NEEDS
IN THE DEVELOPING ENERGY TECHNOLOGIES

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PREFACE

Because of the wide diversity of technologies involved in developing new energy resources for the United States, this report is a compilation of contributions from experts in a number of fields. The authors would like to thank those people in DoE and their contractors, The Bureau of Mines, The Environmental Protection Agency, the mining industry, the oil industry, the electric utility industry, and elsewhere who contributed information. Specific credit is given in the form of references where such contributions have been used in this report.

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EXECUTIVE SUMMARY

This report covers two subject areas: one specific and one general. The specific subject area is an overview of the noise-control problems faced by the developing energy technologies, and the conclusions and recommendations we make regarding those problems. The general area is tutorial material - the language of acoustics, noise and vibration propagation, noise receptors, and noise levels.

Recommendations for future technical work are given in Secs. 1 and 2. These include:

- . A program of research to improve the efficiency of, and reduce the noise output from, draft fans for large boilers (First Priority).
- . Taking advantage of the synergism offered by coordinating Federal programs directed at building retrofit for energy conservation with Federal programs directed at building retrofit for noise control (Second Priority).
- . A study of the effects of steady noise on human sleep - perhaps the most critical alleged health effect of noise from facilities that operate 24 hours per day (Third Priority).
- . A study of the noise characteristics of wind-driven turbine generators, followed, if necessary, by research on blade noise-control design and siting considerations to avoid future community noise problems (Fourth Priority).
- . Selected studies pertinent to the effects of noise on endangered species because of the potential this unknown area has for producing delays in major programs (Fifth Priority).
- . Analyses of and development of means for economically controlling the noise from large cooling tower installations - often the major community noise source of energy-conversion facilities (Sixth Priority).

- . Transfer of the technology available for jet-noise quieting to the problem of noise from free-steam venting at the Geysers and elsewhere (Seventh and Last Priority).

Research programs based upon each of these technical recommendations are outlined in Sec. 2.

Two procedural suggestions are also discussed in Sec. 7:

- . That DoE designate or identify an in-house staff resource to offer Department-wide assistance on noise-control problems, upon request;
- . That DoE prepare its own department-wide policy on guideline documents governing noise exposure from DoE projects.

A final procedural recommendation involving a national defense consideration is discussed in a separate memorandum.

Following an introduction and a description of terminology (Secs. 3 and 4), the noise source characteristics of each of the major developing energy technologies are discussed in Sec. 5. In most cases, these sources are conventional and are amenable to treatment by conventional noise-control techniques where required. In some cases, the noise is regulated by various Federal agencies (i.e., rail transportation of coal), or various Federal or private agencies are already funding noise-control research in the area (i.e., coal mining machinery). In the few instances where a major existing or potential noise problem unique to DoE's interests has been identified, this problem has been singled out and has led to the technical recommendations mentioned above.

Section 6 is devoted to a tutorial discussion of noise and vibration propagation. The effects of noise on people, animals, structures, and equipment are presented in Sec. 7. Physiological

and psychological effects are summarized, as are current standards, regulations, and guidelines intended to mitigate these effects.

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1. CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study, in the form of recommended technical activities in noise control, are listed in decreasing order of importance in Table 1.1. The explanation for each of these recommendations is given in this section. In those cases where the recommendation involves future research, a suggested program of work and an estimate of required resources are given in Sec. 2.

1.1 Fan Efficiency and Noise Reduction

Except for transportation machines, fans are the most common source of noise in the United States today. Furthermore, most of these fans are oversized for their application and much of the noise they produce is a result of their inefficient operation. Fans thus present a major opportunity for both environmental noise reduction and energy conservation.

The problem of fan noise and the potential for fan-efficiency improvements are pertinent to DoE's programs in building energy conservation and fossil-fuel combustion. The latter area seems most amenable to research. Fans are used to supply combustion air for all large, modern fossil-fueled furnaces. They are an inherent component of the burners and heaters required for coal gasification and liquefaction and for retorting oil shales. Fans are used for fluidized-bed boilers, and probably will be used in operational magnetohydrodynamic generators.

The exhaust-gas scrubbing and cleaning equipment required for the burning of "dirtier" fossil fuels increases boiler draft-fan capacity requirements, and thus the potential for noise and inefficiency.

TABLE 1.1. SUMMARY OF MAJOR TECHNICAL RECOMMENDATIONS AND ENERGY TECHNOLOGIES AFFECTED.
IN ORDER OF PRIORITY.

Priority No.	Noise Control Recommendations Description	Developing Energy Technologies Affected												Noise Effects		
		Coal			Oil & Gas		Conser- vation			Advanced						
		Mining	Preparation and Conversion	Combustion	Oil Shale	Oil and Gas	Buildings	Machinery	EHV/UHV	Solar	Geothermal	Wind	OTEC	Fusion	Occupational Health	Environmental
1.	Fan Efficiency and Noise Reduction	X	X	X	X	X		X		X						X
2.	Building Retrofit: Combine Noise Reduction and Conservation Efforts						X									X
3.	Effects of Steady Noise on Sleep		X	X	X	X		X	X	X	X	X		X		X
4.	Noise from Large Wind Turbines											X				X
5.	Effects of Noise on Wildlife	X	X	X	X	X			X	X	X	X		X		X
6.	Cooling-Tower Noise		X	X	X			X		X	X					X
7.	Nozzles for Geothermal Venting			X							X				X	X

As indicated in Sec. 5.1.5.1, boiler draft-fan noise has proven to be a major community-noise problem at a number of fossil-fueled steam-electric generating stations. From an efficiency point of view, a large fossil-fueled generating station capable of producing, say, 600 MWe, typically has drive motors totaling over 20,000 hp to operate induced- and forced-draft boiler fans. At full load, operation of these fans requires over 2.5% of the rated electrical output of the station. Each 10% improvement in the efficiency of the draft-fan system would save 1.5 MWe, or about 10^{11} Btu/yr (4,000 tons of coal or 17,000 bbl of oil). Significant noise reduction would be a concomitant benefit.

Boiler fan noise and fan efficiency are both system problems. The associated ductwork and breeching, dampers, and speed controls are as important as the fan itself in maximizing the efficiency and minimizing the noise emission of the system. Maximum noise and minimum efficiency usually occur under low-load conditions, when the boiler fan is operated at stall with the draft dampers stopped down.

One reason that private industry has not solved the boiler fan noise problem is that fan manufacturers view noise as an installation effect outside their control, whereas plant designers, unaware of the potential difficulty, continue to base their designs on classical static flow parameters. When the problem is discovered, the boiler owner can do little except to add mufflers, thus increasing system losses and further reducing efficiency.

The research program outlined in Sec. 2, which would attack this problem, has been assigned first priority among the recommendations of the study, because:

- a) It is applicable to many of DoE's programs.
- b) It offers a double benefit: energy conservation and noise control.
- c) It offers DoE the opportunity, in commercializing new combustion technologies such as fluidized-bed boilers, to avoid the classical design approach that has led to problems in the past.
- d) The problem is urgent because large numbers of fossil-fueled boilers are now being retrofitted for pollution control and fuel conversion.

1.2 Building Retrofit: Combined Noise-Reduction and Conservation Efforts: A Procedural Recommendation

DoE and other Federal agencies are engaged in a number of programs aimed at reducing energy consumption in buildings. And yet other projects aimed at building noise reduction are proceeding simultaneously:

- . FHWA is investigating the feasibility of "soundproofing" residences adjacent to major highways.
- . FAA [as required by Section 26(3), Appendix B of PL 94-353, "The Airport and Airway Development Act Amendments of 1976"] is investigating the feasibility of soundproofing public buildings near airports.*
- . EPA is developing model building codes specifying noise-reduction requirements for buildings.

As indicated in Sec. 5, the techniques for reducing the heating and cooling loads in buildings overlap in some ways the techniques for improving the noise reduction of building exterior walls. Thus, some building noise-control improvements can lead to energy conservation and vice versa. This potential for mutual benefit has not yet been formally recognized by the various

* A recent report on this investigation used "energy savings" to enhance the cost effectiveness of soundproofing public buildings near airports [1.1].

Federal agencies concerned with either noise control or energy conservation in buildings. It would appear to be in the public interest that they do so.

It is recommended that a coordinating committee be formed, involving representatives of all Federal agencies concerned with building energy conservation and building noise control. This committee could have the following functions:

- . Assuring the compatibility of model building codes separately directed at energy conservation and noise control;
- . Considering the feasibility and mutual benefit of joint demonstration programs;
- . Minimizing costs by avoiding overlapping projects;
- . Highlighting, for the public, benefits of both building retrofit actions.

This procedural recommendation has been assigned second priority as a result of the study because:

- a) A potential for synergism exists, and broad public benefits can be achieved at very modest cost.
- b) Urgent action is indicated: building energy-conservation programs are already well developed and widespread.

1.3 Effects of Steady Noise on Sleep

As indicated in Sec. 7.1.1, there are essentially no data available on the effects of steady noise on human sleep. Yet the generally accepted threshold of sleep disturbance from noise [35 dB(A)] is so low that it often becomes the controlling limit in environmental-impact considerations of noise. There are some indications that this threshold is too low, at least for steady noises, and that higher levels would be acceptable without risk of sleep disturbance.

A research program to investigate the effects of steady noise on sleep is the third-priority recommendation of this study, and it is detailed in Sec. 2. The reasons for the selection of this priority are:

- a) No data are available to define adequately the threshold and effects of a noise consideration that will be pertinent to the noise-control design of a wide variety of energy facilities. It is possible that the generally accepted threshold of sleep disturbance for steady noise is too low.
- b) Other work on sleep disturbance from noise has been sponsored by organizations concerned with intermittent transportation noises. DoE's concern is unique in that it includes steady noise from facilities operating continuously 24 hours a day.

1.4 Noise from Wind Turbines

As indicated in Sec. 5, the authors could find no published data on the noise produced by wind-driven generators. Calculations indicate, however, that if installation of these machines becomes widespread, noise could become a major environmental issue. Furthermore, after-the-fact noise-control improvements would be impractical. Our fourth-priority recommendation is, therefore, that measurements be made of the noise from wind turbines; and that if necessary a research program be initiated to minimize the noise from such machines and to designate siting criteria that take community-noise impact into consideration.

The priority assignment of this recommendation is based upon:

- a) BBN's calculations indicating that noise impact might become an environmental issue that could limit the widespread use of wind turbines;

- b) The most suitable noise control for wind turbines involves blade configuration and design - factors that must be taken into consideration very early in any wind-turbine development program.

1.5 Effects of Noise on Wildlife

As indicated in Sec. 7.1.2, the data on the effects of noise on wildlife are quite sketchy. Available information and common experience suggest that noise control sufficient to protect human listeners will also be adequate to protect wildlife. Nevertheless, the question of the effects of noise on wildlife could become an environmental issue important enough to cause delays in some DoE programs - particularly if endangered species are potentially impacted. If this happens, the program sponsors will be presented with the classic environmental issue of "proving the negative," or demonstrating that noise does not affect wildlife detrimentally. Useful aids in defending such a conclusion are data on the acoustic environment in which wildlife now reside naturally.

Criticism by the Office of Technology Assessment of the lack of Federally supported research on the effects of noise on wildlife should be borne in mind (see Sec. 7.1). Although the criticism is over a year old, it is likely that the present OTA, under the leadership of Russell W. Patterson,* would endorse it. It is also probable that EPA, if funded, would initiate such research. At present, however, EPA has neither funds nor staff for such a program, and it seems unlikely that this agency will have either in the foreseeable future.

* Mr. Patterson was formerly head of the Council of Environmental Quality.

Because of the great diversity of animal species of interest and because of the difficulties of meaningful observation of wildlife in their natural habitat, a comprehensive study of the effects of noise on wildlife would be very costly and time-consuming. A more limited program of research in this subject area is outlined in Sec. 2. It is directed specifically at:

- . Animals on the endangered species list whose habitats are likely to be disturbed by DoE projects;
- . Quantification of the natural noise environment of the undisturbed habitats of these animals. (The goal is to determine the noise levels now tolerated by these animals without apparent effect: Do they choose to live near highways or waterfalls?);
- . Careful field studies of the tolerance to, and effects of, noise on a few selected endangered species.

We have assigned the fifth-priority level to this recommendation because, quite frankly, we feel that the question of the effects of noise on wildlife is more of a legal problem than an environmental one. However, because of the possibility that this question may result in significant program delays, research should be directed toward answering it.

1.6 Cooling Tower Noise

At large industrial installations, such as process plants and electric generating stations, cooling towers are often the major source of noise radiating to the surrounding community. This is particularly true at nuclear power plants that use cooling towers rather than once-through condenser cooling. Cooling-tower noise comes from two sources: waterfall and, in mechanical-draft towers, fans.

Cooling towers with quieted fans are commercially available. However, no work has been done on quieting waterfall noise.

Applying conventional noise-control techniques to large cooling-tower installations is extraordinarily expensive because of the very large radiating area. Therefore, it appears desirable to initiate research on practical means for assessing and controlling cooling-tower (waterfall) noise in order to minimize facility cost and/or buffer-land area requirements.

A program of research directed at cooling-tower noise, the sixth-priority recommendation of this study, is given in Sec. 2.

1.7 Steam-Vent Muffler for Geothermal Wells and Other Applications

As indicated in Sec. 5.6.2, the unique and most intractable noise source at the Geysers' geothermal field is the free-venting of steam wells to the atmosphere. Conventional mufflers are not practical for this noise source, either because they are gutted by rocks blown from the well or because they are too expensive and too bulky for practical use at the site.

Steam-well developers at the Geysers have indicated a need for a small, portable, reasonably priced muffler; a need reiterated at the workshop on Geothermal Noise sponsored by The Lawrence Livermore Laboratory at Davis, CA.

Although the Geysers' dry-steam fields are in commercial operation and are geologically unique in the U.S., there are other justifications for DoE sponsorship of research on steam-vent mufflers. Venting of dry steam will perhaps be a necessity at hot-rock geothermal sites in the future for the same reason it is necessary at the Geysers - cleaning wells of solid materials. Furthermore, steam venting from safety valves at large boiler installations is a frequent noise problem, and no economically practical noise control for such vents is presently available.

There are two reasons for believing that some effective noise reduction can be achieved for steam vents such as those at the Geysers:

- . Little consideration has been given, as yet, to the highly directive nature of the jet noise from a steam vent. If some practical means can be found to rotate the jet 90 degrees, so that it exits horizontally, perhaps as much as 10 dB of noise reduction can be achieved at selected locations far from the vent.
- . Considerable research has been done by NASA on configuring jet nozzles to reduce the noise from aircraft and rocket engines and/or to shift the noise spectrum to higher frequencies, so that the sound is more rapidly attenuated in the atmosphere. The results of that research suggest that perhaps another 10 dB(A) of noise reduction could be achieved for locations distant from steam vents, within the operational constraints present at the Geysers.*

A program of research, in reality a technology-transfer program, is outlined in Sec. 2 to take advantage of these facts and to develop a suitable muffling device for free-steam vents at the Geysers. This is the seventh-priority recommendation of this study.

1.8 Procedural Suggestions

In addition to the technical recommendations discussed above, this study has led to two procedural suggestions, as follows:

- . Identification of a DoE Staff/Resource
- . Preparation of Policy Guidelines on Occupational and Environmental Noise Exposure.

* There have been preliminary attempts at such projects at the Geysers. See, for example, the last two rows in Table 5.16. They have failed, reportedly, because the experimenters did not take into consideration some of the fundamental properties of supersonic jet flow.

To the best of our knowledge, there are no identified resources within DoE to whom Departmental program staff members can turn for assistance on noise-control problems. Although a variety of acoustical talents exists throughout the Department, these talents are often program-oriented, and they tend to be specialized in such areas as industrial hygiene, environmental impact assessment, or noise-control engineering. There appears to be a need for at least one central resource with broad-based expertise in general acoustics and noise control: an identified resource that is available for assistance, when requested, on any of the programs of the Department. Symptoms of the lack of such a resource appeared from time to time during this study.

Clearly, a number of identified resources are presently available within DoE to address problems of air and water quality, hazards of ionizing radiation, ecological impacts, etc. We recommend that at least one resource be identified for noise. The duties of the staff selected to provide this resource could include:

- a) Providing a central repository of data and experience on acoustics and noise control;
- b) Monitoring on-going noise research and legal and regulatory developments both within and outside of DoE;
- c) Providing technology transfer in the noise-control area;*

* Several opportunities for such transfer have been identified. They include:

- . Applying the results of NASA-sponsored research on jet noise to the reduction of noise from vented geothermal wells;
- . Applying the technology of light-weight, aircraft-cabin noise control to reduce interior noise in electric-powered vehicles;
- . Applying the results of community-noise-response-prediction procedures to the evaluation of siting criteria for energy facilities.

- d) Providing technical recommendations for the development of DoE policies and guidelines on noise (see below).
- e) Reducing the risk of committing DoE's resources to excessively topical noise-control research.

Preparation of Policy/Guidelines on Occupational and Environmental Noise Exposure

DoE and its predecessor organizations have reportedly utilized the technical recommendations of AF Regulation 161-35 for guidance in establishing occupational noise-control requirements (see Sec. 7.2.1). We have not identified any corresponding guidelines that DoE or its predecessor organizations have consistently applied for the evaluation of environmental and community-noise control requirements.* It is suggested that DoE prepare its own guideline or policy documents covering both these noise-control areas.

The difficulties with DoE's use of AF Regulation 161-35 for occupational noise exposures are procedural rather than technical. The reporting, audiometric testing, and record-keeping sections of the AF document do not fit DoE's organizational structure. The military aspects (i.e., exposure to gunfire sounds) of the AF document seem inappropriate for DoE's civilian missions. If DoE or its contractors should become involved in litigation regarding hearing loss caused by occupational exposure, the lack of an official document addressing DoE's (as opposed to the USAF's) policy on occupational noise exposure could be a detriment. Finally, the USAF Regulation is presently undergoing revision, and the version used by DoE may become obsolete.

* Note, however, that USAEC (now NRC) Regulatory Guide 4.2 does refer to the use of the HUD Guidelines in the preparation of Environmental Reports for Nuclear Power Plants (see Sec. 7.2.2).

The principal purposes of a DoE guideline or policy on environmental (community) noise exposure would be to:

- . Avoid duplication of such an effort on a project-by-project basis;
- . Assure, both for DoE and its contractors, uniformity of noise-control design objectives for new facilities;
- . Minimize the risk of omitting noise assessment and control as a design objective, where appropriate, for new projects;
- . Facilitate the preparation of acceptable environmental impact statements;
- . Provide, in the absence of applicable state or local regulations, a quantitative noise-control design objective for new projects that is technically and economically feasible and compatible with DoE's missions.

As indicated in Sec. 7, EPA does not have the authority to regulate noise radiated into communities from fixed sources, such as most energy facilities. This authority is left to state and local jurisdictions. However, EPA has published community noise-exposure guidelines "without consideration of technical and economic feasibility" that are available to the states.

Several other Federal agencies have established their own environmental noise impact policies in response to NEPA and the Noise Control Act. These policies are presumably based upon an evaluation of feasibility, as well as public welfare, in the light of the particular agencies' mission. As a result, these policies generally permit higher noise exposures than are indicated by EPA's guidelines. The efforts of these agencies, HUD, DOD, FHWA, EPA, and FAA, could serve as models for DoE's consideration. However, DoE's policy or guideline should be viewed in terms of DoE's specific missions.

REFERENCES

- 1.1 Anonymous, "Report to Congress - Study - The Feasibility, Practicality, and Cost of the Soundproofing of Schools, Hospitals, and Public Health Facilities Located Near Airports," U.S. DOT/FAA (July 1977).

2. SUGGESTIONS FOR FUTURE NOISE-CONTROL RESEARCH

Suggested statements of work for research programs, based on each of the technical recommendations of Sec. 1, are outlined below. In each case, estimates are given for the manpower and calendar time required to complete the research.

2.1 Noise Reduction and Efficiency Improvement of Large Boiler Draft-Fan Installations

Boiler draft-fan noise is the major source of community noise complaints resulting from the operation of large fossil-fueled boilers. To a considerable extent, this fan noise (including large, fan-induced duct wall vibrations) is associated with design constraints that also lead to inefficiencies in draft-system performance. A program of research is recommended to develop and demonstrate economic means for simultaneously reducing the noise output and increasing the operating efficiency of boiler draft installations.

Techniques are available to improve the aerodynamic efficiencies of fans and other air system components. In some cases, these techniques have not been implemented by designers because they required a significant initial capital investment that provided only a marginal return, based on extrapolations of fuel costs at the time of plant design. In this category fall variable-speed fan drives that allow matching of the fan to the desired air flow rates, resulting in reduced noise and improved efficiency.

In other cases, techniques were available but unknown to the designer, or rejected by him as impractical. In the latter category fall such items as variable inlet-guide vanes for induced draft (ID) fans, which are rejected in many applications

because of the tendency of the mechanism to become clogged with particulates in the exhaust flow.

A third category includes those techniques that have yet to be developed or applied to the industrial market. Development work that would lead to reduced noise and more efficient fan operation over a wide airflow range at a fixed shaft speed is recommended. Examples of this type of work might include variable-geometry casings and rotors, as well as improvements in existing guide-vane mechanisms.

The air duct losses in large boilers are typically caused by inattention to well-known physical principles of air handling. The reasons are various, but they often result from the need for minimizing the space to be occupied by the installation. This leads to noisy and inefficient systems: for example, stalled flow in angles in diffuser sections. Mufflers themselves can produce unnecessary losses, as, for example, when they are installed without regard to the impinging airflow patterns that lead to excessive pressure drops.

It is our recommendation that a development program be implemented with the following major tasks:

- a) A comprehensive review of the inefficiencies of the air handling systems now employed in large fossil-fueled boilers,
- b) Estimation of the energy savings that can be achieved by incorporating known technology into the air handling systems of large boilers,
- c) Identification of those areas where noise reduction and energy savings are most promising economically because of low capital and maintenance costs,
- d) Design, and testing with models and full-scale installations, of those boiler draft-fan system improvements that show the greatest promise of economically achieving both fan efficiency improvements and fan noise reduction,

- e) Preparation of a document, directed toward the designers and users of large boilers, which discusses the technical aspects of airhandling efficiency and noise reduction, points out common errors, and presents demonstrated ways they can be avoided.

This program would require an estimated 5 to 10 man-years of professional work and would require 2 to 3 calendar years for completion, depending upon the number of full-scale installations to be built and tested. Equipment and nonprofessional labor costs could be quite high for the full-scale testing effort. The program should be performed with the participation of a manufacturer of large fans, and with the assistance of an operator (user) of large fossil-fueled boilers. Cost-sharing, such as a cooperative research program with an industry association like the Electric Power Research Institute (EPRI), should be pursued.

2.2 Effects of Steady Noise on Sleep

The most often alleged deleterious effect of exposure to nighttime noise sources is sleep disturbance. At present, allegations of sleep disturbance from steady nighttime noise sources, such as those associated with process plants, fuel-conversion facilities, electric generating stations, transformers, and powerlines, cannot be refuted on the basis of scientific information, since no useful information of the required sort exists. What little is known about noise-induced sleep disturbance is derived primarily from laboratory studies of transient noise sources, such as intermittent surface and air traffic.

A systematic, large-scale study of sleep disturbance from exposure to steady noise sources is recommended. The fundamental goal of such a study should be to determine the proportion of the population awakened by steady noises of various intensities. This basic dosage-response information should be developed under field

conditions (in people's homes, not in artificial laboratory settings), from relatively large numbers of people, and by a single, easily understood, and cost-effective methodology.

The recommended measure of sleep disturbance is behavioral awakening, instead of conventional sleep electrophysiology. Behavioral awakening, determined directly by providing a person sleeping in his own home with a bedside button to push if awakened during the night (or if unable to go to sleep), affords numerous advantages over electrophysiological measures of sleep disturbance. Perhaps the greatest advantages are the clarity of definition and simplicity of interpretation of behavioral awakening data. A button push is a simple and understandable measure of sleep disturbance. Electroencephalograph (EEG) records are vulnerable to numerous artifacts of electrode placement and electronic failure, and they require arguable medical interpretation of arbitrary classifications of brain-wave patterns. Thus, they do not offer comparable advantages of simplicity and clarity. Furthermore, the costs and logistics of electrophysiological recordings from large numbers of people in the field are far higher than for the measurement of behavioral awakening.

The technique recommended for collecting behavioral-awakening data in the field is to make use of commercial telephone lines to connect a laboratory computer with peoples' homes. Software would permit the computer to conduct nightly experiments in many homes simultaneously. The computer could play recorded steady noises of various types and at various levels over loudspeakers in the subjects' bedrooms, and log the time of any subsequent awakenings. The computer could also observe responses from control tests of subjects not exposed to the artificial noises.

This technique should be applied on a large scale to clarify the dosage-response relationships of noise exposure and sleep disturbance under the following conditions.

a. Shape of the Dosage-Effect Curve

Behavioral awakening data should be collected in approximately 100 homes for a period of at least one month, at steady noise levels ranging from about 30 dB(A) to about 70 dB(A). Following a control period during which the normal awakening rate of the subjects should be established, noise should be presented nightly to determine the levels at which the test subjects reliably awaken, or are unable to go to sleep.

b. Relative Disturbance of Steady and Transient Noise Sources

Inherently steady noise sources may be less disturbing to sleep than time-varying environmental noise sources of comparable levels. The relative rates of awakening associated with exposure to steady and transient noise levels should be studied in approximately 30 homes for periods of about six weeks.

c. Habituation

The time course of habituation to exposure to steady noise sources needs careful study. Sounds that may awaken people upon initial exposure may eventually fail to elicit any response. A six-month study of nightly exposure to steady noises is recommended in approximately 20 homes.

It is estimated that 25 to 50 man-years of research effort have been expended on studies of the effects of transient noises on human sleep over the last decade and a half. The program

outlined above would require an additional 5 to 10 man-years of research effort, plus equipment, travel, and subject costs. The program would take 1-1/2 to 3 years to complete.

2.3 Noise from Wind-Driven Turbine Generators

In the absence of measured data, calculations indicate that noise could become a significant environmental impact consideration affecting the widespread use of wind-driven turbine generators (WTGs). Conventional noise-control techniques (other than large buffer-land purchases) are not applicable to these devices. Rather, noise control must be taken into consideration during blade design and in the definition of operating parameters, in order to avoid compromising performance for noise-control reasons. The recommended research would have three objectives:

- . The measurement of noise from existing WTGs and the evaluation of this noise against accepted community-noise criteria (Sec. 7.2.2)
- . The definition, if necessary, of quieter blade designs that do not compromise performance
- . The preparation of noise-prediction methods and siting criteria that will avoid excessive community noise exposures following installation.

A program to analyze the environmental noise generated by wind turbines requires measurements on existing systems. Analytical studies could then be performed as required to adapt existing knowledge of noise generation and reduction for helicopters and low-speed fans to the wind-turbine problem. Furthermore, scale-model studies could be performed to develop trend data not presently achievable with full-scale systems (because of the limited number of design alternatives currently operating and the lack of control over environmental wind).

Noise generation by airfoil-bladed turbines is a function of gross geometric characteristics (disc diameter, blade chord, blade number, and separation between disc and tower), gross aerodynamic characteristics (wind speed and turbulence level, rotational speed, pitch setting, and power coefficient), and smaller scale blade and flow details, such as thickness distribution, boundary layer, and wake characteristics. Many of these characteristics are interrelated. The following tasks are recommended:

- a) A program to measure the noise levels produced by existing WTGs, and to compare the results of these measurements to existing community-noise criteria. The need for subsequent tasks will be determined from the results of this initial effort.
- b) In a study that involves both full-scale installations and scale models, the effects of variations in the above parameters should be investigated. A model would allow a greater range of variables than the full-scale installations and should be tested in a low-noise, atmospheric-boundary-layer-type wind tunnel. Effects of Reynolds number variations between model and full scale should be determined as early in the study as possible to ensure that the modeling approach produces consistent results.
- c) Diagnosis should be performed on a full-scale WTG (such as at Plumb Brook, Ohio) to identify and quantify the regions of noise generation on the blade. Suitable techniques should be used to localize aerodynamic noise sources.

This diagnosis can be supported by wind-tunnel tests of stationary blade sections to determine (1) noise generation vs angle of attack and (2) the differences between various airfoil sections.

- d) The above analysis and data base should be consolidated into a verified noise generation model, and from this model favorable design parameter choices should be identified that could lead to low-noise output with minimum performance degradation. Comparisons should be made with noise produced by other sources (e.g., mechanical equipment, transportation, UHV/EHV transmission lines).

- e) The environmental noise impact vs WTG size, distance, azimuth, and meteorological conditions for various representative background environments should be estimated.
- f) Design and siting guides for WTG designers and planners should be prepared.

It is estimated that 4 to 8 professional man-years would be necessary to complete this program, plus travel and equipment costs. About 2 calendar years would be required. Note that the "V-STOL and Noise Division" at NASA-Lewis, not presently involved in DoE's WTG program, has the capability to manage the research recommended here.

2.4 Effects of Noise on Wildlife

Nothing really useful is known about the effects of noise on wildlife. It will probably be only a matter of time before Congressional pressure and/or environmental impact uncertainties will spotlight this knowledge gap. The result could be delays in DoE programs.

It is recommended that DoE institute research on the effects of noise on endangered species that may be impacted by DoE programs. The initial effort of this research should be directed toward determining the natural noise environments in which the designated species now normally choose to live. It is most important that the research be designed and conducted by a team that has skills and experience in both zoology and acoustics. Past work in the field has generally lacked one of these disciplines.

It is recommended that the research proceed as follows:

a) A list of candidate endangered species should be compiled by comparing the normal habitats of all endangered species with the geographic locations where major noise-producing DoE projects are anticipated.

b) Field surveys should be conducted to establish the natural noise levels in several normal habitats of each of the candidate endangered species. The surveys should not be restricted to sites where DoE plans activities. They should attempt to encompass the entire range of natural noise levels within which the animal has chosen to live. The noise properties surveyed should cover the normal range of hearing of the animals, as best as it is known.

c) The normal range of noise levels in which each selected animal has chosen to live should be compared to the anticipated noise levels from the DoE activities proposed for their habitats. Where this comparison indicates that the DoE activity will greatly increase the noise exposure of certain endangered species, then step d should be implemented.

d) Selected, long-term field studies should be made of the effects of noise on the "greatly exposed" animals identified in step c. A useful technique, employed by Lietner at the Geysers, would be to study the effects of noise on the population densities of the selected animals to determine if density reduction occurs as a function of noise exposure.

It is estimated that steps a to c could be completed with 7 to 15 man-years of research effort, plus associated equipment and travel costs. At least 2 calendar years would be required. The resources required for step d would depend upon the number of greatly exposed animals identified, and would vary from case to case. Step d could best be performed by researchers living in the

area - perhaps from the nearest university. Some central coordination and uniformity of methodology would be necessary, however.

2.5 Analysis and Control of Cooling-Tower Waterfall Noise

The noise from massive cooling-tower installations is often the largest or controlling noise source around major industrial facilities, such as nuclear power plants. Although methods are available for minimizing the noise from fans in mechanical-draft towers, no practical noise-control method is available for the waterfall noise component from mechanical and natural-draft towers.

In spite of this lack, and in spite of the frequency with which cooling-tower noise exceeds recommended community noise exposure guidelines and regulations, there are no recorded instances of complaints about noise from large industrial cooling towers. It is presumed that people are more tolerant of this steady, "natural" sound than of, say, the noise from large fans. No experimental evidence exists to support this presumption.

A two-pronged research program is recommended to address the subject of cooling-tower noise:

- a) Determine, through laboratory tests and community attitude surveys near existing installations, the annoyance vs noise level characteristics of cooling-tower noise, both with and without fans.
- b) Develop through laboratory experimentation and perfect through field life tests a low-cost method for minimizing waterfall noise in large cooling towers. This work should probably be directed at reducing the noise produced by the basic generating mechanisms: water flow from the manifold and the fall of water drops in the fill and the sump.

The performance of task a would probably require 2 to 3 man-years and 1 calendar year of effort. The performance of task b would require 3 to 4 man-years and at least 2 calendar years of effort. A knowledgeable cooling-tower manufacturer should be included in the team performing task b to assure the feasibility and economy of the results.

2.6 Development of Noise-Reducing Nozzle Configurations for Large Steam Vents

The one major noise-control problem at the Geysers that remains unsolved is the need for small, low-cost, noise-reducing devices for free-venting steam wells. Such a muffling device would also be useful for boiler safety valves and possibly for hot, dry-rock geothermal installations. We recommend a technology-transfer program to design and demonstrate such a device, on the basis of existing knowledge of jet-noise control methods utilizing directivity and nozzle shaping. The goal should be to obtain a 20-dB(A) noise reduction at selected locations far (1/2 mile or more) from the well. The noise-reducing device should be developed with the close participation of one or more steam developers at the Geysers, so that the end product is designed to meet practical operational needs at the site.

The following tasks are recommended:

- a) Results of research by NASA and others on the noise-reduction effects of various jet nozzle configurations should be reviewed to select those configurations most suitable for use at the Geysers.
- b) The selected configurations should be model-tested in the laboratory, using steam flow.
- c) One or two of the most promising configurations, based upon the results of step b, should be designed, built in full scale, and tested at the Geysers.

This program could be completed with 1 to 2 man-years of professional effort, plus travel and equipment costs. Less than 1 calendar year would be required. Cost-sharing with operators at the Geysers should be investigated.

3. NOISE: AN INTRODUCTION

Before the Industrial Revolution, the world was probably a much quieter place than at present. The rattling of carriage wheels and some construction noise may have intruded into the natural sounds men heard most of their lives, but the noise of machinery, so predominant in our environment, was unknown to them. Though we enjoy the benefits of our modern mechanical society, we have to cope with the concomitant noise problems that have grown up with it. Indeed, in 1955 it was observed that the noise level of our environment had increased 1 dB per year over the previous 25 years, presumably in proportion to our increasing reliance upon mechanical devices [3.1].

All mechanical operations involve some energy loss - mostly in the form of heat. A corollary is the radiation of a very small portion of the energy involved in a mechanical operation as dynamic mechanical motion in the surrounding medium (sound and vibration). We can conclude, therefore, that the amount of noise produced by our society is roughly in proportion to the amount of energy we consume with our machines (see Fig. 3.1 [3.2]).

In the past 5 years, the knowledge that our mechanized society faces inevitable exhaustion of its traditional fossil fuel sources has become a matter of national concern. A number of efforts - the developing energy technologies - have been made to conserve existing fuel sources and to develop new ones. These efforts carry with them the threat of a whole family of new industrial noise problems, for we must consume energy to get it. However, the developing energy technologies also offer a promise - an opportunity to halt the inexorable growth of noise our society has experienced in the past. Reduced energy consumption will result in reduced noise, of course, but the greater challenge lies in also reducing the noise produced by the new technologies.

FIG. 3.1. RELATIONSHIP BETWEEN MECHANICAL POWER AND RADIATED ACOUSTICAL POWER FOR SELECTED ENERGY-CONSUMING PRODUCTS. (After Shaw [3.2].)

Note: The Parameter is Conversion Efficiency.

Noise control can thus become a design consideration, part of the conception of new processes and devices, rather than an afterthought as has so often happened. Perhaps one of the best-known examples is the case of turbojet engines for commercial aircraft. The first generation of such engines, used on 707 and DC-8 aircraft, was designed without much consideration of the noise exposure to people living around airports. Years of attempts to retrofit these engines and aircraft to make them quieter have resulted in only moderate success. On the other hand, the newer turbofan engines, used on wide-body aircraft such as the L-1011 and DC-10, were designed to be quieter than their predecessors, as well as more powerful and more efficient. The result, shown in Fig. 3.1, is that we now have 700,000-lb aircraft that are 10 to 12 dB quieter than their 300,000-lb predecessors, and are powered by engines with half the specific fuel consumption.

Similar opportunities exist in the developing energy technologies. One of the goals of this study is to begin to identify such opportunities.

3.1 Purpose and Objectives

The broad goals of this study were (1) to survey the developing energy technologies and (2) to determine the existing and/or anticipated noise-control needs of these technologies. Specific objectives of the study included:

- . Identification of practical noise-control knowledge for the mitigation of noise impacts, where appropriate,
- . Identification of areas where existing knowledge of noise-control needs is inadequate,
- . Recommendations for noise-control research programs and procedural suggestions to clarify areas of inadequate knowledge.

3.2 Outline of Report

Section 4 of this report presents a brief introduction to the terminology of sound measurement and of rating the impact of noise on people. Section 5 presents a detailed discussion of the noise sources associated with the developing energy technologies, with emphasis on those sources that are likely to present unique control problems. Section 6 contains a discussion of propagation phenomena; Sec. 7 is devoted to a consideration of receivers and noise immission criteria.

The various noise-control problems identified in Secs. 5 through 7 are singled out for discussion and ranking in Sec. 8; they are the basis for the conclusions and recommendations presented in Sec. 1. For those cases where future DoE noise-control research appears justifiable, research programs are outlined in Sec. 2.

Because of the general unfamiliarity of many readers with noise-control problems outside the occupational-exposure area, this report is somewhat tutorial. In particular, methods for the assessment and control of community noise impacts - such as those encountered by DoE in studies of UHV/EHV power transmission and of the Geysers geothermal activity - have been stressed in Sec. 7.

3.3 Sources of Information

The information in this report is based upon formal literature searches, correspondence and telephone calls, and seminar attendance. The literature searches included:

- . The Environmental Protection Agency/Office of Noise Abatement and Control "ONAC Technical Reference Center"
- . The National Technical Information Service (NTIS)
- . "Compendex," The Engineering Index data base
- . The ERDA Technical Information Center, Oak Ridge, TN
- . The Bolt Beranek and Newman Inc. (BBN) library of acoustics and noise-control documents.

When suitable information on the noise characteristics of particular technologies was not uncovered by the literature searches (and this was typically the case), correspondence and telephone conversations were conducted with organizations knowledgeable in the fields of interest. In one instance - geothermal energy - BBN attended a seminar where noise was the subject of discussion.

REFERENCES

- 3.1 Vern D. Knudsen, "Noise, The Bane of Hearing," Noise Control 1, p. 11 (May 1955).
- 3.2 E.A.G. Shaw, "Noise Pollution - What Can be Done?"

4. NOISE-CONTROL CONCEPTS AND TERMINOLOGY: A BASIC GUIDE TO ACOUSTICS

4.1 Source, Path, and Receiver

All noise problems have three elements: a sound source, a propagation path or paths, and receivers that may respond to the sounds. Sections 5, 6, and 7 of this report separately address noise sources, paths, and receivers.

A sound source can be completely characterized by the amount of acoustic power, in watts, that the source radiates into the area surrounding it as a function of frequency, direction, and time. This acoustic power is generally a very small fraction of the mechanical power of the source. Such a characterization of sound emission is often necessary to quantify noise-control requirements for the source (see Sec. 5).

As discussed in Sec. 6, sound (including vibration) propagating through a medium is altered by the medium. This alteration can include absorption and attenuation at various frequencies, reflection, refraction and scattering of the sound energy, and modal changes. These effects tend in general to reduce the sound energy incident at a receiver relative to that radiated by a source. Thus, they reduce the amount of noise control required in most situations.

In discussions of noise control, it is useful to distinguish between the emissions of noise by sources, and the immission of noise at receptors. The two are distinguished not only by the effects of intermediate propagation paths, but also by the possibility that one receptor can be impacted by the noise from many sources.

Sound immission at a receiver can be characterized by the frequency spectrum of sound pressure or acceleration incident upon the receiver, as a function of time. If the receiver is a piece of dynamically sensitive equipment, such a characterization of the sound immission is sufficient for comparison with the levels to which the equipment has been environmentally qualified in order to establish any noise-control requirements. However, as discussed in Sec. 7, this is not sufficient in the more general situation. When people or animals are the receivers, noise-control design involves considerations both of the physical properties of the incident sound and of the listener's reaction to it. Noise is defined as "unwanted sound" [4.1]. Thus, a noise problem is characterized both by the physical properties of the sound and by the judgment of and reaction to the sound by the listeners. One man's music is another man's noise. This sociological or psychophysical aspect of noise control is one of the unique features of noise analysis. Sometimes treated as an aesthetic consideration, it is nonetheless of increasing regulatory significance.

A critical step in the solution of any noise-control problem is the definition of an acceptable noise immission level, often called an "acoustic criterion" or a regulatory limit, for the amount of noise that will be permitted at a specific receiver.

The utility of the source-path-receiver concept in the solution of noise-control problems is now evident. In the case where the noise immission at the receiver is entirely from one source, the noise control (NC) required is:

$$\text{NC required} = \text{Source Level} - \text{Path Losses} - \text{Criterion Level.}$$

Of course, the problem becomes more complicated when a number of sources contribute to the immission at the receiver. But even in this case, the basic source-path-receiver concept is useful.

4.2 The Problem with Decibels

A frequent source of confusion in the field of acoustics is the use of decibels. The decibel is not a unit of measure, like a meter or a second. It is, rather, an expression of the value of a ratio, and is thus a kind of numbering system. Many acoustical parameters are quantified on the decibel scale. One should not make the mistake of assuming that two quantities reported in decibels are the same; this depends on the basis for the ratio comparison. They could be as different as a bushel of apples and a pound of oranges.

The decibel scale is a log ratio scale defined as follows:

$$Q(\text{dB}) = 10 \log_{10} \frac{q_1}{q_{\text{ref}}} ,$$

where Q is the value of q_1 in decibels; q_1 is the magnitude of the parameter of interest - usually, the parameter is in units proportional to power; and q_{ref} is a reference value, often standardized, of the parameter q .

Thus, sound pressure level (SPL) is defined as:

$$\begin{aligned} \text{SPL}(\text{dB}) &= 10 \log_{10} \frac{(p)^2}{(p_{\text{ref}})^2} \\ &= 20 \log_{10} \frac{p}{p_{\text{ref}}} , \end{aligned}$$

where p is the rms sound pressure in the medium, and the standard value of p_{ref} is 2×10^{-5} N/m² (20 micropascals). This is approximately equal to 2×10^{-4} psi.

On the other hand, sound power level (PWL), such as used to characterize a sound source, is defined as:

$$\text{PWL(dB)} = 10 \log_{10} \frac{W}{W_{\text{ref}}} .$$

where W is the power in watts (acoustic) radiated by the source, and W_{ref} is 10^{-12} watts.

Obviously, sound pressure level and acoustic power level are two very different quantities. Just because they are both reported on the decibel scale does not mean they are equal, or even related.

Because of the use of the logarithmic scale, the addition of like quantities expressed in decibels is not straightforward. Two equal sound levels added together (incoherently) produce a new level that is 3 dB greater than either component [i.e., $60 \text{ dB(A)} + 60 \text{ dB(A)} = 63 \text{ dB(A)}$]. If one sound level is 10 dB less than the other, the larger is unaffected by the addition of the smaller [$60 \text{ dB(A)} + 50 \text{ dB(A)} = 60 \text{ dB(A)}$]. Many acoustic texts contain tables or graphs to simplify the addition of quantities expressed in decibels [4.2].

Additional acoustic terminology is given in Appendix A. The points to be made here are:

- . Decibels are a kind of numerical scale, not a unit of measurement. The parameter, its units, and the reference value must be specified, as well as the level in decibels.
- . By definition [4.1], quantities in decibels are called "levels."

4.3 Some Important Terminology

Some acoustic terminology has been described in the preceding subsections, and a good deal more is given in Appendix A. A few terms, however, are singled out here because they are so important to the understanding of modern noise control that the reader must know them in order to follow the rest of this report.

Sound

Sound is a disturbance that propagates as a wave through an elastic medium such as air, causing the particles of the medium to vibrate. It should be clear by now that we consider vibration to be a sound propagating through a solid medium. Sound waves in air can be generated by the motion of an object or by the movement of the air itself from turbulence or other causes. Although the generating motion is very small and the resulting motion of the medium is likewise very small, a sound wave in air can propagate over several miles. The wave is propagated by the transfer of momentum from one vibrating air particle to adjacent air particles. Sound waves in still air travel at about 350 meters per second or 770 miles per hour; this speed varies a bit with temperature. The propagation velocity in water is about four times faster than in air; in solids, it varies widely, depending upon the material and shape of the solid.

Sound Pressure

To describe a sound wave, those characteristics of the wave that can be quantified must be measured. One important characteristic is the magnitude or size of the wave. In fluids, this characteristic is usually observed in terms of the mean square amplitude of the localized pressure variations (compressions and rarefactions) of the wave. These slight pressure variations, caused by the motion of the disturbed air particles, are what our eardrums sense when we hear a sound.

The range of pressure variations that the human ear can detect is tremendous. A very loud sound wave can have as much as 1,000,000 times the pressure variation of a very quiet sound. To describe sound in terms of pressure variations would be very cumbersome because of the great range of amplitudes that is involved. Therefore, a "compressed" scale has been devised on the basis of the logarithm of the mean square pressure. This is the decibel scale described in Sec. 4.2. With the decibel scale, the range of normally encountered sounds can be expressed as "from 20 to 140 decibels (dB)" rather than "1,000,000 to 1."

Frequency and Spectrum

A second characteristic of a sound wave that can be quantified is its frequency. As a simple sound wave passes a point, the air pressure alternately rises and falls. Each time the pressure rises and falls, it is said to go through one cycle. The number of cycles per second (or Hertz, abbreviated "Hz") is the unit in which frequency is expressed.

Frequency is observed subjectively as the tone or pitch of a sound. High-frequency sounds have a high pitch; low-frequency sounds have a low pitch. The human ear can detect a range of fre-

quencies from about 20 to 17,000 Hz. The "low" frequencies (20 to 500 Hz) have a low-pitched or bass sound. The "mid" frequency range is from roughly 500 to 3000 Hz, where most speech information is carried. "High" frequencies are from 3000 to 17,000 Hz.

In practice, most sounds contain a large number of frequencies simultaneously, although a few frequencies may stand out from the others. A table or graph showing the amplitudes of all of the different frequency components contained in a sound is called the spectrum of the sound.

4.4 Noise Rating Scales for Sound Immission [4.3]

For most purposes, an adequate physical description of a sound is given by its spectrum: a display of the sound pressure level in decibels as a function of frequency in Hz. Additional information is necessary, however, to determine what effect the sound immission will have on people. Noise rating scales attempt to take such additional information into account and are thus used to rate, or estimate, the impact of a noise intrusion on people.

The undesirable effects of noise on people fall into two classes: physiological damage and activity interference. The only generally accepted type of physiological damage is hearing loss, which can occur after prolonged exposure to intense noise. Activity interference can include interference with speech communication and sleep, annoyance, and the generation of complaints about noise.

Factors influencing these undesirable effects of noise (in addition to the physical properties of the noise itself) include:

- . The listener's hearing sensitivity
- . The duration and/or rapidity of occurrence of the sound
- . The time of day and season of year when the sound occurs
- . The properties of other sounds existing at the listener's location
- . The tonal or impulsive nature of the intruding sound
- . Individual and community attributes and values, such as attitude towards the noise-maker, prior exposure to the noise, community cohesiveness, social status, etc.

Because of the uncertainties associated with quantifying some of these factors, rating scales are only approximate prediction tools. Because of individual differences in the factors, rating scales are useful only for estimating the effects on large groups of people ("communities"). They cannot be applied to predict an individual's response to a noise or the response of a very small group.

A-Weighted Sound Level

The simplest and by far the most popular noise rating scale is the A-weighted sound level, expressed in dB(A).

From many experiments with human listeners, it has been found that the human ear is more sensitive to the mid-range of frequencies, where most speech information is carried, than it is to low frequencies or very high frequencies. This characteristic of the human ear can be taken into account by adjusting the spectrum of the measured sound pressure level for the sensitivity of human hearing. In standardized sound-measuring instruments, this is implemented with selectable "A," "B," and "C" weighting functions [4.4]. The term "weighting" or "weighted" is used because some frequencies are given more or less importance, or weight, than other frequencies. A-weighting is the most commonly

used, and the data so obtained are expressed as "A-weighted Sound Levels." (The word "pressure" is omitted when describing weighted sound levels.) C-weighting is sometimes used for rating impulsive sounds, and other weighting functions have been suggested for various specific purposes.

Variable Sounds: Statistical Descriptors

Generally, the effects of an occasional noise intrusion are less than the effects of a continuous one, even though the sound level of the intrusion is the same in both cases. Occasional use of a noisy home vacuum cleaner is not nearly so disturbing as if it were to be operated all the time. One method for dealing with such fluctuating or intermittent sounds is to examine the sound level statistically as a function of time.

Statistical descriptors are often applied to A-weighted sound levels, and are called "L-levels." For example, the L_{10} is the A-weighted sound level exceeded 10% of the time over a specified time period. The other 90% of the time, the sound level is less than the L_{10} . Similarly, the L_{50} is the sound level exceeded 50% of the time; the L_{90} is the sound level exceeded 90% of the time, etc.

Variable Sounds: L_{eq}

The simplest and most popular method for rating intermittent or fluctuating noise intrusions is to rely upon some measure of the average sound magnitude over time. This approach is inherent in the OSHA method for evaluating employee noise exposure [4.5], and in all methods for estimating noise impact around airports. The commonest such average is the equivalent sound level, L_{eq} .

The equivalent sound level is the energy average of the level (usually A-weighted) of a varying sound over a specified period of time. The term "equivalent" signifies that a steady sound having the same level as the L_{eq} would have the same sound energy as the fluctuating sound. The term energy is used because the sound amplitude is averaged on an rms-pressure-squared basis, and pressure squared is proportional to energy. For example, two sounds, one of which contains 24 times as much energy as the other, but lasts for 1 hour instead of 24 hours, would have the same equivalent sound level.

Because sound is measured on a logarithmic scale, the L_{eq} of a fluctuating sound is essentially determined by the maximum sound levels observed over the time period, rather than by the median (L_{50}) and other lower sound levels. (See the discussion in Sec. 4.2 on the addition of quantities in decibels.)

It is most important that the reader understand the concept of equivalent sound level. Mathematically, it is defined as:

$$L_{eq} = 10 \log_{10} \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p^2(t)}{p_{ref}^2} dt \right]$$

where $p(t)$ is the time-varying, A-weighted sound pressure, p_{ref} is the reference pressure, 2×10^{-5} N/m², and $t_2 - t_1$ is the time period of interest.

Thus, if a 55-dB(A) sound exists all the time, its L_{eq} is 55 dB(A). If it exists only half the time, its L_{eq} is 52 dB(A). If it exists one-third of the time, its L_{eq} is 50 dB(A); one-tenth the time, 45 dB(A), etc. The equivalent-sound-level approach

allows quantification of the fact that occasional noises are less disturbing than continuous ones of the same level. A noise occurring one-tenth of the time is presumed to be as disturbing as one having a 10 dB(A) lower level, but occurring all the time.

The L_{eq} approach to rating fluctuating and intermittent noises has been verified by many psychoacoustic studies and is the preferred method of the Federal Environmental Protection Agency [4.6].

The Day-Night Sound Level (L_{dn})

The day-night sound level, L_{dn} , is an energy average level with a 10-dB(A) nighttime penalty. The L_{dn} rating is intended to improve upon the L_{eq} rating by adding a correction for nighttime noise intrusions, because people are more sensitive to such intrusions. The penalty is applied to all sounds occurring between 10 p.m. and 7 a.m.

Essentially, L_{dn} was introduced as a simple method for predicting the effects on a population of a long-term exposure to environmental noise. L_{dn} is presently used for assessing the impact of rail transit noise and aircraft noise and is beginning to be used to assess the impact of highway traffic noise.

The L_{dn} can be derived from daytime and nighttime L_{eq} values as follows:

$$L_{dn} = 10 \log_{10} \left\{ \left(\frac{1}{24} \right) \left[15 \text{ antilog } \frac{L_d}{10} + 9 \text{ antilog } \frac{L_n + 10}{10} \right] \right\}$$

where L_d is the L_{eq} for the 15 daytime hours, and L_n is the L_{eq} for the 9 nighttime hours.

It can be shown that the L_{dn} of a steady noise is 6.4 dB(A) higher than the A-weighted sound level of the noise. Thus, the L_{dn} of a steady 50-dB(A) noise would be 56.4 dB(A).

REFERENCES

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- 4.3. T.J. Schultz, Community Noise Ratings (Applied Science Publishers, London, 1972).
- 4.4. American National Standard Specification for Sound Level Meters, S1.4-1971 (American National Standards Institute, New York).
- 4.5. 29 CFR 1910.95. (See also Federal Register, 20 May 1969.)
- 4.6. "Information on Levels of Environmental Noise Requisite to Protect the Public Health and Welfare With an Adequate Margin of Safety," Publication 550/9-74-004, U.S. Environmental Protection Agency (March 1974).

5. MAJOR NOISE SOURCES OF THE DEVELOPING ENERGY TECHNOLOGIES

In this section, the principal noise sources of many of the developing energy technologies - coal, oil shale, tar sands, oil and gas, advanced, and conservation - have been identified. (Little is said about the direct use of solar energy, because no significant noise problems have been identified for this technology.) Where possible, each noise source has been quantified. In most cases, the significance of the various noise sources has been assessed in terms of:

- . Impact on workers
- . Impact on surrounding communities
- . Difficulty of control.

Readers interested in a single technology, such as geothermal energy, may choose to turn immediately to the section in which that technology is discussed. Note, however, that most of the noise sources discussed in this section are not unique to one technology or even to the energy field as a whole. They are generally the same noise sources that Americans encounter daily. Diesel engines, for example, are a major noise source at geothermal well-drilling sites, as well as at surface coal mines, oil and gas drilling and enhanced-recovery operations, and in many forms of everyday transportation.

It is not surprising, then, that conventional noise-control technologies are applicable to most of the noise sources identified in the developing energy technologies, and that special noise-control situations, unique to one technology, are rare. Where they exist, however, they have been identified.

5.1 Coal Technologies

Coal is by far the nation's most plentiful source of fossil energy, an energy resource so valuable that millions of research dollars are committed to it. Coal is a fuel for which the nation's demand, experts agree, will grow. How much? On the answer to that question, experts do not agree (see Table 5.1), but clearly production will soar.

In the pages that follow, the discussion of coal is subdivided into four categories, paralleling the four stages of coal development and use employed by the coal industry itself (Fig. 5.1). They are mining, preparation, transportation, and utilization. For each, noise sources are examined, and government agencies (DoE, BoM, EPA, DOT, etc.) funding noise-control research or already providing for abatement of noise are identified.

Broadly, noise from coal mining operations in 1977 may be characterized as:

- . An occupational hazard. (The allowable noise exposure for coal miners is specified in the Coal Mine Health and Safety Act of 1969 [5.3]. The Bureau of Mines has already funded noise-control research and development [5.4, 5.5, 5.6] and is expected to continue support.)
- . An annoyance to residents adjacent to mines. (Such noise affects residents near surface mines who may experience noise and vibration, such as from blasting operations. Blasting noise is also an area in which the Bureau of Mines is funding research [5.7]. Residents adjacent to deep mines are usually subjected to, at most, noise associated with the loading of railroad hopper cars.)
- . A possible impact on wildlife on adjacent property.
- . An indirect source of national noise and vibration to all Americans living near any of the means of transportation - by road, rail, or water - by which coal is moved to the ultimate user.

TABLE 5.1. COMPARATIVE COAL DEMAND FORECASTS FOR 1985 [5.1]

	Millions of Tons
Manalytics, Inc.	
High-Demand Scenario	1,514
Low-Demand Scenario	1,242
National Petroleum Council	
<u>U.S. Energy Outlook - An Initial Appraisal,</u> 1971-1985, NPC	1,001
Federal Energy Administration	
<u>Project Independence - Coal Task Force</u> <u>Report, November 1974</u>	
Business as Usual	1,100
Accelerated Demand	2,063
Department of the Interior, Bureau of Mines	
L. Westerstorm	920
Department of the Interior	
<u>U.S. Energy - A Summary Review</u>	1,000
<u>U.S. Energy - Through Year 2000</u>	980
Atomic Energy Commission	
<u>Understanding the Energy Dilemma</u>	1,075
Batelle Memorial Institute	1,708
National Academy of Engineering	
<u>U.S. Energy Prospects - An Engineering</u> <u>Viewpoint, NAE, Washington, DC, May 1974</u>	1,260
National Energy Plan [5.2]	1,050

FIG. 5.1. STAGES OF COAL RESOURCE DEVELOPMENT AND USE.

5.1.1 Coal mining technologies

A survey, conducted in January 1977 by the Keystone Coal Industry Manual and based on future-planning data from 315 mines, predicts that in 1985 there will be 617 million tons (MT) of new annual capacity beyond the 1976 production figure of 655 MT. The new capacity is expected to include 211 MT of deep-mined coal and 406 MT of surface-mined coal. To meet that production goal, present mining technologies will have to be increased, although few radically new technologies will need to be developed. Simultaneously, transportation of coal will have to be increased, with concomitant noise impacts. Mechanical equipment is, and is expected to be, the chief source of noise in deep and surface mining. The mining equipment now in use is summarized in Table 5.2, and Tables 5.3 and 5.4 present average noise levels of typical equipment. Discussions of the present and future equipment use in deep and surface mining follow.

Deep Mining

During the exploration and development phases of deep mining, surface equipment is used. Consequently, workers, wildlife, and adjacent residents may be exposed to noise and vibration.

Once the mine enters the production phase, the noise becomes confined to the underground work areas, except at surface unloading points. Typical sound levels measured at operator positions during underground operations are presented in Table 5.4. The final item in the table is taken from BBN data and serves to illustrate the importance of fan noise even in the underground environment.

TABLE 5.2. SUMMARY OF MINING EQUIPMENT.

Deep Mining			Surface Mining	
Mining Stage	Current Equipment	Equipment Under Development	Current Equipment	Equipment Under Development
Exploration	Coring drill	-	Coring drill	-
Development	Tunnel borer Mucker Rotary drill Explosives	High speed tunnel borer In-seam header Blind shaft borer Conical borer	Scraper Bulldozer Blast-hole drill Dragline Front-end loader Stripping shovel Bucket-wheel excavator Graders Explosives	-
Production	Mantrip Continuous miner Loading machine Shuttle car Roof bolter Cutting machine Stoper drill Coal drill Longwall shear Face ventilation fan Mine ventilation fan	Automated long wall Hydraulic mining Longwall auger Conveyors Bore-hole mining	Coal drill Loading shovel Front-end loader Haulage truck	Conveyors Constant-rotating cutting machines Continuous surface miner
Reclamation	-	-	Scraper Bulldozer Grader Seeder	Side-by-side dozer

TABLE 5.3. AVERAGE NOISE LEVELS OF EQUIPMENT USED IN THE EXPLORATION AND DEVELOPMENT PHASES OF UNDERGROUND COAL MINING OPERATIONS.

Equipment	Level dB(A) re 20 μ Pa	Measurement Location
Long drill		
Air track	115/120*	Operator position
High wall	100/105*	Operator position
Tunnel borer	100/105*	Operator position
Mucker	110*	Operator position
Rotary drill	89*	Helper position
Explosives	124.4 $\pm$ 6.6dB**	1000 ft from blast

*BBN data files

**Calculated from Ref. [5.7].

TABLE 5.4. AVERAGE NOISE LEVELS AND OPERATING TIMES OF COAL MINING FACE EQUIPMENT [5.8].

Machine Type	Number Surveyed	Operating Mode	Average Noise Level (dBA)	Average Operating Time Per Shift (min)
Continuous miner	33	Tram.....	87.3 $\pm$ 4.1*	57 $\pm$ 34*
		Cut only...	95.1 $\pm$ 3.1	29 $\pm$ 19
		Load only..	94.2 $\pm$ 2.3	29 $\pm$ 26
		Cut and load.**	97.2 $\pm$ 2.6	108 $\pm$ 47
Loading machine	18	Tram.....	91.7 $\pm$ 3.6	73 $\pm$ 25
		Load**.....	96.7 $\pm$ 3.6	97 $\pm$ 32
		Clean-up...	99.3 $\pm$ 3.1	47 $\pm$ 27
Shuttle car	47	Tram.....	86.6 $\pm$ 1.8	106 $\pm$ 58
		Load**.....	89.7 $\pm$ 2.5	61 $\pm$ 30
		Unload.....	89.0 $\pm$ 2.7	38 $\pm$ 17
Cutting machine	17	Tram.....	85.7 $\pm$ 3.3	51 $\pm$ 21
		Cut**.....	91.4 $\pm$ 2.3	118 $\pm$ 43
		Slump.....	94.9 $\pm$ 2.0	18 $\pm$ 6
Coal drill	17	Tram.....	83.6 $\pm$ 2.9	51 $\pm$ 23
		Drill**.....	87.7 $\pm$ 3.2	47 $\pm$ 16
		Maneuver...	84.2 $\pm$ 2.0	22 $\pm$ 12
Rotary roof bolter	37	Tram.....	85.5 $\pm$ 2.2	46 $\pm$ 27
		Drill**.....	93.2 $\pm$ 3.2	91 $\pm$ 31
		Bolt.....	91.2 $\pm$ 3.6	7 $\pm$ 3
		Idle.....	85.1 $\pm$ 2.0	34 $\pm$ 10
Stoper	11	Drill**.....	119.4 $\pm$ 1.8	139 $\pm$ 58
		Bolt.....	106.1 $\pm$ 7.8	33 $\pm$ 27
		Idle.....	100.1 $\pm$ 4.0	32 $\pm$ 3
Longwall shear	2	Cutting....	89.5 $\pm$ 4.9	177 $\pm$ 3
Mantrip	58	—	92.6 $\pm$ 3.2	31 $\pm$ 14
Face ventilation fan	1	Operating	92	400

* $\pm$ values represent one standard deviation in the measurements.

** Major operating mode.

Experimental machinery being developed under Bureau of Mines sponsorship includes blind-shaft borers, conical borers, high-speed tunnel borers, and in-seam headers. The major noise sources of these machines are the same as those of present-day equipment (e.g., rock fracturing, conveying, electric motors, and hydraulic devices). Consequently, we expect that noise levels will be similar to those of current machines.

In the deep-mine production area, the technique with the greatest promise is longwall mining. The January 1977 issue of Coal Age indicates that 3.6% of 1975 underground coal production was obtained by longwall mining, and estimates an increase to 15% by 1985. Additionally it is estimated that by the year 2000 longwall production could equal continuous-miner production. This trend toward longwall mining is beneficial to the noise exposure of miners not only because the noise level is lower, but also because the number of miners exposed per ton mined is drastically reduced.

The longwall auger, which combines auger mining and longwall operation, is a new concept in mining. It presents no new problems with noise and is expected to have a noise level similar to longwall shearers. Hydraulic mining will utilize water jets to cut coal rather than the conventional cutting picks. This change is expected to reduce the noise radiated from the cutting head. However, since the remainder of the machine will be acoustically similar to other continuous miners, it is not expected to result in much overall noise improvement.

In summary, we expect that the deep-mining noise in the future will be similar to that of today, with some reductions anticipated owing to noise-control research funded by the Bureau of Mines and the increased use of longwall mining.

Surface Mining

Major increases in future surface mining are expected to occur in the western states and to be associated with large mines. Since these mines occupy large geographical areas, the noise effect on adjacent communities is expected to be minimal, except, as discussed later, in the case of transportation. The effects on wildlife on the property are unknown.

Typical measured noise levels for present surface mining equipment are presented in Table 5.5. Increased production will probably come from increased utilization of this same equipment. New concepts for surface mining include the application of continuous-mining machines to surface mining, constant-rotating cutting machines similar to bucket wheel excavators, and continuous-haulage systems using conveyors to eliminate on-property truck haulage. The continuous-mining machines and constant-rotating machines are expected to increase noise levels somewhat - similar to the noise of underground mining machines - but ongoing research in noise control is expected to reduce the impact. Conveying systems are expected to be belt conveyors, which are quiet compared to other surface mining operations.

Borehole mining is a new surface mining technique wherein a hole is drilled to the coal and high-pressure water is used to fracture and wash out the coal. This system would be highly automated, and, consequently, worker exposure would be minimized. Effects on other parts of the environment should be similar to the effect of drills and high-pressure pumps used in slurry pipelines.

In summary, no major new noise sources are expected to result from new surface mining techniques or concepts.

TABLE 5.5. SUMMARY OF WORKING NOISE LEVELS AND OPERATING TIMES FOR SURFACE MINING EQUIPMENT.

Machine Description	Working Noise Level dB(A)*		Percent of Shift Time Working
	Mean	Std Dev'n	
Dozers, track, >150 HP	103	1.5	77
Dozers, track, <150 HP	94 ^(L)	3.5 ^(L)	77
Dozers, wheel	96 ^(E)	5.0 ^(E)	54
Loader, wheel, >150 HP	94.5	1.5	80
Loader, wheel, <150 HP	97 ^(I)	3 ^(I,E)	80
Loader, track	91.5 ^(L)	4 ^(L,E)	80
Hauler	88.5	4.6	69
Truck, highway	85 ^(E)	5 ^(E)	50 ^(E)
Scraper, tandem	92 ^(E)	7 ^(E)	76
Scraper, single	96 ^(E)	5 ^(E)	76
Motor grader	96 ^(E)	5 ^(E)	74
Shovels & draglines, electric, >30 cu yd	77.5	6.7	85
Shovels & draglines, electric, <30 cu yd	86	3.8	71
Shovels & draglines, I.C. engine power	91	6.5	80
Drill, blast hole	90	2.1	74
Drill, coring	87 ^(E)	5 ^(E)	11
Auger	95 ^(E,M)	5 ^(E)	74

*All based on BBN and verified MESA data, except as specified otherwise:

(L) = from literature, (E) = estimated, (I) = includes literature data,
(M) = misc. MESA data

Note: Averages rounded off to nearest 0.5 dB(A), Std. Dev'n to nearest 0.1 dB(A)

5.1.2 Preparation technologies

Preparation, or cleaning, is the second basic stage in the development and use of coal. It involves the crushing, cleaning, and sizing of coal prior to use.

In 1969, the number of coal preparation plants in the United States was estimated at 1100. Approximately half - partial-preparation facilities - crushed and sized raw coal. The rest - full-preparation facilities - provided mechanical cleaning (the separation of clean coal from refuse and impurities such as pyritic sulfur and ash) as well as crushing and sizing. In the future, coal-cleaning technology may require greater attention as a method of controlling air pollution emissions.

Between 1942 and 1965, the fraction of raw coal that was mechanically cleaned and classified rose from 25% to 65%. The reason: increasing sophistication of coal usage (i.e., blending for coking, efficient steam generation, etc.) as well as increased use of continuous-mining machines. Recently, however, production from surface mines, which typically produce a more uniform product, has resulted in the fraction of total coal production that is mechanically cleaned dropping below 50%. The ratio of mechanically cleaned coal to total production will probably remain around 50% for some time. Therefore, an anticipated increase in coal production will require a corresponding increase in preparation-plant capacity. Additional capacity for chemical cleaning of coal is also likely.

Equipment used in coal cleaning differs little from that used 10 or 20 years ago, and, though newer cleaning methods will continue to evolve, no new noise sources are anticipated.

Coal Preparation Plants: Current

Basic equipment in present preparation plants includes conveyors, feeders, crushers, screens, and chutes. Plants that receive raw coal via rail have unloading mechanisms such as vibratory shakeouts, rotary dumps, etc.

Full-process plants performing actual cleaning of coal contain equipment to separate refuse from clean coal. Their design is based on the principle that such refuse has a higher or lower specific gravity than the desired clean coal. Separators include washers, concentrating tables, cyclones, and dry concentrators. Some plants also contain flotation cells, which use chemical depressants to separate ash and pyritic sulfur from the coal.

In addition to crushing, sizing, and cleaning equipment, preparation plants relying on wet processing typically contain equipment to remove excess water from the clean coal. This dewatering and drying equipment includes vibrating screens, centrifugal dryers, thermal dryers, thickeners, and vacuum filters (disc).

Coal-preparation equipment is listed in Table 5.6, along with the noise levels typically measured alongside the equipment. The noise generated by the majority of this equipment is usually confined to the interior or working areas of the plant. As a result it is most likely to affect plant workers. Thus, it is regulated by the Mining Enforcement and Safety Administration and benefits from the noise-control research sponsored by the Bureau of Mines.

In some cases, however, equipment may not be located within the confines of a plant's walls, or the noise generated by the equipment may radiate from building openings to the area surrounding the plant. Primary examples are:

TABLE 5.6. REPRESENTATIVE COAL-PREPARATION-PLANT EQUIPMENT AND ASSOCIATED NOISE LEVELS [5.9].

Equipment Type	Typical Noise Level* [dB(A)]
Material Handling	
1. Conveyors (drive units)	90 - 95
Flighted Belt	85 - 95
Belt	75 - 85
2. Vibrating Feeders	90 - 100
3. Crushers	90 - 100
4. Screens	
Shaking	95 - 100
Vibrating	95 - 105
5. Rail Car Unloading	
Rotary Dumps	85 [†]
Mechanical Vibration	105 [†]
6. Chutes	85 - 95
Cleaning Equipment	
1. Washers	
Dense Medium	95 - 90
Jigs	90 - 100
2. Concentrating Tables	82 - 87
3. Cyclones	80 - 90
Drying Equipment	
1. Centrifugal Dryers	95 - 100
2. Cyclones	82 - 87
3. Dewatering Screens	92 - 97
4. Thermal Dryers	85 - 95
5. Vacuum Disc Filters	85 - 90
Miscellaneous Equipment	
1. Vacuum Pumps	95
2. Roots Blowers	95 - 100
3. Fans	90 - 100
4. Gear Drives	90 - 95

*At nearest worker locations, typically 3--15-ft.

†At opening to building.

- . Rail car shakers, which are typically located outside the main plant,
- . Fan and blower exhausts, which are ducted out of the plant,
- . Equipment located in open or semiopen structures.

In these cases, the noise generated by the equipment can affect adjacent land areas. This radiation would ordinarily indicate a potential for community noise problems (considering the sound levels listed in Table 5.6). However, full-process preparation plants usually require large land areas for stockpiling, wastewater processing, etc., which tend to act as buffers between the plants and adjacent communities.

On the other hand, smaller crushing, sizing, and loading facilities, which do not require such large land areas, can be located relatively close to residential communities. In addition, it is common for these small facilities to use open structures. At this time, the impact of the noise of coal-preparation plants on residential areas and wildlife is dealt with by compliance with local noise ordinances, if any.

Coal-Preparation Plants: Future Developments

Following are brief descriptions of new developments in coal preparation that may receive increasing attention in the near future. Table 5.7 presents the technologies considered, together with their current status and expected future utilization.

a. Chemical coal cleaning (benefication). Several methods of chemical cleaning of coal are currently under development. A list of some of the more promising projects is given in Table 5.8. Such processes are based on chemical reactions that render the undesirable waste material, primarily sulfur, soluble, and thus

TABLE 5.7. FUTURE COAL-PREPARATION TECHNOLOGIES [5.10].

Technology	Present Stage of Development	Date or Expected Date of 1st U.S. Operatnl Facility	Estimated Use in U.S. ... Now → year 2000
1. Two-stage froth flotation/pyrite flotation	Near Commercial	1977	0 High
2. Portable preparation plants	Commercial	1977	<1% High
3. FMC dry table concept	Prototype	1977	0 High
4. Otisca process	Pilot Plant	1977	0 NA
5. Chemical beneficiation	Pilot Plant	1977	0 NA

TABLE 5.8. DEVELOPMENT STATUS OF CHEMICAL CLEANING PROCESSES.

Process	Treatment	% Sulfur Removal		Development Status
		Pyritic	Organic	
1. Magnex	$\text{Fe}(\text{CO}_5)/\text{Magnetic}$	0-90+	0	1TPD pilot units
2. KVB	$\text{NO}_x/\text{H}_2\text{O}/\text{NaOH}$	0-90+	0-40	Preliminary bench-scale
3. Battelle	$\text{NaOH}/\text{Ca}(\text{OH})_2/\text{H}_2\text{O}$	0-90+	0-70	Small Pilot Unit
4. Meyers	$\text{Fe}(\text{SO}_4)_3/\text{H}_2\text{O}/\text{O}_2/\text{Naphtha}$	0-90+	0	8 TPD Pilot Plants
5. Ledgemont	$\text{O}_2/\text{H}_2\text{O}$	0-90+	0	Bench Scale
	$\text{O}_2/\text{H}_2\text{O}/\text{NH}_3$	0-90+	0-25	Bench Scale
6. Bureau of Mines/ ERDA	$\text{Air}/\text{H}_2\text{O}$	0-90+	0-40	1-4 lb/hr pilot unit
7. Ames	$\text{Air or O}_2/\text{H}_2\text{O}/\text{Na}_2\text{CO}_3$	0-90+	0-25+	Bench Scale
8. Chlorinolysis	$\text{Cl}_2/\text{H}_2\text{O}$	0-90+	0-70	Preliminary bench-scale
9. Mixed Leachant (Soviet Union)	$\text{Fe}_2(\text{SO}_4)_3/\text{HNO}_3$	0-90+	?	5-10 TPD Pilot Plant

make the extraction of clean coal feasible. Large-scale commercial use of these processes is estimated to be 5 to 10 years away. The noise properties of the chemical cleaning processes are not expected to be serious.

b. Two-stage pyrite flotation. This process separates ash and pyritic sulfur from fine coal in two distinct stages. The equipment involved is expected to be similar to commercially available flotation equipment. This equipment would be located within the plant and would thus affect primarily the plant workers. Past experience has indicated that flotation cells are not a major source of noise.

c. Portable preparation plants. These are relatively small preparation plants, packaged in modular, open-steel frame boxes, which are delivered and erected in a matter of days at the site. These plants typically include:

- . Crushers
- . Screens
- . Washers and/or Cyclones
- . Centrifuges
- . Miscellaneous pumps, motors, etc.

Since these facilities use commercially available equipment, the noise levels should be comparable to those listed in Table 5.6. Their open framework and minimal land requirements pose a greater potential for causing environmental noise problems. The growth in their use, such as at industrial facilities converting to coal, is expected to be rapid in the near term because of their low cost and simplicity.

d. Dry table concept. This is a method of separating clean coal from refuse, using the difference in specific gravities without using water or other liquid media [5.11]. The separation

is accomplished by vibration and is "particularly applicable as an economic rougher for removing high-ash materials from Western coal." This equipment may be practical for use in smaller, open preparation facilities. The sound levels for this equipment should be comparable to those listed in Table 5.6 for vibrating feeders.

e. Otisca Process. The otisca process is a new liquid-based mechanical separation process that offers operational advantages over other such processes that have been in use for many years. It is not expected to have any unique noise characteristics.

5.1.3 Coal transportation technologies

The transportation of coal from the mine to the ultimate fuel user involves a variety of transportation equipment and will probably provide the single largest noise impact of increasing coal production. In many cases, the coal may be carried by several types of transportation equipment between the mine and its final destination. The primary modes of transportation currently in use are:

- . Railroads
- . Trucks
- . Conveyors
- . Barges
- . Slurry Pipelines.

Equipment used to transfer coal from one transportation mode to another, or into and out of interim storage, is also considered coal transportation.

With the anticipated growth in the demand for energy from coal, the transportation capacity in this country will have to expand significantly. At present, according to a recent U.S.

Bureau of Mines study [5.12], rail movements account for 49% of all coal shipments. Waterborne transport (including river, lake and tidal routes) is the second largest carrier of coal (26%). Trucks and conveyors account for 12% and 8%, respectively. The same report estimates that while train traffic should increase rapidly with the expanded use of unit trains, the present relationship between the various modes of transportation will remain roughly the same into the 1980's.

The transportation of coal through pipelines is an idea that originated in the late 1800's. However, its role as a major transportation medium has been quite limited. Until recently, interest concentrated on slurry pipelines, which use water as the medium to carry finely crushed coal. Pipelines designed to carry coarse coal, while not commercially in use, are the subject of recent investigations.

Table 5.9 summarizes the various modes of transportation, together with some of their characteristics, government agencies involved with noise regulations, current usage, and anticipated growth.

The noise and vibration from trains can affect residential and wildlife areas along the rail line as well as the railroad workers themselves. EPA has a mandate to regulate noise from trains under PL 92-774 (see Sec. 7.2.2). A recent BBN study measured the peak noise levels of train passbys for a variety of locomotives and passby speeds. The mean A-weighted sound level at 100 feet was 91.7 dB(A) with a standard deviation of 3.2 dB.

A study of the impact of coal trains on Colorado communities indicated that 14 to 21 two-way trains will run daily through Colorado from Montana and Wyoming by 1985. This represents a 700% increase over current train traffic in the study area. In addi-

TABLE 5.9. COAL TRANSPORTATION TECHNOLOGY.

Mode	Affected Population	Federal Agency Currently Regulating Noise	Current Usage	Anticipated Growth
Rail • On Site • Long Haul	Rail Workers Residential Wildlife	Dot EPA	Commercial	High
Off-road Trucks	Drivers Mine Workers Wildlife	USBOM } * MESA	Commercial	As Coal
Highway Trucks	Drivers Residential Wildlife	DOT EPA	Commercial	As Coal
Conveyors	Mine Workers Wildlife	USBOM } * MESA	Commercial & Development	High in Surface Operations
Inland Water	Workers Residential Wildlife	-	Commercial	As Coal
Tide Water	Workers	-	Commercial	Uncertain
Slurry Pipelines	Workers Residential Wildlife	USBOM } * MESA	Limited Commercial	Uncertain
Coarse Coal Pipelines	Workers Residential Wildlife	-	Experimental	Uncertain
Transfer Equipment	Workers Residential Wildlife	USBOM } * MESA	Commercial	As Coal

*Regulation is applicable to occupational exposures only.

tion to the increase in the number of trains and distances covered as new coal areas are developed on existing rail lines, new lines connecting the coal supply and use areas of the country will be needed to meet the anticipated demand. The most dramatic increase is expected to be west of the Mississippi, where large amounts of coal from Western mines will be transported to new users in the South and Southwest.

On a national scale, the increase in rail coal haulage can be summarized as follows [5.1]:

Annual number of carloads shipped	7.4×10^6	$15.3 - 18.6 \times 10^6$
Average carload distance traveled	230 $\frac{\text{miles}}{\text{carload}}$	430-600 $\frac{\text{miles}}{\text{carload}}$

The noise of heavy trucks, which can affect the public as well as workers and wildlife, is composed of engine/exhaust noise at low speed and a combination of engine/exhaust and tire noise at higher speeds. A recent BBN study measured the passby sound level for a population of 384 trucks. The results of tests, which focused on engine exhaust noise, indicated that the mean sound level at 50 feet was 84.7 dB(A). Tire noise at 50 mph can range from 71 to 87 dB(A) at 50 feet, depending upon the tire type, conditions, loads, etc. Noise from new trucks and interstate motor carriers is regulated by the Department of Transportation and the Environmental Protection Agency, and DOT sponsors considerable noise-control research in this area.

Until recently, because of limited commercial use of conveyors, there have been few studies of their noise-generating characteristics. New interest in the development of extensible conveyors (i.e., those with the ability to expand and move with mining operations) may in the future result in such studies by

the U.S. Bureau of Mines or by the Mining Enforcement and Safety Administration (MESA). However, these agencies have historically been concerned only with the effect of such equipment noise on occupational hearing loss of mine workers, and not on the effects on wildlife or nearby communities.

Of the total waterborne coal transportation, river shipments accounted for 69%, Great Lake shipments, 27%, and tidal shipments, 4%. Because of the low cost of such waterborne transport, traffic should increase with the increase in coal production.

River tow boats are typically powered by locomotive-type diesel engines, and these can be sources of substantial noise. Sound levels to which the crew are exposed in the interior spaces of these boats can reach 95 to 100 dB(A) in forward cabin areas. It is difficult to estimate what effect the noise of these boats has on shoreline residential or wildlife areas. However, estimates based on measurements made by BBN indicate that such boats can generate 65 to 70 dB(A) at a distance of 100 yards.

At this time, the noise of these boats is not under the specific jurisdiction of any agency of the Federal government, though both the Department of Labor and the Coast Guard are investigating it.

Of the two types of pipelines mentioned previously - slurry and coarse coal -- only slurry pipelines are presently in use. The basic components of such pipelines are a water supply system, a slurry preparation plant, the pipeline itself, pumping stations, and a dewatering/drying station. Although there is only one slurry pipeline presently in service in the U.S., and no sound level data are available from it, many of the components mentioned above contain equipment similar to that used in other facilities. The noise generated by these components should there-

fore be comparable. Noise from the water supply will be caused by the pumps, which will probably be enclosed in a building. The slurry preparation plant contains much of the same equipment used in coal preparation plants (see Sec. 5.1.2). The pipeline itself should not be a major problem with respect to noise; however, the pumping stations would contain relatively large motor-driven pumps that generate substantial noise. The dewatering and drying station would contain the drying equipment, similar to that in large coal-preparation plants, and would probably also be located within a building.

The major noise-generating components of a slurry pipeline are all enclosed in some type of building, and the noise impact on nearby communities and wildlife will depend on the type of building used.

As of 1975, there were four coal-slurry pipelines in the planning stages, the longest being over 1000 miles. The construction of these pipelines is dependent on the acquisition of extensive rights of way and is therefore uncertain. If such systems become major coal carriers, various Federal agencies presently have the authority to regulate noise exposure of pipeline workers.

Coarse coal piping is presently in the experimental stages. The advantages of this system are that the coal need not be finely crushed before entering the pipeline. The future of these systems is uncertain because of the difficulties in developing efficient pumps to handle coarse coal.

The "transfer equipment" listing in Table 5.9 is a catchall category for the equipment used to transfer coal from one mode of transport to another or to and from stock piles. The typical equipment involved consists of car dumpers or shakers, bull-

dozers, stacker-reclaimers, conveyors, hoppers, and occasionally crushers. For the most part, the noise of these transfer points is dominated by that from the transportation vehicles or the car shakers.

The use of this equipment is common throughout the country and is expected to grow with the opening of new mines, transportation facilities, preparation plants, and utilization facilities.

In general, none of the coal transportation modes involves unique or intractable noise problems. All known problems are amenable to conventional noise-control techniques, where required. Both occupational noise exposure and, for the major transportation modes, community noise exposures are regulated by various Federal agencies. The reader should appreciate, though, that coal transportation will produce the largest noise impact of all of the activities associated with increased coal production, in terms of the number of people affected.

5.1.4 Coal utilization technologies

At present, there are two major coal utilization technologies: coal liquefaction and coal gasification. (Direct combustion is discussed in Sec. 5.1.5). Table 5.10 lists these technologies, their current state of development, and their expected future use.

5.1.4.1 Coal gasification

An alternative to the direct combustion of solid coal is the conversion of coal to a gaseous state. At present, numerous processes for producing gaseous fuels from solid coal are being

TABLE 5.10. COAL UTILIZATION TECHNOLOGIES.

Technology		Present Stage of Development	For Deep (D) &/or Surface (S) Mining	Estimated Use in U.S. Now → year 2000	
3.	Coal Gasification (many processes)	Pilot Plant		0	NA
4.	Coal Liquification (many processes)	Pilot Plant		0	NA
5.	<i>In Situ</i> Coal Gasification	Pilot Experiments	(D)	0	NA
6.	<i>In Situ</i> Coal Liquefaction	Research	(D)	0	NA

studied (see Table 5.11). Which of these processes are commercially viable depends on the results of pilot and demonstration plant experiments, and the extent of their commercial use will depend on the economics of energy production over the next 10 to 15 years. Thus, it is impossible to forecast which process or processes will be successful. However, it is possible to make some generalization which will allow the gasification techniques to be discussed as a common technology, at least in terms of noise.

Gaseous fuels with low and intermediate energy content (100 to 200 Btu/cf and 300-650 Btu/cf, respectively) are typically produced by a two-stage process involving coal preparation followed by chemical transformation. High-energy gas (900 to 1000 Btu/cf) is generally the result of upgrading lower-energy gas (see Fig. 5.2).

The amount and type of coal preparation (and, therefore, preparation equipment) depend on the requirements of the specific gasification process involved, but usually include equipment to size, crush, handle, and store the coal, either at the gasification unit itself or at independent preparation plants. Thus, much of the information known about the noise of preparation plants also applies here (see Sec. 5.1.2), and the same noise-control technologies are applicable.

As mentioned above, many different gasification processes are under investigation. No published data on the noise levels of these processes have been uncovered. In terms of the actual operating equipment, and, hence, noise-generating mechanisms, some similarities are likely to exist. For the most part, gasification centers around some type of reactor in which the coal is mixed with various ingredients (oxygen, hydrogen, water, etc.) and heated to form the desired gas. Auxiliary equipment may

TABLE 5.11. PRINCIPAL COAL GASIFICATION TECHNIQUES UNDER INVESTIGATION [5.13].

1. Hygas Process
2. CO₂ Acceptor Process
3. Bi-Gas Process
4. Synthane Process
5. Lurgi with Methanation
6. Lurgi without Methanation
7. Koppers-Totzbek
8. Winkler Gasifier
9. Wellman-Galusha
10. Hydrane Process
11. Atgas Process
12. Molten Salt or Molten Carbonate
13. Union Carbide-Battelle Process
14. Garrett Process
15. COED Process
16. Exxon Catalytic Coal Gasification Process
17. Fixed-Bed Gasification, Stirred Process
18. Fluidized-Bed Gasification (Two-Stage Pressurized)
19. Entrained-Bed Gasification
20. Hydrogen from Coal

FIG. 5.2. SUMMARY OF PROCESSES FOR PRODUCING GAS FROM COAL.

include burners, pumps, motors, fluid piping and valves, fans, etc. Much of this equipment is standard in present-day refineries and chemical process plants. As such, the noise associated with the gasification process should be comparable to that of similarly sized chemical process plants. Table 5.12 lists some of the common equipment in these plants, together with typical sound levels.

TABLE 5.12. SOUND LEVELS OF PROCESS-PLANT EQUIPMENT [5.14]

Equipment	Sound Level in dB(A) at 3 feet
Heaters and Furnaces	95 - 110
Pressure Reducing Valves	<80 - 105
General Gas Pipelines	90 - 105
Electric Motors	90 - 110
Compressors	90 - 120
Air Coolers	87 - 94
Flare	70 at 2000 ft

Process-plant noise is conventionally analyzed and controlled to protect plant workers and, where indicated, to minimize community noise complaints. Because of the many hundreds of noise sources involved and the complex distribution of these sources, noise-control analyses of process plants can be quite involved. BBN and several other organizations maintain computer programs to facilitate this analysis.

Upgrading the gas produced by the initial gasification stage involves shift conversion, purification, and methanation. These processes, which increase the energy content of the gas, also take place in a reactor and require an assortment of process equipment.

An alternative to in-plant gasification is gasification of a coal bed in the ground without mining. This process, called in-situ coal gasification, is presently in the experimental stages. Briefly, the process involves drilling holes into a coal bed for air injection, and fracturing, and other holes to remove the low-Btu gas which is formed when the coal bed is ignited. Ground water may participate in the process. While recent experiments have demonstrated the capability of obtaining relatively constant gas production, some major engineering problems still must be solved before the process can be considered commercially viable.

While no specific noise data are currently available, it would be reasonable to assume that the noise generated by this process can be attributed to the drills used during the development phase and to the compressors, valves, and plumbing operated during the production phase. The noise from the drills should be comparable to that generated by overburden drills used in surface mining and by oil drilling rigs and compressions for fracturing [85 to 95 dB(A) at operators' positions]. The noise during the production phase would be comparable to that indicated for such sources in Table 5.12.

5.1.4.2 Coal liquefaction

Coal liquefaction is a general term for the group of chemical processes which transform solid coal into a liquid fuel. While many liquefaction techniques are being investigated (see

Table 5.13), they are typically based on increasing the carbon-to-hydrogen ratio in the fuel by one of three processes:

Hydrogenation - in which hydrogen is chemically combined with the carbon in the coal.

Pyrolysis - in which the coal is heated in the absence of an oxidizer to produce a liquid hydrocarbon.

Catalytic Conversion - in which an intermediate gas is produced out of which the hydrogen and carbon monoxide are combined to form the liquid fuel.

These three processes are illustrated in Fig. 5.3.

No published data have been found on the noise levels of coal liquefaction processes. In general, however, the comments regarding the noise source characteristics of the coal gasification processes can be made for coal liquefaction processes. That is, the majority of the equipment used is similar to current chemical-process-plant equipment and will generate comparable noise levels.

In-situ coal liquefaction involves liquefying coal without its removal from the ground. This process is in the earliest stages of consideration, but it is probable that it will involve the same noise sources, and thus produce noise levels comparable to in-situ coal gasification and secondary/tertiary oil recovery.

5.1.5 Direct combustion of coal and other fuels

5.1.5.1 Conventional combustion

The direct combustion of coal and other fuels is a mature technology, the noise properties of which are well known. Typical noise sources include:

TABLE 5.13: PRINCIPAL COAL LIQUIFACTION TECHNIQUES [5.13].

1. COED Process	
2. Solvent-Refined Coal Process	
3. H-Coal Process	
4. Consolidation Synthetic Fuel	
5. Burgius Process	
6. COG Refining	
7. Union Carbide Process	
8. Synthoil Process	
9. Disposable-Catalyst Hydrogenation	
10. Lummus Multistage Process	
11. Solvent-Extraction of Liquids	
12. C-O Steam Process	
13. Clean Metallurgical Coke/Liquid Process	
14. Flash Liquefaction Process	
15. Occidental Research Corp. (ORC Process)	
16. Hydrocarbonization	
17. Fluid-Coke Process	
18. Indirect Liquefaction	
19. Donor-Solvent Process	

FIG. 5.3. PRINCIPAL COAL LIQUEFACTION REACTIONS AND PROCESSES.

- . coal-handling machinery (stacker reclaimers, bulldozers, conveyors, car shakers, crushers) (see Sec. 5.1.2)
- . Burners
- . Boiler draft fans
- . Pumps for condensate, boiler feed water, condenser cooling water, etc.,
- . steam valves and piping
- . Percipitator rappers
- . Safety valves
- . Ash-handling equipment
- . Cooling towers or spray ponds
- . Other auxiliary equipment.

At electric generating stations, other sources are:

- . Turbine generators
- . Transformers
- . Circuit breakers
- . Electric corona (if EHV/UHV transmission. See Sec. 5.5.3)

Data on these noise sources are reported extensively in the literature, and conventional noise-control techniques are usually available [5.15]. It is useful here to single out a few particular areas that may be of interest to DoE with respect to the developing energy technologies.

Fuels conversion

In general, retrofit of an existing boiler to convert from the combustion of gas or oil to the combustion of coal will result in an increased noise level because of the noise associated with coal and ash handling, and with air pollution control equipment.

Cooling towers

When cooling towers are installed at large, carefully designed steam-electric generating stations, they usually are the dominant noise source affecting the surrounding community. Thus, they set the limit for compliance with applicable community noise ordinances. Conventional noise-control treatment of cooling towers is exorbitantly expensive because of their large size. Yet it is not at all clear that such noise control, when required by local law, is really necessary to avoid community annoyance.

Transformers

Transformers, at substations as well as electric power plants, are a familiar community noise source. We note that DoE is supporting research in this area [5.16].

Boiler draft fans

Forced- and induced-draft fans are used on all large, modern fossil-fueled boilers. At typical electric generating stations in the 600- to 800-MWe size range, total draft-fan requirements can exceed 20,000 horsepower. With these very large fans, boiler owners are experiencing increased vibration and associated structural failure, increased noise, and reduced fan efficiencies. A recent U.S. study, for example, indicates that induced-draft fans are the single most common source of community noise complaints at fossil-fueled generating stations [5.17]. This noise problem is often most severe when the fan flow is reduced for low-load operation, the same operating condition at which the fan efficiency is lowest. Table 5.14, from Ref. 5.17, illustrates the problem. Often, fan noise is audible at locations as distant as 3 miles from the boiler. In some cases, legal action has been taken against the boiler owner.

TABLE 5.14. DATA ON SOUND LEVELS PRODUCING COMPLAINTS IN COMMUNITIES NEAR POWER PLANTS [5.17].

Power Plant	Sound Level in dB(A) at Complaint Location	Source of Noise	Distance from Noise Source
A-1	58	Induced draft fans	1500 ft
A-2	58	Induced draft fans	1500
B	65	Induced draft fans	500
C-1	64	Induced draft fans	2200
C-2	56	Induced draft fans	5500
D	49	Induced draft fans	2000
E-1	59	Induced draft fans	600
E-2	52	Induced draft fans	2200
F	47	Induced draft fans	600
G-1	77	Induced draft fans	300
G-2	53	Induced draft fans	3000
H	55	Induced draft fans	2000
I-1	62	Induced draft fans	600
I-2	48	Induced draft fans	2200
J	43	Induced draft fans	2500
K-1	60	Forced draft fan	500
K-2	50	Forced draft fan	1300
L (Nuclear)	36	Transformer, vent fans	10,000
M (Nuclear)	41	Transformer	5500
N	50	Transformer, and F.D. fan system	600
O	44	F.D. fans, transformers, air compressor	2500

TABLE 5.14. (Cont.)

Power Plant	Sound Level in dB(A) at Complaint Location	Source of Noise	Distance from Noise Source
P	57	F.D. fans, precipitator, air compressor	600 ft
Q	46	F.D. fans, deairator vents	1500
R	73	Coal car shaker	600
S	56	Fans, pumps, piping and valves	1000
T	58	Steam valve venting	15,000
U	43	Circulating pump motors	4500
V	45	Circulating pump	4000
W	56	Coal-car shaker	2000
X	60	Loudspeaker paging system	600

The repeated occurrence of this problem even at the most modern boiler installations is a serious situation that plant designers have, apparently, been unable to solve. Within the last five years, this noise and vibration problem has come to BBN's attention at 10 new fossil-fueled electric generating stations designed by a variety of organizations (see Table 5.15). There are probably many other instances of which we are unaware. Retrofit installation of mufflers and structural reinforcing of breeching is the conventional means of reducing the noise and curing the symptom, if not the fundamental problem. A reduction in system efficiency is incurred, however, because of the aerodynamic pressure loss across the muffler.

Fan-inlet, damper, and duct design are known to be important parameters affecting both energy usage and noise generation in boiler draft systems. Fan designers and boiler designers must interface at this boundary. It has been our experience that poorly designed fan/duct systems have resulted from inadequate mutual understanding of this interface.

5.1.5.2 Developing technologies

Fluidized-bed boilers

Fluidized-bed boilers, in which the fuel is supported in a vertical flow of combustion air, are receiving considerable attention from DoE and others. A 30-MWe pilot plant supported by DoE is operating in West Virginia. Fluidized-bed boilers are attractive because their relatively small size, compared to conventional boilers, promises lower costs and higher efficiencies. They also have certain advantages for the control of air pollution. No published data have been found on the noise levels of fluidized-bed boilers. It is anticipated, however, that noise will be produced by draft fans or - for pressurized fluidized-bed

TABLE 5.15. NEW (since 1972) ELECTRIC GENERATING STATIONS AT WHICH BOILER DRAFT-FAN NOISE HAS RESULTED IN SERIOUS COMMUNITY NOISE PROBLEMS, STATION DOWN-TIME AND OPERATING INEFFICIENCIES.

Location	Size, MWe
Northeast	600
Northeast	375
Northeast	550
Northeast	600
Northeast	200
Northeast	200
Northeast	550
Mid-Atlantic	700
North Central	700
Rocky Mountain	700

boilers - by air compressors. The noise levels are probably predictable on this basis.

Combined-cycle plants

In combined-cycle plants, the hot exhaust flow of a combustion turbine is used to produce steam, thus increasing the plant efficiency over that obtainable with the turbine alone. From a noise point of view (although no published data are available), it is expected that such plants could be quieter than conventional combustion turbines. The steam boiler would tend to reduce the turbine exhaust noise.

Magnetohydrodynamic generators

Magnetohydrodynamic (MHD) generators produce electricity by forcing on ionized gas through a magnetic field. The ionized gas is produced by fuel combustion. MHD generators offer the promise of greater generating efficiency by avoiding the theoretical limitations of the Carnot cycle. However, they are still very much in the development stage. It is expected that the noise sources of the combustion portion of MHD generators will be similar to those with conventional combustion (i.e., fans).

5.1.6 Waste disposal and surface-mine reclamation

The noise associated with solid-waste disposal from coal utilization and with the reclamation of surface coal mines will generally be that usually associated with transportation and with earth-moving equipment. These are conventional noise sources that, to an increasing extent, are coming under Federal regulation.

Typical noise levels for transportation equipment are given in Sec. 5.1.3. Limits for occupational noise exposure have been established by the Department of Labor (OSHA or MESA, as applicable). Limits for sideline (community) noise exposure are being regulated by DOT and EPA.

Representative noise levels observed at 50 feet from earth-moving equipment are given in Fig. 5.4. Sideline noise radiation by this type of equipment, classed as construction equipment, is increasingly being regulated by the EPA.

In surface-mine reclamation, there is a tendency toward larger bulldozers and also to side-by-side dozer configurations, where one blade is powered by two dozers. The latter increases dozer noise by 3 to 6 dB(A) relative to a single machine.

5.2 Oil Shale Technologies

Oil shale is a sedimentary rock containing a solid organic material called kerogen. When heated, the kerogen is released from the shale in the form of gas and heavy oil. The oil can then be upgraded to synthetic crude for conventional refining.

Shale oil has long been recognized as a potential source of energy in the United States. Until recently, the availability of inexpensive crude oil stalled development of this resource. Widespread commercial development of shale oil depends more on economic considerations than on the invention of new technological processes.

Approximately 90% of the nation's identified oil shale resources are found in a single geological formation, known as the Green River Formation, located in eastern Utah, western

FIG. 5.4. REPRESENTATIVE NOISE LEVELS, IN dB(A), OF SOUND AT 50 FT FROM EARTH-MOVING EQUIPMENT [5.18].

Colorado, and southwestern Wyoming. Although the U.S. Geological Survey estimates that U.S. deposits contain over two trillion barrels of oil, only a very small portion of these are regarded as economically recoverable. Estimates of the economically recoverable amounts range from a low of 80 billion barrels to a high of 418 billion barrels. Even if the lower estimate is correct, oil shale reserves contain more energy than that combined in the nation's reserves of oil and natural gas.

5.2.1 Mining and crushing

Shale deposits vary greatly in terms of oil yields per ton (high-grade deposits average 30 or more gallons per ton), and seam or zone thickness and depth. Techniques being tested for mining are roughly similar to those used in coal mining, although shale is a good deal harder than coal and the seam thicknesses can be much greater [5.19]. To date, only underground mining of shale has been tried. However, it is expected that surface mining will be attempted on some tracts [5.20]. Literature describing in-use and experimental mining and preparation techniques for oil-shale mentions only one piece of equipment, the gyratory crusher, which is not used in conventional coal development [5.19]. (Noise aspects of equipment used in coal development have been discussed earlier in this report. See Secs. 5.1.1 and 5.1.2.). Noise from gyratory crushers has been measured at from 98 to 106 dB(A) at a distance of 3 feet [5.21]. Work on quieting this type of crusher (for the taconite industry) is currently being performed by several groups under sponsorship of the Bureau of Mines.

Since shale-oil mine sites are almost always located far from populated areas, mine and process workers are the only impacted individuals.

Because shale is processed on or close to the mine site, long-haul transportation equipment, including the use of railroads, is not required.

5.2.2 Retorting

Oil shale process equipment consists of surface retorts and upgrading facilities. In each of the retort processes currently under study, crushed shale enters the system, is heated to release oil and gas, and leaves the system as spent shale. Noise associated with retorting emanates principally from rock movement, heating, and the pumping of oil. Noise levels of surface-retorting facilities should be very similar to that from coal gasification and liquefaction plants (see Sec. 5.1.4).

It is also considered feasible to retort oil-shale in situ and to extract only the oil from the ground [5.22]. This would require drilling, reducing to rubble a portion of the shale - presumably with explosives - and maintaining controlled combustion in the rubble-filled cavern to provide heat to release the oil. Except for blasting, noise sources associated with such an operation would be conventional and similar to those encountered with in-situ gasification and enhanced petroleum recovery (see Secs. 5.1.4 and 5.4). Methods for the assessment of ground shock from underground blasting are also available [5.23].

5.2.3 Waste disposal

The volume of solid waste resulting from the surface retorting of oil shale is reportedly greater than the volume of shale processed. Nevertheless, the noise associated with disposing of this waste in surface landfills should be no different than that associated with disposing of coal wastes (Sec. 5.1.7).

5.3 Tar Sand Technologies

Tar sands are deposits of porous rock or sediment containing viscous hydrocarbon oils. When processed, the tar or bitumen is released from the rock and upgraded to a product resembling crude oil.

Significant deposits of tar sands were first identified in North America in the late 1800's. Although commercial ventures have been launched to develop the vast Athabasca deposits in Canada, no commercial development has taken place in the United States. It may be between 15 and 30 years, according to Department of the Interior estimates, before it becomes economically feasible to begin recovery of U.S. deposits.

Over 500 tar sand deposits have been identified in 22 states, but only five states, California, Kentucky, New Mexico, Texas, and Utah, have deposits of more than a million barrels. The largest deposits in the U.S. are located in Utah. The Bureau of Mines estimates that from 2.5 to 5.5 billion barrels of oil are potentially recoverable from all U.S. deposits.

Tar sands vary in terms of bitumen content, seam thickness and depth, and sulfur content. U.S. deposits range in bitumen content between 9 and 16% of total weight. Rich deposits with a bitumen content of 14% or more yield approximately 1 barrel of oil per 1-1/2 tons of tar sand. The development of tar sand deposits would be similar to oil shale development, except that the material to be handled is softer. The sands can either be mined and then processed on the surface, or in-situ techniques can be used to release the bitumen underground and pump it to the surface. As in the cases of coal and oil shale, tar sands can be mined from the surface or underground.

Equipment very similar to that used in the mining and processing of coal and oil shale will probably be used for tar sand development. (For a discussion of the noise aspects of this equipment, see Secs. 5.1 and 5.2 of this report.)

Several methods have been used and suggested for use in recovering the bitumen from the mined tar sand [5.24]. The methods involve mixing and/or heating the bitumen with various solvents, or heating the bitumen alone in a pyrolysis reactor. Noise from the various methods emanates from material movement, furnaces, centrifuges, and pumps; again, a process-plant-type noise source.

5.4 Oil and Gas

The oil and gas development technologies are mature technologies. The noise sources associated with these technologies are well known, and noise-control techniques for these sources are available. Indeed, it is characteristic of that industry - noted for its innovativeness - that it was solving noise problems before many other industrial areas had even encountered them. For instance, quieted oil-drilling and production equipment has been operating in residential areas of such places as Los Angeles and Oklahoma City for decades.

The industry and DoE are presently developing several technologies that may increase oil and gas recovery from existing fields or permit the development of new fields [5.25]. The more important of these developing technologies are discussed below.

5.4.1 Advanced fracturing [5.26, 5.27]

Hydraulic fracturing* is a technique designed to allow

* Explosive fracturing is discussed in Sec. 5.4.4.

production from oil or gas formations in highly compacted sand. Variations of the technique have been in use for some years, and improvements are under development. In general, fluid at very high pressures is injected into the compacted sand formation. The injected fluid creates cracks and fissures in the compacted sand that may propagate as far as a mile from the injection site. The voids are filled with coarse sand or other propping materials injected through the same well, so that cracks in the compacted sand are kept open and the petroleum or gas can flow through the fissures to production wells (which may be the original injection well).

No published data on the sound levels of these operations are known, but good estimates could probably be made on the basis of equipment types and ratings. The noise sources associated with hydraulic fracturing involve large high-pressure fluid pumps, gears, diesel engines, gas turbines, large aggregate pumps, motors, production compressors, control valves and piping systems, vents, and flares. The resulting sound levels are somewhat greater than typical of well-head operations, because of the high-powered machinery involved. Available noise-control methods include inline silencers, quiet valves, and standard machinery enclosures, as well as specially designed quiet equipment. Retrofit noise control methods are also available, but they are usually application-limited by existing hardware. These methods include acoustical shrouds and barriers, custom enclosures, and lagging of piping and valves.

Noise control for hydraulic-fracturing equipment is sufficient to protect development workers from excessive occupational noise exposure and to minimize noise in adjacent communities, where necessary. There is no reason to believe that advanced fracturing methods which may come into use in the future will produce significantly more noise than present fracturing

methods. Thus, present noise-control techniques should be adequate.

5.4.2 Secondary/tertiary recovery

Secondary and tertiary recovery methods consist of a variety of techniques to increase the extraction of oil from underground formations from the present limit of roughly 30% of oil-in-place to 69 to 90% [5.28]. Many such enhanced-recovery methods have been investigated in the laboratory and under field conditions. Three general categories have received particular attention [5.27, 5.29]:

- . Fluid-injection methods. Fluids are injected into oil-producing sands to force the crude oil toward producing wells. Micellar fluids, surfactants, and polymers, mixed with water, are used as flooding agents in this category.
- . Thermal recovery methods. As the name implies, heat is introduced into the underground reservoir to make the crude less viscous. Steam or hot-water injection, in-situ combustion supported by air pumped from above, and wellbore heating have been used.
- . Miscible-fluid displacement. Gaseous or liquid hydrocarbons or carbon dioxide are injected to dissolve or reduce the viscosity of the crude.

The particular method used in any given situation depends upon the geological formation, properties of the crude, available surface facilities, and economics.

The noise sources associated with enhanced-recovery methods are conventional. They include boilers (for some thermal methods), water treatment facilities, specially drilled injection wells in some cases, pumps, diesel engines, motors, or turbines and speed reducers, control valves, pipe lines, and vents. Thermal methods such as in-situ combustion (including forward, reverse, and wet combustion) require the injection of large

amounts of air (and water in the case of wet combustion) into the reservoir. This process requires large air compressors. Wellbore heating utilizes electric heaters or gas burners in the producing well. The gas burners require large quantities of fuel gas and, usually, compressors to pump the gas.

The noise levels associated with present enhanced-recovery methods are probably similar to those associated with hydraulic fracturing, although no published data are known. Conventional noise-control methods are applicable where required. Thermal recovery methods can have many of the characteristics of drilling in steam at the Geysers geothermal area (see Sec. 5.6). It is not anticipated that enhanced-recovery methods now under development will lead to greater well-head noise levels in the future.

5.4.3 Offshore operations

Technological development offers the promise of extending oil and gas production capabilities from the present limit of roughly 60 fathoms of water depth to the edges of the continental shelves [5.30]. It is thought that around 85% of the offshore reserves are as yet undiscovered. Thus one can expect a rapid development in offshore technology [5.28].

Offshore drilling is undertaken with fixed platforms in relatively shallow waters; mobile platforms such as jack-ups for water depths to 40 fathoms; and highly mobile drill ships and stable semisubmersibles for depths up to 160 fathoms. Improved offshore drilling techniques for deep water applications require platform mobility for exploration, as well as platform stability and accurate positioning capabilities for drilling.

Offshore production is presently done from fixed platforms and is considered to have reached its technical and economic limits at water depths of roughly 60 fathoms in the North Sea fields. Extending production capabilities to deeper waters of the continental shelves will require reliable underwater production techniques. Systems that have been studied to meet this requirement generally fall into two categories [5.31]:

- . Systems wherein the production equipment on the sea bottom is encapsulated, operating dry and at atmospheric pressure using proven equipment
- . Systems which operate in the sea environment, called submarine production trees.

Maintenance and inspection would be provided by divers. In the first case, diving bells which mate with the production capsule would be used, while in the second case, suited divers (limited in effectiveness) can presently be used down to depths of 160 fathoms.

The noise sources associated with off-shore drilling rigs include brake drums, air winches, mud and cement pumps, air compressors, engines, numerous pumps and motors, thruster drives, and diesel engine/generator sets, plus typical shipboard noise sources.

The noise from offshore surface production is caused by gas turbines, compressors, diesel engine/generator sets, control valves and piping, water injection pumps, air compressors, ventilating fans, circulating and oil transfer pumps, and motors. These sources contribute not only to airborne noise typical of well head operations on land, but also produce structureborne vibration which propagates throughout the platform and re-radiates as airborne and underwater noise. Nothing is known about the noise associated with sea bottom production operations.

Noise control for the protection of working personnel in surface operations includes all of the techniques normally available for well head operations on land. In addition, special attention must be paid to vibration isolation and vibration damping to reduce structureborne noise. The confined quarters for drilling and production operations allow a greater noise impact because of the close proximity of numerous noise sources. Off-shore living and relaxation spaces, where required, also need special attention. Noise control by design rather than retrofit is essential both from the technological and economic viewpoints.

Nothing has been reported about the amount of or the effects of noise radiated into the ocean from offshore drilling and production operations. There are reasons to suspect, however, that this may have have national-defense implications as offshore operations intensify and approach the edges of the continental shelves. This concern, which has to do with the effects of noise from offshore development on the U.S. Navy's sonar systems, is discussed in a separate memorandum. Information on underwater sound propagation is given in Sec. 6.4.

5.4.4 Eastern Devonian shales

DoE and a number of gas companies are investigating the possibility of extracting hydrocarbon gas from extensive beds of Eastern Devonian shale. Studies are being made of core samples from wells 2000-4000 feet deep in West Virginia, Ohio, Indiana and Kentucky [5.32].

The most promising technique for commercial production of gas from Eastern Devonian shale would involve conventional drilling, fracturing by hydraulic methods or explosives, and conventional gas production from the well. Although no data have

been published, the noise sources and levels associated with such an operation would be the same as those associated with any other well head operations, except perhaps for the explosive fracturing. If the explosive charges are no greater than those used in underground hard-rock mining, surface problems from ground shock at the depths mentioned above are very unlikely.

5.4.5 Methane stripping from brines

Along the Gulf Coast, large underground resources of hot, geopressurized brines are known to exist. Considerable quantities of methane are dissolved in these brines. Long considered a nuisance to oil drillers, the development of this geopressurized resource is presently under study. Geopressurized zones can be penetrated with production wells to extract the geothermal brine from which the methane can be removed. Gas production above the saturation level of the brine (about 20 cubic feet per barrel of brine) could result from using known stripping techniques to knock out the liquid and particulate matter and thus recover the methane. Electrical generating equipment could also be used to convert the thermal and mechanical energy of the brine into electrical energy [5.33]. Further discussion of this resource is given in Sec. 5.6.

The noise sources associated with development would include typical drill site equipment like motors, pumps, control valves, diesel engines, piping systems and compressors. Production operations would involve, in addition, flash drums and vessels, vents, flares, and electrical generating equipment. Although the noise from some of these operations may be intense (e.g., well venting, flashing), it is likely that conventional noise-control technologies will be adequate, where required.

5.5 Conservation

Energy conservation is the cornerstone of the Carter Administration's Energy Plan. Reducing energy consumption will generally reduce the noise levels in our society (see Fig. 3.1). Certainly, for example, reduced vehicle speeds on our highways will reduce the noise levels at adjacent homes. Cutbacks in commercial aircraft flights, and the shift to larger, more fuel-efficient aircraft have already decreased the noise exposures around many of the nations' airports. Thus, no major noise-control problems are anticipated in the energy conservation area. There are some noise-related considerations, however, of which DoE should be cognizant. They are discussed below.

5.5.1 Building energy conservation

In two areas, the techniques of building energy conservation are identical to those used to increase the noise reduction of building exterior walls. These are:

1. The doubling of barriers, as in double-glazing of windows or the addition of storm windows
2. The elimination of unintentional air leaks through caulking and weatherstripping.

To the extent that these methods are used, energy-conservation retrofit of buildings will result in an improved interior noise environment for exterior sounds.* Likewise, building "sound-proofing" will generally result in some energy conservation.

Although architects and engineers are aware of the dual energy reduction/noise reduction benefits of some building retro-

* Note however, that the presence or absence of thermal insulation has very little effect on the noise reduction through a normal structure.

fit actions, the general public is not. Furthermore, Federally sponsored programs directed towards one of the objectives do not generally recognize or publicize the other benefit.

5.5.2 Machinery efficiency

There are some areas where improved machinery efficiency can tend to increase noise levels. This is not a serious problem. Nevertheless, some observers see a conflict of requirements in this area and use this conflict to resist efforts at either noise reduction or at reduction of energy consumption. Examples are:

- . Building ventilation systems, where noise-control treatments increase pressure drops, and thus increase the load on fans
- . Home appliances - particularly window air conditioners - where fan loads are also increased by noise-control treatments
- . Lighter weight vehicles, particularly electrically powered vehicles, where classic motor-vehicle noise control techniques cannot be relied upon to reduce the sound levels for vehicle occupants.

In the first two areas, building ventilation and appliance fans, it is believed that more careful design and sizing of the fan/duct systems themselves can result in simultaneous efficiency improvement and noise reduction [5.34]. The efficiency improvement should more than offset the system losses due to any conventional duct mufflers required.

In the latter area, it should be noted that (although no data are available) some electric-powered vehicles look as if

they would be very noisy inside. Apparently, little consideration has been given to protecting the occupants from normal roadway noise levels [which can exceed 100 dB(A)]. If this is true, it could restrict the market appeal of such vehicles.*

The aircraft industry has developed excellent, lightweight noise-control treatments for aircraft. This technology is also applicable to lightweight motor vehicles.

5.5.3 EHV/UHV power transmission

Bulk electric-power transmission at very high voltages is more efficient than transmission at conventional voltages. It also costs less to build such transmission lines, and they require less land for rights-of-way. As a result, DoE, its predecessor agencies, the Electric Power Research Institute, and others have been conducting research towards increasing system transmission voltages.

Transmission at 345 kV and 500 kV AC is conventional in the U.S. A few systems are operating at 765 kV AC, and one operates at +400 kV DC. Experimental installations are operating in the 1100 to 1200 kV AC range and at +750 kV DC.

Under some weather conditions, the electrical field strength at the surface of the conductors operating at these voltages exceeds the breakdown voltage of the air, and corona occurs. This corona produces sound (called "audible noise" - AN - in the industry), radio and TV interference, and corona losses. For AC lines, this condition is most evident during foul weather, when the conductors are covered with water droplets, ice, or snow.

* A design goal of 80 dB(A) max. is often sought in motor vehicle, and has been recommended as a performance standard for electric and hybrid vehicles [5.35].

AN has been studied extensively over the last decade [5.36, 5.37], and the utility industry has become increasingly concerned about this noise problem. Occasional serious community noise complaints were encountered when some early-design 500-kV and 765-kV transmission lines were first put into operation. Abutting residences were subjected to levels as high as 60 to 65 dB(A), sometimes with a strong 120-Hz tonal component.

The predicted foul-weather audible noise for a typical, modern 565-kV transmission line is shown in Fig. 5.5 [5.38]. The L_{eq} of this distribution is about 53 dB(A). The annual L_{dn} would depend on the local weather conditions, but would also be about 53 dB(A) if foul weather were to occur about 25% of the time.

Combined with other environmental concerns, particularly questions about the biological effects of electric fields under transmission lines, AN has become an issue contributing to major delays in the approval and construction of new, more efficient transmission facilities. The following statement, for example, was made about a proposed transmission line in Minnesota:

A survey done by the U.S. Census Bureau in 1974 shows that the No. 1 complaint among Americans in their living conditions is noise.

In another survey taken by the Minneapolis Tribune, noise was the determining factor with people when choosing a place to live.

There are growing signs of physical effects. They are nerve deafness (hearing loss), increase in blood-pressure, vasco-constriction and a thickening of arterial walls.

William H. Stewart, the former Surgeon General of the United States, said noises of Twentieth Century living are a major contributory factor to more than twenty cardio-vascular problems.

This power line will be a 24-hour source of noise [5.39].

FIG. 5.5. PREDICTED CUMULATIVE FREQUENCY DISTRIBUTION OF FOUL WEATHER AUDIBLE NOISE FOR 765 kV LINE AT 125 ft FROM CENTERLINE [5.38].

Louise B. Young, author of an environmental book, Power Over People, and TV's "60 Minutes" show have addressed the AN issue.

Audible noise from EHV/UHV transmission lines has thus become a sensitive environmental issue. From a technical point of view, the noise level could increase as higher voltages come into use. Furthermore, because AN decreases at a slower rate than all other effects as one moves away from a line, it may become the controlling parameter in establishing right-of-way widths for future lines.

DoE is presently sponsoring research at the National Bureau of Standards on the psychoacoustic effects of AN. The Electric Power Research Institute (EPRI) is supporting similar work. The Canadian Electrical Association is also sponsoring research in this area, as are some private utilities. The Bonneville Power Administration and "Project UHV" (the latter under EPRI sponsorship) are investigating AN from experimental 1100 to 1200-kV transmission lines.

Research programs on transmission line noise are under way, and DoE's work in this area is adequately coordinated with that of other organizations. Much needs to be done in such areas as data gathering, prediction methodologies, and low-cost noise-control techniques.

It should be pointed out that transmission line noise is a rather minor noise problem. The levels are low, and the noise occurs with AC lines only when people are indoors. The number of people affected is small. The extensive amount of research in this area - most of it quite topical - is more a reaction to the concerns of environmentalists (some unfounded) than to the

seriousness of the noise impact on the public. And yet the environmental concerns are an outgrowth of industry's failure to anticipate and correct for the AN problem when some early 500-kV and 765-kV lines were designed - a regrettable oversight. It could happen again in the wide array of energy technologies DoE and others are developing. Some of the recommendations and suggestions of this study are directed at minimizing a recurrence.

5.6 Noise Associated With the Utilization of Geothermal Resources

Acoustic noise radiation from the Geysers geothermal facilities in California has received considerable attention in the last few years. Perhaps as a result, noise is viewed as a "big problem" by some workers concerned with geothermal development in the U.S. Indeed, noise appears in more environmental literature citations involving geothermal energy than in the literature for all of the other developing energy technologies put together.

While we do not minimize the existence of some major noise sources at the Geysers and the occurrence of numerous noise complaints there, we believe that the issue of geothermal noise has received disproportionate emphasis relative to noise from other developing energy technologies. It is unlikely that noise presents a significant technological barrier to the long-term development of geothermal resources.

5.6.1 Types of geothermal resources

Existing and potential sources of geothermal heat in the United States can be divided into three general categories [5.40]:

- . Dry steam resources
- . Hot water resources, including those containing dissolved methane (e.g., geopressurized geothermal resources. See Sec. 5.4.5.)
- . Hot dry rock resources.

The first - dry steam - is the simplest and most economical to develop, as at the Geysers field in California. The potential capacity of the Geysers field has been estimated at 2000 MWe. However, dry steam resources have been described as "a geological freak" [5.41]. There are no other known dry steam fields in the United States that are developable.

Geothermal sources of hot water are far more common. In some parts of the world where the total dissolved solids in the water is low and waste water is readily disposable, geothermal hot water is being used for building and process heating and for electric power generation. However, at a few locations in the United States where geothermal hot water is available, the total-dissolved-solids content is very high - up to 250,000 parts per million [5.42]. Major technical problems involving scale build-up, corrosion, and brine disposal must be solved before such resources can be developed economically.

Some hot-water resources, such as the geopressurized geothermal brines found extensively along the western coast of the Gulf of Mexico, may contain dissolved methane that can be extracted and used as natural gas.

Hot-rock sources of geothermal heat are even more common than hot-water sources. With sufficiently deep drilling, hot rock can be found anywhere in the country. However, the technology required to utilize this resource is still in its infancy. Optimal methods have not been determined for maintaining heat flow to the

surface over a period of time long enough to be economically useful.

In terms of potential electric generating capacity, the estimated geothermal resources of the United States are believed to be capable of generating 130,000 MWe of power - about 60 times the capacity of the Geysers field [5.43].

5.6.2 Noise from existing geothermal facilities: the Geysers

Opened in 1960 with 12-MWe generating capacity, the Geysers now can supply 502 MWe to the Pacific Gas and Electric Company's (PG&E) power grid. Additional capacity of 406 MWe is under construction, and further expansion is planned [5.44].

The Geysers facility is located in a sparsely settled area and in extremely rugged terrain. The facility consists of a number of small (typically 50 MWe each) turbo-generators connected by overground pipes to steam wells: perhaps to 10 wells per turbine. From time to time, new wells must be drilled to maintain steam delivery to existing turbines [5.45]. Generating plants are located at several points throughout the steam fields.

The major noise sources at the Geysers can be treated in two broad classes: those associated with steam production and delivery and those associated with electric power generation. The former are typically under the control of a steam-supply company. The latter are under the control of the electric utility that buys the steam from the supplier. Starting in 1973, extensive data have been acquired on each of these two classes of noise source.*

* The recent data surge, compared to the first 12 years of operation, results from new California environmental regulations and from expansion of activities nearer to populated areas.

Typical noise sources during steam production at the Geysers include:

- . Those associated with well drilling and completion. These are conventional, except that some drilling is done with compressed air rather than drilling mud. Furthermore, steam may be vented to the atmosphere for prolonged periods during the process of bringing in a new well.
- . Flow noise in choked valves and piping: a conventional noise source.
- . Occasional prolonged venting of steam to the atmosphere from wells whose steam output is not required for electrical generation. Such venting is an abnormal condition and is becoming less frequent with the installation of industry-designed "rock mufflers" at generating sites (see below).

Measurements of the noise produced by representative steam-well drilling and production operations at the Geysers are given in Table 5.16. It can be seen that large, unmuffled steam vents are the major noise source. A free-vented well exhausts typically 150,000 lb/hr of 200- to 300-psi steam to the atmosphere through an 8- to 10-in. pipe [5.46]. The noise output of such a choked jet would be about the same as that of a small rocket engine. In many circumstances, conventional muffling of vented steam wells is not practical because rocks are ejected at high velocity from the well.

Other noise sources associated with steam supply include diesel-engine-driven drilling rigs, mud pumps and air compressors, steam flow in valves and pipes, and vehicular traffic. These sources are conventional, and the technology exists to quiet them when quieting is economically justified. Steam venting is thus the unique and most intractable noise source of this developing energy technology.

TABLE 5.16. REPRESENTATIVE MEASURED SOUND LEVELS ASSOCIATED WITH STEAM-WELL DRILLING AND STEAM PRODUCTION AT THE GEYSERS FACILITY.

Sound Levels While Drilling in Steam [5.50]						
Location	Date	Equipment	Water Injection	Steam (#/Hr)	Measurement Distance	Sound Level dB(A)
Ott-St 19	9/5/74	Blooie line Sampler	Yes	~200M	25 ft east	83
Ott-St 19	9/5/74	"	"	200M	25 ft west	84
"	"	"	No	"	25 ft east	93
"	"	"	"	"	25 ft west	96
DX-St 7	5/16/72	Blooie line	"	75-100M	20 ft	109
GDC-32-A-13	6/13/72	"	Yes	199M	22 ft	118
"	"	"	No	"	22 ft	121
Pac Energy Corp 4th Well-Big Chief Rig	5/16/72	"	"	180M	25 ft	114
Sound Levels at Small (Typically 1/4 in.) Bleeds [5.45]						
Noise Source	Distance (ft)	Sound Level dB(A)	Comment			
Steam well--Sulphur Bank No. 3	45 180	89/92 73/75	Main valve closed, bleed line exhausting freely.			
Muffled Bleeds [5.47]						
Steam well--Sulphur Bank No. 13	45	59/62	Main valve closed, bleed equipped with silencer, exhausting freely			
Additional Muffled Bleeds [5.50]						
Noise Source	Measured Point					dB(A)
Lakoma Fame 13	5 ft from open hole at inlet end of rock-filled ditch					86
"	15 ft from center of line to rock ditch					70
Ott-Fed 1	25 ft from rock-filled ditch. Sound fluctuates; values measured are maxia.					65
Sulfur Bank 18	25 ft from rock pit. Separator bleeds nearby probably raise the sound level here					73
GDC-Thermal 14	~2 ft from edge of pit					69

TABLE 5.16. (Cont.)

Large Steam Vents, Unmuffled [5.47]			
Noise Source	Distance (ft)	Sound Level dB(A)	Comment
Steam well--name unknown.	450	105/110	Main valve open, unsilenced. Steam plume about 50 yd high.
Steam well--name unknown.	3000	71/83	Main valve open, unsilenced. Steam plume about 50 yd high.
Steam well--name unknown.	50	125	
Steam Throttled Through Drag Valve [5.50]			
			Sound Level dB(A)
Relief Load			25 ft 100 ft
Background-Valve closed			83 --
1/4 load	down 7 MW	128# line press.	95 91
1/2 load	" 14	130# "	97 93
Full load	" 27	145# "	101 96

In order to control steam-vent noise when the flow is not contaminated by solid materials from the well, the steam producers at the Geysers have used a number of muffling devices. The most effective of these is their own development: the "rock muffler." The rock muffler is a swimming-pool-sized concrete box, in the bottom of which the steam is distributed through an array of pipes with small holes. The pipes are covered with cinder blocks, and the box is then filled with size-graded rock [5.47]. Acoustically, the rock muffler is effective, as indicated in Table 5.17. Unfortunately, the device is quite costly, and must be used at a fixed location.

Another effective development of the steam producers is the Blooie-Line* muffler. This is a combination centrifugal separator and muffler, which reduces the noise from vented compressed air and steam during drilling.

The noise sources from power generation at the Geysers are the same as those found at many other steam-electric generating facilities. Differences include the lack of noise from boilers or associated draft fans, and continuous use of steam ejectors in the condenser discharge. Representative measured sound levels are given in Table 5.18. The controlling source of the A-weighted level at locations distant from the generating facility is the array of cooling towers.

5.6.2.1 LLL workshop on geothermal noise

Under the sponsorship of DoE's Lawrence Livermore Laboratory, a workshop on geothermal noise was held at the University of California, Davis, CA, on November 14 and 15, 1977. The

* The Blooie-Line carries drill cuttings from the well head during drilling operations.

TABLE 5.17. COMPARISON OF WELL VENT MUFFLERS [5.47]..

Condition	Steam Lb/Hr	Sound Level dB(A)		
		50 ft NW	50 ft NE	100 ft SW
Open Well	270,000	118	117	122
Rock Muffler	150,000	89	92	84
Long Cone	170,000	116	114	118
Short Cone, with center torpedo	270,000	114	116	119

TABLE 5.18. REPRESENTATIVE MEASUREMENTS OF NOISE LEVELS OF STEAM-ELECTRIC GENERATING FACILITIES AT THE GEYSERS [5.44].

Noise Source	Distance, ft	Sound Level dB(A)	Comments
Steam jet gas ejector - Unit 5	5	91	Microphone height 5 ft, Unit 5 load unknown
Steam jet gas ejector - Unit 8	10	88	Microphone height 5 ft, Unit 8 load 41 MW.
Cooling tower Units 5 and 6	10	81	Microphone height, 5 ft
Cooling tower Units 9 and 10	10 40 140	84 80 72	Microphone height, 5 ft
Outside Unit 5 & 6 turbine generator building	25	72	Unit 5 - 44 MW Unit 6 - 54 MW

results and conclusions of this workshop will be reported separately by the Chairman, Dr. Philip Leitner of Saint Mary's College, Morenga, CA 94575. In general, it was reported that significant progress had been made by the various developers of the Geysers in reducing community noise impact.

During the workshop, a number of proposals were entertained for acoustical research at the Geysers field. These included:

- . Outdoor sound propagation studies
- . "Baseline" ambient noise studies
- . Community attitude surveys
- . Development of new muffling techniques
- . Continuous noise monitoring installations.

5.6.3 Noise from hot-water geothermal facilities

Aside from a few measurements taken by Dr. Lietner [5.48], no data have been reported on the noise produced by activities utilizing hot-water geothermal facilities. However, there is every reason to believe that there will be less noise at such facilities than has been encountered at the Geysers, because it is less likely that free venting of high-pressure steam to the atmosphere would be necessary or appropriate at such facilities.

Low-enthalpy geothermal resources, such as those that are used only for building and process heat, are not likely to radiate significant noise. The only anticipated sources are drilling, pumps, and flow noise in valves and piping. The technology is available to reduce the noise from such sources, where necessary.

Candidate technologies for the utilization of geopressurized and high-temperature hot-water geothermal resources for the

generation of electric power include flashing to steam, hydraulic turbines, and heat exchange to suitable turbine working fluids. In every case, the spent brines would be reinjected into the earth [5.49]. These technologies will probably not require free venting of high-pressure fluids to the atmosphere. Such venting would be undesirable for both environmental and economic reasons. All other noise sources, such as flashing, should be conventional and subject to conventional treatment by containment.

Because of the concerns about noise raised by the activities at the Geysers, future geothermal facilities will probably be designed with conventional noise control in mind - particularly in states, like California, that have strict environmental laws.

5.6.4 Noise from hot-rock geothermal facilities

The most appropriate technologies for widespread utilization of geothermal energy from dry rock strata are not yet determined. Experimental work to date has concentrated on drilling a pair of wells, fracturing the rock between them, and then pumping a working fluid down one well and up the other. The implication of this technique is that venting of steam to the atmosphere may be required for some of the same reasons that such venting is required at the Geysers: removal of loose rock and other materials from the outlet well. If such should be the case, the noise-reduction technology developed for the Geysers should be usable when necessary.

5.7 Advanced Energy Systems

5.7.1 Wind

We could find no published information on the noise levels, or noise design criteria for wind-driven electric generating devices.

When the potential of wind power is being appraised, it is necessary to acknowledge that noise problems could result from the inherent acoustic signatures of wind turbine generators (WTG). Lacking measured data, we have used a simple technique to predict the overall SPL and spectra of noise generated by a typical wind machine. We have used the existing knowledge of noise radiation from helicopter rotors and low-speed propellers to develop this prediction.

The typical acoustic signature of multibladed rotating machinery may be classified into:

- (1) rotational noise,
- (2) broadband noise, and
- (3) narrowband or vortex-shedding noise.

The rotational noise occurs at multiples of the blade passage frequency and does not pose a significant problem in the present case because of low rotational speeds. The broadband noise is caused by interaction of turbulence in the flow with the rotor blades. The narrowband or vortex-shedding noise is attributed to the periodic vortex shedding from air foils and is very sensitive to operating Reynolds number.

On the basis of the experimental results of Aravamudan et al. [5.50] for model helicopter rotors, we have assumed that the

outer one-quarter of the blade span is the efficient radiating surface for the analysis of broadband noise and vortex shedding noise. Figure 5.6 depicts the assumed observer position relative to the radiating surface for the NASA MOD-0 Turbine. Following Hayden's prediction scheme [5.51, 5.52], the overall SPL is given by:

$$\text{OASPL} = 10 \log [\delta W_c U_m^6] - 20 \log r + 10 \log [\sin^2 \theta \cos^2 X/2] - 20 \quad (1)$$

where U_m = mean velocity in FPS

δ = turbulent boundary layer thickness, in ft

W_c = wetted span, in ft

r = observer distance, in ft

θ, X = angles subtended between observer and radiating surface (see Fig. 5.6).

The MOD-0 blades have a mean chord of 1.91 ft at the radiating surface, and the velocity is $U_m = 229$ ft/sec. This leads to a Reynolds number, R_e , based on chord of 2.73×10^6 . Assuming a fully developed turbulent boundary layer, the boundary layer thickness is given by:

$$\delta = \frac{0.22 \times \text{chord}}{R_e} = 0.0217 \text{ ft.}$$

The corresponding Strouhal frequency is given by:

$$f_1 = \frac{0.15 \times U_m}{\delta} = 1584 \text{ Hz (1600-Hz Octave Band) .}$$

A spectrum may be readily filled by utilizing the normalized spectrum of Ref. 5.52.

FIG. 5.6. GEOMETRY ASSUMED FOR THE CALCULATION OF WIND-TURBINE NOISE.

FIG. 5.7: CALCULATED ACOUSTIC NOISE SPECTRA 300 ft FROM MOD-0 WIND TURBINE
[CORRESPONDS TO ~62 dB(A)].

The narrowband or vortex-shedding noise is characterized by the thickness of the wake. This is given by

$$\delta_w = t + 2\delta^* ,$$

where δ^* is the momentum thickness of the wake and t is the thickness of the air foil at its trailing edge. Using the air-foil data for the 23000 series air foils used in the MOD-0, we have a wake thickness of 0.0102 ft. The frequency is given by:

$$\begin{aligned} F_2 &= \frac{0.25U_m}{\delta_w} \\ &= 5500 \text{ Hz} . \end{aligned}$$

And the corresponding overall SPL is given by replacing δ by δ_w and the constant by 22 dB in Eq. 1. The result is an overall SPL of 63.5 dB. Although the frequency of shed vortices will vary along the span of a rotating blade, the acoustic spectrum is confined to a narrow frequency band because the end of the blade will be controlling. The typical acoustic spectra of the MOD-0 turbine at the chosen observer location are shown in Fig. 5.7.

The calculated sound-level spectrum in Fig. 5.7 corresponds to about 62 dB(A). If indeed this calculation is correct, such a noise level is sufficient to cause serious community-noise reactions from rural residents. [It is 9 dB(A) above the noise level produced by modern 765-kV transmission lines - a noise that has caused environmental concern and contributed to lengthy project delays. See Sec. 5.5.3.] To satisfy the typical nighttime residential noise ordinance [a 45-dB(A) limit], the turbine would have to be located over 2000 feet from the nearest residential property line.

On the basis of the above calculation, the authors conclude that noise could become a major environmental consideration during the approval of sites for large wind turbines. Because WTGs present the same aesthetic problems as transmission lines - and affect the same group of people (rural residents) - noise concerns are anticipated as large numbers of these devices come into use.*

Of course, it is impractical to apply conventional noise-control techniques to the aerodynamic noise sources of a wind turbine. However, there are many techniques applied to aircraft and helicopter aerodynamic components that can reduce the broadband-noise radiation. Hersh and Hayden [5.53] and Lee et al. [5.54], have demonstrated the use of leading-edge and pressure-surface serrations in reducing the narrowband vortex-shedding noise from isolated and rotating air foils. Porous trailing edges and variable-impedance surface concepts are often used as a means for reducing noise from lift-augmenting flaps [5.55].

5.7.2 Ocean thermal energy conversion systems

Still in the conceptual design stage, Ocean Thermal Energy Conversion (OTEC) systems would generate usable electricity by operating a suitable working fluid between the temperatures of the warm surface and cold depths of the ocean. Nothing is known about the noise-source characteristics of such systems, but it is

* It is of interest that one community-noise problem has already been encountered because of the installation of a small telephone-company wind turbine at Block Island, RI (since removed). That problem was caused by alternator noise rather than blade noise and required derating of the alternator. Expressions of concern about noise can be expected from Block Island residents when the 200-kWe MOD-0A turbine is presented for discussion there.

expected that unique (for industrial facilities) noise-control requirements will exist if residential spaces are provided in offshore, floating platforms. These spaces should be designed for a quieter environment than normal workspaces. Conventional ship noise-control design should be applicable.

5.7.3 Other solar systems

There are no known noise problems associated with other solar technologies, nor are any anticipated that cannot be readily solved with conventional techniques.

5.8 Fusion Systems

It is difficult to speculate about the noise-control problems that might be encountered with operational fusion energy sources; even the processes to be utilized are not yet defined. To a considerable extent, though, it is expected that most of the noise will be associated with familiar noise sources (rotating machinery, fluid flow in pipes, etc.) subject to conventional noise-control techniques.

Some candidate processes for fusion-energy use involve the storage and transient release of large quantities of electrical power - such as that required to create a brief, intense magnetic field. The magnetostrictive forces produced by such an operation can be expected to result in a strong acoustic pulse in the supporting structure and ground. Conventional shock-isolation design may be used to avert problems caused by such pulses. Certainly, acoustic studies would be premature before a usable fusion-energy process is known.

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6. NOISE AND VIBRATION PROPAGATION

As dynamic waves propagate from their source to receivers of concern, they can be profoundly altered by the characteristics of the propagation paths. For example, everyone knows that the sound level from a source decreases as the listener moves away from the source. Also, beyond a few hundred feet from a steady sound source, the sound level varies with time, being unnoticeable at some times and quite pronounced at others. Such effects, which are characteristic of the propagation of sound out-of-doors, are caused by the phenomena described below.

6.1 Propagation of Sound Out-of-Doors Near the Ground

6.1.1 Divergence

As sound radiates away from a source, its intensity decreases with distance because its energy is spread over a larger and larger surface area. From a point-source of sound, this decrease is called "spherical divergence" or "inverse square loss," because the sound intensity decreases inversely with the square of the distance from the source to the receiver (i.e., sound pressure level decreases 6 dB for each doubling of source-receiver distance).

If the input spectrum is specified at some small reference distance, D_r , then the attenuation due to spherical divergence, A_D , is:

$$A_D = 20 \log_{10} \left(\frac{r}{D_r} \right) \text{ dB,}$$

where r is the source-to-receiver distance.

If the input spectrum is in terms of sound power level, PWL in dB re 10^{-12} watts, then:

$$A_D = 10 \log_{10} (4\pi r^2) - 3 \text{ dB} ,$$

where r is the source-receiver distance in meters, and the factor of 3 dB is an allowance for hemispherical, as opposed to spherical, radiation close to the ground. In English units:

$$A_D = 20 \log_{10} r - 2 \text{ dB}.$$

If the source is linear, such as a railroad train, a transmission line, or a highway, the attenuation is 3 dB per doubling of distance.

6.1.2 Attenuation caused by ground effects

The presence of the ground plane produces a number of interesting and interrelated effects on the propagation of sound near the ground. Perhaps the simplest of these is the interferometer effect, which occurs when sound is propagated over a hard, flat surface. For any given source and receiver height, there are two sound-wave paths between the source and the receiver: one direct, and the other - somewhat longer - reflected off the ground surface. When the difference between the lengths of these two paths is an odd number of half-wavelengths, the two waves interfere and (theoretically) cancel at the receiver. The opposite effect occurs when the path lengths differ by an even number of half-wavelengths: The two waves add and a "gain" (negative attenuation) is observed.

Obviously, the interferometer effect is frequency-dependent and would be most evident with tonal sounds. Because it is also

dependent upon the phase relationship between the direct and reflected waves, it can occur as predicted only when the atmosphere is homogeneous and the reflection from the ground plane is specular. For normal source and receiver heights (5 to 10 ft), the interferometer effect is rarely detectable beyond a few hundred feet from the source. It is normally ignored in noise analyses. (For more information on the interferometer effect, see Ref. 6.1).

When the ground is acoustically absorbent (soft), the interferometer effect changes dramatically because of the phase shift experienced by the reflected wave at the ground surface. (The shift is 180 degrees for a perfectly soft surface.) This situation has been studied by Ingard [6.2], by Piercy and Embleton [6.3], and by Chessell [6.4]. They have shown that, as the source-receiver distance becomes large (so that the difference between the direct and reflected paths is small), the propagation of plane acoustic waves over a soft-ground surface is not possible. Only spherical waves can propagate in this region. Because the sphericity of a wavefront decreases with distance from the source, attenuations proportional to $1/r^2$ (6 dB per doubling of distance)* are predicted. Where (in frequency and geometry) this effect occurs is greatly dependent upon the complex acoustic impedance of the ground surface.

When measurements are made of sound propagated over the ground out-of-doors, it is common to observe a peak of attenuation in the frequency range from 100 to 500 Hz. Piercy and Embleton's explanation of this peak of low-frequency attenuation can be paraphrased by pointing out that the peak should approach infinity as frequency goes to zero (when the path difference between direct and reflected waves approaches zero) because of

* This is in addition to, and should not be confused with, spherical divergence (Sec. 6.1.1).

the 180-degree phase reversal of the reflected wave from the (soft) ground. However, the peak is limited by the sphericity of the sound wave and by any increase in the ground impedance as frequency decreases. Ingard [6.5] gives a similar explanation and goes on to remind his readers that the effect is based upon coherence between the direct and reflected sound waves. It will be modified by nonspecular reflection from the ground and by atmospheric inhomogeneities, such as those described in Sec. 6.1.4.

6.1.3 Effects of barriers

There are well-developed analytical procedures for calculating attenuation of sound by barriers. In general, these procedures have been confirmed experimentally, provided that some allowance is made for limiting the ultimate theoretical attenuation to about 20 dB, because of sound energy scattered into the region behind the barrier via indirect wave paths.

The most widely used barrier calculation method is based upon Fresnel-Kirchoff diffraction theory and is generally attributed to Maekawa [6.6]. This method, which has gained acceptance for use in highway noise studies [6.7,6.8], is the recommended procedure for environmental impact studies of proposed highways [6.9].

6.1.4 Effects of vertical temperature and wind gradients: atmospheric refraction

The speed of sound in air increases with the square root of the absolute temperature. Furthermore, when the atmosphere is in motion, the speed of sound is the vector sum of the sound speed in still air and the wind speed. The temperature and the wind in the atmosphere near the ground are frequently nonuniform. This atmospheric nonuniformity produces gradients of the speed of

sound, and, thus, refraction (bending) of sound wave paths. Near the ground, this refraction can have a major effect on the apparent attenuation of sound propagated through the atmosphere. See Fig. 6.1.

In analyzing this effect, we usually assume a horizontally stratified atmosphere in which temperature and wind speed vary only with height above the ground. During the daytime in fair weather, temperature normally decreases with height (lapse), so that sound waves from a source near the ground are refracted upward. In the absence of wind, an "acoustic shadow," into which no direct sound waves can penetrate, forms around the source. Marked attenuations are observed at receiving points well into the shadow zone - just as if a solid barrier had been built around the source.

On clear nights, a temperature increase with height is common near the ground (inversion) and the "barrier" disappears.

Wind speed almost always increases with height near the ground. Because the speed of sound is the vector sum of its speed in still air and the wind vector, a shadow zone can form upwind of a sound source, but is suppressed downwind.

The combined effects of wind and temperature are usually such as to create acoustic shadows upwind of a source, but not downwind. Only under rare circumstances will a temperature lapse be sufficient to overpower wind effects and create a shadow surrounding a source. It is less rare, but still uncommon, for a surface inversion to be sufficiently strong to overcome an upwind shadow entirely.

Analytical procedures are available for quantitative prediction of these effects on the basis of meteorological observations at the site [6.10, 6.11].

FIG. 6.1. SKETCHES ILLUSTRATING THE EFFECT OF VERTICAL TEMPERATURE AND WIND GRADIENTS IN FORMING ACOUSTIC SHADOW ZONES AROUND A SOURCE NEAR THE GROUND.

Blast waves and intense sounds like rocket-engine noise can be objectionable or even damaging at points on the ground many miles from their source. Often this effect occurs after such sound waves have traveled to considerable altitude in the atmosphere, and then have been refracted downward. Under certain atmospheric conditions, such refraction can produce focusing of the sound at regions on the ground remote from the source. In these regions, the level will be higher than predicted from consideration of simple spherical divergence.

This phenomenon has been studied extensively by the AEC [6.12], NASA [6.13], and the U.S. Army [6.14]. More recently, it has become of interest in environmental issues involving surface mines and quarries [6.15].

6.1.5 Absorption of sound by foliage

The study of the attenuation of sound by foliage has had a murky history. A very early study by Eyring [6.16] uncovered absorptions approaching 8 dB/100 feet at 1000 Hz in "dense Panamanian jungles." This attenuation appeared to be related to visibility in the jungle. Wiener and Keast [6.17] found no such correlation. Nor did Embleton [6.18], who, in an extensive study of Canadian forests, found "edge effects" along with attenuations considerably in excess of those observed in very similar Russian forests [6.19]. The result is such a wide range of attenuation observations (neatly summarized by Kurze and Beranek [6.20]) that no useful prediction model can be postulated.

Recently, Aylor [6.21,6.22] has done some excellent work in this area that hints at the difficulty that may have been encountered by previous observers: inability to separate adequately the various scattering, interference, and absorption mechanisms which

are involved in attempting to measure "attenuation due to foliage." Unfortunately, Aylor's results cover only a limited range of foliage types and require for prediction a knowledge of average leaf widths and leaf area densities.

For practical engineering purposes, the foliage-attenuation figures in Table 6.1 are often used. These apply for propagation through dense foliage, not over or under the foliage.

6.1.6 Absorption of sound in the atmosphere

The available information on the absorption of sound in the atmosphere was summarized by an SAE committee over a decade ago [6.23]. Although the results have been subject to some recent minor criticism [6.24], it has become common practice to use them for prediction purposes [6.7, 6.25]. The SAE atmospheric absorption coefficients, in dB/1000 feet, are given in Fig. 6.2. The attenuation, A_m , is then calculated:

$$A_m = \frac{r\alpha}{1000} \text{ ("}\alpha\text{" from Fig. 6.2) dB.}$$

6.2 Propagation of Sound Inside Enclosures

The propagation of sound inside enclosures is predominantly determined by the properties of the enclosure boundaries. The most common case involves enclosures whose dimensions are large compared to the acoustic wavelengths of interest. This case applies to normal indoor acoustic phenomena in rooms, and is discussed below. Other situations, such as those involving enclosures with dimensions comparable to the acoustic wavelength (i.e., sound in ducts) and enclosures with dimensions small compared to the acoustic wavelength (i.e., loudspeaker en-

TABLE 6.1. ATTENUATION COEFFICIENTS FOR SOUND PROPAGATED *THROUGH* DENSE FOLIAGE [6.11].

Octave Frequency Band, Hz	Attenuation Coefficient: dB per 1000 ft
63	0
125	10
250	15
500	20
1000	20
2000	30
4000	30
8000	30

Total attenuations greater than 15 dB shall be assumed to = 15 dB.

FIG. 6.2. ATMOSPHERIC ABSORPTION COEFFICIENTS FOR OCTAVE BANDS OF NOISE AT DIFFERENT TEMPERATURES AND HUMIDITIES (From SAE ARP 866, Ref. [6.23]).

closures) are treated in the literature and will not be discussed here [6.26].

The analysis of sound propagation in large enclosures (i.e., room acoustics) is of considerable practical and historic significance. A good introduction is provided by Beranek [6.27]. Figure 6.3 illustrates the situation in a typical, irregularly shaped room. Close to the source, the sound pressure level (L_p) decreases at a rate of 6 dB per doubling of distance, r , just as it does out-of-doors. However, beyond a certain distance from the source, the level becomes constant and independent of distance. This constant level, called the reverberant level, is a function of the amount of acoustic absorption, R_T , within the room. The less R_T , the more "reverberant" the room becomes, and the more the sound pressure level tends to be large and constant throughout the room. On the other hand, as R_T is increased the reverberant level decreases, and L_p vs r approaches the out-of-doors situation.

In Fig. 6.3, the quantity L_w is the acoustic power level of the source, and Q_θ is the directivity factor of the source.

The absorption within a room, R_T , can be calculated from the surface areas of the various materials that make up the boundaries of the room, and from the absorption coefficients of these materials. Absorption coefficients of common materials are tabulated [6.28]. In particularly large rooms, atmospheric absorption, described in Sec. 6.1.6, contributes to R_T at high frequencies.

FIG. 6.3. CHART FOR DETERMINING THE SOUND-PRESSURE LEVEL IN A LARGE IRREGULAR ENCLOSURE AT A DISTANCE r FROM THE CENTER OF A SOURCE OF DIRECTIVITY FACTOR Q_0 . WHEN ALL DIMENSIONS ARE IN ENGLISH UNITS USE THE ORDINATE ON THE LEFT-HAND SIDE; FOR DIMENSIONS IN SI UNITS THE RIGHT-HAND ORDINATE SHOULD BE USED. (FIGURE FROM BERANEK [6.27]).

Propagation of Sound Energy Through Walls

When sound impinges upon a wall, the wall is set in motion. As a result of this motion, sound is reradiated and can be observed on the other side of the wall. The process whereby this reradiation occurs is quite complex and has been studied for many years. (See also Sec. 6.5.)

The problem has been to generalize from the variety of complex, site-specific parameters that influence acoustic energy propagation through walls, and to develop practical engineering methods for predicting and controlling acoustic isolation between spaces separated by walls. For the most part, this problem has been solved.

The property of a wall that is of interest in this context is the acoustic transmission loss (TL) of the wall.

$$TL = 10 \log \frac{\text{sound energy incident on wall}}{\text{sound energy transmitted through wall}} ,$$

where TL is in decibels. It is approximately equal to the ratio of sound pressure levels on opposite sides of the wall after adjusting for wall area and the relative amount of acoustic absorption on opposite sides of the wall. Various standards have been written to prescribe methods for the measurement of TL [6.29].

The TL properties of a typical wall are illustrated in Fig. 6.4. In most practical situations involving building structures, the acoustic frequencies of interest are above the first resonant frequency of the wall. The gross motion of the wall is thus controlled by the mass of the wall. As a result, TL increases at a rate of 6 dB for each doubling of frequency. How-

FIG. 6.4. SEPARATION OF THE TL BEHAVIOR OF A WALL INTO THREE FREQUENCY REGIONS: (I) STIFFNESS CONTROLLED AND RESONANCES; (II) MASS CONTROLLED; (III) WAVE-COINCIDENCE CONTROLLED. f_c IS THE CRITICAL FREQUENCY. (AFTER BERANEK [6.30]).

ever, when sound is incident on the wall from all directions (i.e., random incidence, as in the typical case of a reverberant sound field), a critical frequency is reached where "coincidence" occurs. At the critical frequency, the trace velocity of sound waves impinging on the wall at some oblique angle matches the flexural wave velocity in the wall. Above this frequency, the TL of the wall becomes less than the mass-controlled value and is determined by the damping properties of the wall.

Analytical descriptions of the transmission loss of walls, as well as useful engineering design procedures, are given in the literature [6.27, 6.30].

6.4 Underwater Sound Propagation

6.4.1 Introduction

Underwater sound propagation is important to the consideration of noise from ocean-based energy technologies, such as Ocean Thermal Energy Conversion (OTEC) and oil and gas drilling on the continental shelf. This brief review is designed to give the reader some insight into the characteristics of the ocean that influence sound propagation. A more thorough discussion is given by Urlick and other texts [6.31].

The medium in which sound waves propagate - in this case, water - determines the sound speed, paths, divergence/spreading, attenuation, and absorption of acoustic energy. The boundaries (i.e., the sea surface and ocean bottom) play an important role in how sound energy is reflected, scattered, and absorbed as it propagates in the ocean. Although the physics of sound propagation in air and water are similar, the results are very different, primarily because of the ability of the ocean to transmit sound energy over significant distances.

In the past few decades, the technology of underwater sound sources and receivers, e.g., Navy sonar, navigation, and communications equipment, has advanced at a rapid rate. An understanding of underwater sound propagation is central to the design and operation of these highly sophisticated detection and ranging systems. For example, in the search for off-shore resources, underwater sound is the primary medium in which acoustic systems involving high-intensity sources, receiving arrays, and computer-based signal processing are used for mapping and classifying sub-bottom geologic structures. Oil drilling positioning systems use shipboard "pingers" and acoustic transponders located on the ocean bottom that provide information by which the ship is automatically positioned over the drill hole. The Navy continues to conduct an extensive program in underwater acoustics in support of both undersea surveillance and antisubmarine warfare. Much of this latter work is classified.

6.4.2 The sonar equation

To understand the role of underwater sound propagation, it is helpful to view it as part of a source-path-receiver system. This system is best described by the sonar equation for passive sonars.

Sonars fall into two general system categories: passive and active. Applications must consider a wide range of mechanical, electrical, economic, and physical constraints. Where the goal is to meet a specified performance, such as achieving a certain range or distance, performance objectives may be expressed acoustically by the sonar transmission loss, which is associated with an assumed set of propagation conditions. This establishes requirements for power and source level, frequency bands, and directivity for active systems. In passive systems, the range

requirement determines such design considerations as array and processing gains based on assumptions of signal and noise levels. In fact, ocean ambient noise, a combination of wind, biological, and machine-generated noise, is a critical factor in the performance of underwater detection systems.

The elements of the passive sonar equation are reviewed in the figure below:

where:

L_S is the source level at 1 yard from the target in the frequency band of the sonar, in dB re a reference pressure or intensity (S, I_0, L);*

TL is the transmission loss from 1 yard to the receiver at range R , in dB (H, N_W);

L_N is the omnidirectional noise level in the water at the sonar receiver, in the sonar frequency band of interest, in dB re the same reference pressure as the source level, L_S .

$(S/N)_W = L_S - TL - L_N$ is the signal-to-noise ratio in the water at the receiver

$(S/N)_{in} = (S/N)_W + A.G. = (L_S - TL - L_N) + A.G.$

$(S/N)_{out} = (S/N)_{in} + P.G._1 = (L_S - TL - L_N) + A.G. + P.G._1$,

and where

$A.G.$ is the array gain of the receiver for signal and noise

$(P.G.)_1$ is the processing gain from signal-to-noise enhancement in the signal processor

* The symbols in parentheses are additional symbols often used to represent the same terms of the sonar equation.

$(S/N)_{out}$ is the signal-to-noise ratio presented to the observer.

$(P.G.)_2$ is the processing gain provided by the display method and the human operator who must make a decision regarding the detection of the source.

The discussion herein is limited to the transmission loss term in the sonar equation.

6.4.3 Wave propagation

The basic physics of sound in the water involves a simple concept:

- . A vibrating source in contact with the water
- . The generation of pressure fluctuations due to particle motions
- . The propagation of waves in the medium
- . The detection of the pressure field by a hydrophone or an array with directional properties.

The solution to the wave equation may be written:

$$p(x,t) = p_0 \sin \left(\frac{2\pi x}{\lambda} - 2\pi f t + \phi \right) ,$$

where the phase speed of a plane wave traveling in the x direction is $c=f\lambda$ and $p(x,t)$ is the instantaneous pressure. The nominal speed of sound in water is about 1500 m/sec or four times that in air. Variations in sound speed are discussed below in Sec. 6.4.6.

The ratio of the acoustic pressure, p , to the acoustic volume velocity, v , of a wave is called the specific acoustic impedance of the medium. It is equal to the density, ρ , times the speed of sound in the medium, c . Thus:

$$\frac{p}{v_3} = \rho c.$$

In water, $\rho = 1.02 \text{ gm/cm}^3$ and $c = 150,000 \text{ cm/sec}^2$. Thus, the specific acoustic impedance is $154,000 \text{ gm/sec cm}^2$, compared to 42 gm/sec cm^2 in air. For a given particle volume velocity, the acoustic pressure in water will be about 4000 times greater than in air, since $p = \rho c v$. This is one reason why sound waves can be transmitted so effectively in water.

6.4.4 Transmission loss*

Consider a sound source in a homogeneous unbounded and, for a moment, lossless medium. As indicated in Sec. 6.1.1, the simple laws of spherical spreading result in a reduction of intensity corresponding to the spherical surface area at a given range. For a given source power P ,

$$P = 4\pi r_1^2 I_1 = 4\pi r_2^2 I_2.$$

This reduction in intensity may be expressed as the transmission loss TL in dB:

$$TL = 10 \log \frac{I_1}{I_2} = 10 \log r_2^2 = 20 \log r_2$$

where $r_1 = 1 \text{ m}$ from the source.

In many cases, a sound channel occurs in water that leads to ducted transmission (see Secs. 6.4.6 and 6.4.7). This occurrence

* The concept is physically analogous to the transmission loss of walls described in Sec. 6.3.

results in cylindrical spreading, for which the corresponding transmission loss is:

$$TL = 10 \log r_2 .$$

The simple expressions given above do not account for the extremely large and often rapid fluctuations in sound pressure levels observed at given locations in the sea. Some of these fluctuations can be explained by interference patterns of sound waves arriving at the given location by different paths and by changing oceanographic variables in the sound paths. Therefore, propagation loss estimates are generally based on the statistical averages of a large number of measurements.

6.4.5 Absorption in water

As in sound transmission in air, a reduction in sound intensity results from the conversion of acoustic energy to other forms of energy, e.g., heat. The logarithmic absorption coefficient

$$\alpha = \frac{10 \log I_1 - 10 \log I_2}{r_2 - r_1}$$

is expressed in dB/kyd. Figure 6.5 summarizes measurements for a given temperature. Since the attenuation of sound is highly frequency-dependent, medium- to long-range applications generally utilize sound energy below 15 to 20 kHz. Short-range positioning systems, on the other hand, can operate at higher frequencies where directive characteristics are important.

Figure 6.6 gives typical values of the combined spherical transmission loss in dB/kyd:

FIG. 6.5. THE ATTENUATION COEFFICIENT FOR COMPUTING NOMINAL VALUES OF ABSORPTION IN WATER.

FIG. 6.6. PROPAGATION LOSS IN WATER USING NOMINAL VALUES OF ATTENUATION.

$$TL = 10 + 20 \log R + \alpha R ,$$

where α is the frequency-dependent attenuation coefficient and $20 \log R$ is the geometrical spreading term.

The absorption of sound in seawater decreases by about 2% for every increase in 1000 feet in depth.

In the following paragraphs, we discuss those features of sound propagation which are not included in the above expression, e.g., refraction, or ray curvature, and reflection and scattering at boundaries.

6.4.6 Refraction

The direction in which a sound wave travels in any medium depends on the speed of the wave. For layered media, Snell's law states:

$$\frac{\cos \theta_1}{c_1} = \frac{\cos \theta_2}{c_2} = \frac{\cos \theta_3}{c_3} \dots\dots = \text{constant}$$

where $c_1, c_2, \dots$ is the sound velocity in a given layer and $\theta_1, \theta_2, \dots$ are the angles of incidence relative to grazing at the corresponding layer boundaries (see Fig. 6.7).

Refraction is one of the most important phenomena in underwater sound propagation because the velocity of sound does, in fact, vary significantly with temperature, pressure (depth), and salinity. Sound speed profiles (speed as a function of depth) in a given operating environment provide one of the essential sources of data for understanding and predicting sound propagation in the ocean.

FIG. 6.7. REFRACTION IN A LAYERED MEDIUM.

The speed of sound in seawater may be determined by a variety of empirical formulae. A common expression is:

$$c = 1.445.5 + 4.664T - 0.0554T^2 + 1.307(S-35)$$

where c = sound speed m/sec, T = temperature 0 degrees C, and S = salinity, PPT. In addition, speed increases with depth by about 0.6 m/sec for each 100 feet in depth.

The vertical thermal structure of the ocean can be visualized in three layers as a function of depth. Figure 6.8 represents a three-layer structure made up of the surface layer, the main thermocline, and the deep layer. Seasonal variations in the vertical thermal structure take place in the surface layer, which is essentially isothermal in the winter. In the main thermocline, the temperature decreases rapidly with depth, and this layer is generally not subject to seasonal variations. The deep layer is relatively homogeneous and temperature changes slowly only with depth.

In the surface layer for any given location, temperature profiles vary with season (see Fig. 6.9), time of day, and meteorological conditions. The profile usually varies slowly with horizontal location, although at ocean fronts, e.g., the Gulf Stream, rather abrupt changes can take place.

A typical deep-sea sound velocity profile, due to combined temperature, salinity, and pressure effects, is shown in Fig. 6.10. This type of profile leads to sound refraction and, depending on the location of the sound source, determines the paths by which the sound will propagate.

The sound speed gradients cause refraction which, in certain propagation modes, may involve reflections and scatterings at the boundaries (see Sec. 6.4.7).

FIG. 6.8. VERTICAL THERMAL STRUCTURE IN THE OCEAN.

FIG. 6.9. TYPICAL SEA WATER TEMPERATURES PROFILES IN THE SURFACE LAYER OF THE NORTH ATLANTIC.

FIG. 6.10. TYPICAL DEEP-SEA SOUND VELOCITY PROFILE.

Ray plots for typical sound velocity profiles serve to illustrate various features of sound propagation. Note that the ray paths are bent (refracted) toward regions of lower speed. Thus, layers of sound speed minima play an important role in ducting of sound in the ocean.

Figure 6.11(a) shows regions, called shadow zones, into which direct rays do not penetrate. Thus, transmission loss in these regions is much higher than ideal spherical spreading would indicate.

Figure 6.11(b) shows sound channeling for the case where the source is placed in an isothermal surface layer. Some sound may escape from the layer while the rest is ducted in the layer. Because of scattering at the surface and leakage at the bottom of the layer, the transmission loss is a combination of spherical and cylindrical spreading.

Figure 6.11(c) illustrates two major propagation effects - (1) the deep sound channel, which acts as a duct and is used for very long range transmissions in the deep ocean, and (2) convergence zones in which sound energy is concentrated.

6.4.7 Reflection and scattering

The Sea Surface

The surface of the sea presents a boundary that, because of the large difference in impedance, acts as a reflector of underwater sound. The roughness of the surface, caused by wind and wave action, influences the degree of reflection and causes scattering of the incident sound. Again, these effects are frequency-dependent and are more pronounced at higher frequencies where wavelengths are small in comparison to the roughness scale.

FIG. 6.11a. OCCURRENCE OF SHADOW ZONES DUE TO REFRACTION IN THE OCEAN.

FIG. 6.11b. SOUND SOURCE IN THE ISOTHERMAL SURFACE LAYER.

FIG. 6.11c. THE DEEP SOUND CHANNEL WITH CONVERGENCE ZONE.

The Sea Bottom

The bottom is a reflecting and scattering boundary of the sea, which has some of the same characteristics as the sea surface. Because its form and shape are so much more diverse and complicated, however, its effects are difficult to predict and measure.

The bottom reflection loss depends on the angle of sound incidence, impedance, and frequency. The acoustic characteristics of the subbottom layers depend on the geologic type of the sedimentary materials. For water-saturated materials, porosity is an important factor determining the velocity of sound, and, thus, the reflection properties of sediments.

Typical values of acoustic bottom loss are shown in Fig. 6.12. They have been developed from a series of measurements made at deep-sea locations. For example, at 1 kHz, sound losses of 4 to 6 dB can be expected for sound incident over a wide range of angles.

The area of underwater acoustics is receiving increasing attention because it is often a dominant factor in coastal and long-range propagation. Sound channeling in shallow water is propagated through multireflections from both surface and bottom. Thus, the acoustic characteristics of the boundaries are important factors that determine the sound field.

6.5 Propagation of Vibration in Structures

Vibratory motions of structures result from the action of unsteady forces. These forces and the resulting structural motions may be transient (e.g., impacts) or continuous (e.g., oscillations produced by an unbalanced turbine). A great variety of

FIG. 6.12. BOTTOM LOSS vs GRAZING ANGLE AT VARIOUS FREQUENCIES.

physical phenomena may give rise to unsteady forces, including structural interactions associated with rotating and reciprocating machinery, electromagnetic effects, and interactions between fluids and structural surfaces.

Unsteady fluid forces act on structural surfaces because of fluctuating pressures that occur in flowing or stationary fluids; unsteady flow disturbances (such as produced by fans, compressors, turbines, or hydraulic motors); turbulence (e.g., in atmospheric wind and in high-Reynolds-number regions in ducts or pipes); and other phenomena that produce varying pressures.* The latter category includes sound. Indeed, if a sound field in the interior of an airtight enclosure could not set the enclosure's walls into vibration, no corresponding sound would result on the outside of that enclosure.

Any vibrating structure that is in contact with air (or any other fluid) tends to radiate sound, much in the manner of a loudspeaker. Whether this sound can be heard depends on its intensity and frequency content. Intense low-frequency vibrations - e.g., of a fan room floor - often can be felt and may cause structural damage, but cannot be heard (see Sec. 7.1.3). On the other hand, the minute structural motions of a pipe wall near a valve that produces cavitation cannot be felt and are not likely to cause structural damage, but may produce extremely loud audible sound.

As in the latter example, structural vibrations often play a major role in the path from a primary sound source to a receiver. Vibrations often involve extended structures and may be visualized as propagating from one structural component to the next. Because sound may be radiated by vibrating structures not only in

* Flow-induced vibrations constitute a complex technical topic. A recent summary discussion appears in [6.32].

the immediate vicinity of the locations where the fluctuating forces are applied but also from locations remote from the excitation, structural vibrations can cause enhancement of the spreading of noise produced by a given source.

To obtain some appreciation of the factors involved in structural vibrations, consider the idealized case of a reciprocating pump fastened to the floor of a building (see Fig. 6.13). The inertia forces produced by the reciprocating elements of the pump tend to make the floor vibrate in the vertical direction. If the pump is driven at a very low speed, it produces forces at a very low frequency, and the floor vibrations generally are not severe. At low frequencies, the floor vibrations are not necessarily most pronounced at the location of the pump attachment points; usually, the vibration amplitude is greatest where the stiffness of the floor to vertically applied static forces is minimum - typically in the middle of the unsupported floor span.*

If a given static load is applied to any structural component, such as a floor, the component deflects different amounts at different locations. If a low-frequency fluctuating load is applied in place of the static load, the structure exhibits a distribution of vibratory displacements that is similar to the deflection distribution that results under static loading. As the excitation frequency increases, the dynamic displacement distribution tends to deviate more and more from the static distribution, until at the first resonance frequency (discussed in the following paragraphs) the distribution of

* The situation here is somewhat analogous to that of a lever, where points that are located further from the fulcrum than the point of application of a force move more than the point of application. Well-supported locations, such as floor edges supported by walls, beams, and columns, correspond to relatively immobile fulcrum positions.

FIG. 6.13. SCHEMATIC SKETCH OF FLOOR VIBRATIONS DUE TO RECIPROCATING PUMP.

- a. Instantaneous floor displacement associated with low* frequency vibration.
- b. Typical instantaneous floor displacement associated with high* frequency vibration.
- c. Typical instantaneous floor displacement associated with very high* frequencies.

*"High" and "low" refer to the vibration frequency compared to the lowest natural frequency of the floor.

oscillatory displacements is in essence independent of the location of the exciting force.

At a resonance frequency (also called a "natural frequency"), a structure can be set into motion relatively easily. If a structure is displaced from equilibrium and released, it vibrates - in the absence of externally applied forces - at its natural frequency, just as a pendulum oscillates at its characteristic natural frequency when it is released from a deflected position. And, just as one can "pump" a playground swing into violent motion by pushing on it at the appropriate frequency, one can induce intense motions in structures by small forces that act at a structural resonance frequency.*

However, unlike a simple pendulum, which has a single resonance frequency, a structure has a multitude of resonance frequencies. Each such frequency has a corresponding spatial distribution of displacements called a "mode shape" (see Fig. 6.14). The lowest (or "first") resonance frequency is called the "fundamental resonance frequency"; the condition where the frequency of the applied force matches a resonance frequency is called "resonance." For a simple structure, such as a plate or single-span floor, the mode shape associated with the fundamental natural frequency corresponds to a simple dishing motion, where all points move up and down in unison. The higher frequency mode shapes correspond to more complex dishing motions with multiple corrugations, where some regions move upward, others move downward, and some locations (called "nodes") do not move at all.

* The concepts of resonances and modes, as well as the effects of structural and excitation parameters on the vibration response of structures, are discussed in texts and handbooks dealing with vibrations or structural dynamics; e.g., see [6.33,6.34].

FIG. 6.14. TYPICAL MODE SHAPES OF A PLATE

(a) Fundamental Mode

(b) A Higher Mode

Heavy curves show instantaneous shapes to which light lines on undeflected surface are changed during a particular instant, if the plate vibrates at one of its resonances.

For a given magnitude (amplitude) of oscillatory force acting at a given location on a given structure, the resulting structural motion depends essentially only on the structural stiffness that opposes the force (and varies inversely as this stiffness), as long as the forcing frequency is less than the fundamental resonance frequency. For cases where the forcing frequency matches a resonance frequency, the motion amplitude depends primarily on the structure's damping - i.e., on its capacity for dissipating mechanical energy (or, more properly stated, for converting mechanical energy into heat). At resonance, the amplitude is inversely proportional to the structural damping. At high excitation frequencies, that portion of the structure's mass which is most directly affected by the exciting force determines the amplitude of the resulting motion, the motion, amplitude being inversely proportional to this mass [6.35].

A vibrating structural component that is connected to other components tends to set these neighboring components into vibration. In the majority of instances, a structural component on which an exciting force acts directly may be expected to vibrate more than components connected to the directly excited one. However, the reverse can also occur, particularly if the indirectly excited components are much less stiff or massive than the directly excited one, or if an indirectly excited component has a natural frequency that matches the frequency of the exciting force. For example, because of any one of the foregoing reasons, a thin separation wall in contact with a fan room floor may vibrate much more than the heavier floor (and radiate much more noise), even though the fan unbalance acts directly on the heavier floor.

The propagation of vibrations from one structural component to another depends on how well the components are interconnected,

on the constraints imposed by the interconnection, on the ratios of the masses and stiffnesses of the components, and on how well the resonance frequencies of the components match (see Ref. 6.36). Better connection improves propagation. If the separation wall of the previous example is cemented to the fan room floor along its entire bottom edge, the wall is likely to vibrate more than if it were raised from the floor and connected to it by blocks located a few feet apart. Similarly, if the rigid cement joint were replaced by one of soft rubber, the wall vibrations would be reduced. On the other hand, if a rigid steel beam or massive concrete beam were introduced between the floor and wall, this beam would impede the propagation of vibrations to the wall. In general, propagation at high frequencies is reduced if the mass per unit area of the wall differs from that of the floor by a large ratio (in either direction), if the same is true of the stiffnesses per unit edge length, and if no resonance frequency of the wall matches any of the floor within about 10%.

Vibrations of a structural component, like static deflections, generally involve various types of deformations simultaneously - namely, tension/compression, shear, torsion, and flexure (bending). For radiation of sound, flexure is usually most important because it typically results in the largest displacements normal to structural surfaces. However, all types of deformations may play significant roles in the propagation of vibratory energy; and at structural joints, edges, or reinforcements, complex interactions and conversions generally occur among the various deformation types [6.36].

At high frequencies - that is, at frequencies that are considerably above the fundamental resonance frequency of the structural component of interest - the vibrational behavior of structures that incorporate reasonable amounts of damping may be visualized and analyzed more readily in terms of waves than in

terms of modes. Waves spread out from the excitation point, experience attenuation due to damping, are subject to further amplitude reduction caused by spreading (if the structural geometry permits), and suffer absorption and reflection at any edges or discontinuities.

The situation is usually complicated because waves in structures are much more complex than sound waves in air. Waves in structures generally include longitudinal, torsional, and flexural components that interact, particularly at discontinuities. Also, geometric spreading of waves in structures is different than that for the usual three-dimensional situation corresponding to sound waves propagating in the atmosphere. Waves propagating along one-dimensional structures, such as beams, do not spread and suffer no corresponding attenuation; waves on plates or shells spread in two dimensions, and waves propagating in the interior of solid bodies spread three-dimensionally.

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7. NOISE RECEPTORS AND ACCEPTABLE NOISE LEVELS

Noise can affect people, wildlife and domestic animals, structures, and dynamically sensitive equipment in a variety of ways. Knowledge of these effects is essential to:

- . Quantify noise control requirements that will preserve the health and welfare of people exposed to noise;
- . Assess and control environmental impacts in compliance with the National Environmental Policy Act and similar state legislation;
- . Assure the integrity of structures and the reliability of dynamically sensitive equipment.

The discussion of noise in this section is divided into noise effects (Sec. 7.1) and noise regulations, practices, and guidelines (Sec.7.2). Noise effects, shown graphically in Fig. 7.1, include those on people, wildlife, and equipment. Noise regulations, practices, and guidelines represent attempts to standardize the selection of suitable noise immission limits.

7.1 Noise Effects

7.1.1 People

The effects of noise on people can be divided into two classes: primary, which result in loss of hearing acuity, and secondary, which interfere with activities. Primary effects include noise-induced temporary or permanent hearing threshold shifts (TTS or NIPTS). The secondary effects include interference with aural communication, recreational activities (radio and television listening), and sleep; annoyance; and the generation of complaints about noise.

Both classes of noise effects have been studied in detail over the past three decades. This discussion has been drawn

FIG. 7.1. EFFECTS OF NOISE.

primarily from the excellent summary of these studies published by Dr. J.D. Miller of the Central Institute for the Deaf [7.1]. Dr. Miller's summary was approved for publication by a majority of members of the National Academy of Sciences - National Research Council Committee on Hearing, Bioacoustics and Biomechanics (CHABA). Members of this committee are generally considered to be the country's foremost scientific authorities on noise effects.

PRIMARY EFFECTS

Hearing Damage

Exposure to brief, intense sounds can cause immediate damage to the ear, but this is a rare occurrence. Of greater importance is the fact that lower level sounds of sufficient intensity and duration can reduce the ability to hear. Some of this hearing loss is temporary (TTS), though it can last for hours after the noise ceases. However, if the exposure is sufficiently intense or prolonged, it can cause chronic or permanent hearing loss (NIPTS).

Analysis of this phenomenon is complicated by the difficulty of observing or defining prolonged noise exposure (i.e., over a working lifetime), by differences among individuals, by the normal hearing loss of middle and old age, and by the problem of defining an "important" hearing loss. Controversy has centered around all these issues during recent Department of Labor (DOL) regulatory hearings on employee noise-exposure standards.

Hearing damage is illustrated in Fig. 7.2 [7.2]. Three groups of workers, exposed for various periods of time* to

* Normally assumed to be 8 hours/day, 5 days/week, 50 weeks/year.

FIG. 7.2. NOISE-INDUCED PERMANENT THRESHOLD SHIFTS (NIPTS) PLOTTED AGAINST YEARS OF OCCUPATIONAL EXPOSURE TO NOISE FOR WORKERS IN THREE LEVELS OF NOISE.

Note: These Threshold Shifts Have Been Corrected For The Changes With Age Found In Persons Without Occupational Exposure To Noise. The Graphs Are For A Test Tone Of 4000 Hz, And The Data Points Are Medians [7.2].

workday environments of 83, 92, and 97 dB(A), were found after about 10 years to have an average NIPTS ranging from 11 to 45 dB. The threshold shifts were tested at 4000 Hz, the test frequency at which noise-induced hearing loss is most pronounced. Numerous other studies have shown similar effects, although the worker-to-worker variations are large.

Temporary threshold shift (TTS) is not usually considered to be a health problem, except in cases where it is so severe that recovery is not possible over the employee's 16-hour-per-day rest period, or over a weekend. However, while it lasts, TTS certainly interferes with speech communication and the detection of hazards by hearing. Figure 7.3 shows Miller's attempt to summarize the available information on noise-induced threshold shift for noise exposures in the 2400- to 4800-Hz range.

Temporary threshold shifts greater than 35 to 40 dB at 4000 Hz are said to be in the "region of possible acoustic trauma." In this region, Miller says, "for some people, the normal processes of the ear may 'break down' and permanent threshold shifts - hearing loss - may result from even a single exposure to noise."

From a study of all available data, Miller concludes that "clear evidence is available that noise with A-weighted sound levels above 80 decibels can contribute to inner-ear damage and eventual hearing handicap if such noises are frequently and regularly encountered."

It is important to note that the hazard to hearing from noise exposure is a function of the duration and frequency of exposure as well as a function of the level of the noise.

FIG. 7.3. HYPOTHETICAL GROWTH OF THRESHOLD SHIFT AFTER VARIOUS SINGLE AND CONTINUOUS EXPOSURES TO NOISE.

Note: These Curves Represent Predictions For An Average, Normally Hearing Young Adult Exposed To A Band Of Noise Or Pure Tone Centered Near 4000 Hz. These Are "Worst-Case" Conditions, As The Ear Is Most Susceptible To Noise In This Region. These Hypothetical Curves Were Drawn To Be Consistent With Current Facts And Theory. They Are For An Average Ear; Wide Differences Among Individuals Can Be Expected. In Many Cases, Extrapolations Had to Be Made From Appropriately Corrected Data From Animals (Cats and Chinchillas).

Impulsive Sounds

The physiological mechanisms by which brief impulsive sounds can cause permanent hearing damage are believed to be somewhat different than the causative mechanisms of more or less continuous noise exposure. They are dependent upon the instantaneous peak overpressure and the duration of the impulse. When the impulse is heard indoors, the durations of secondary pulses reflected from the walls of the room must also be included [7.3].

In general, it is believed that exposures to as many as 100 impulses a day that have instantaneous peak overpressures below 138 dB will not result in a permanent threshold shift.

Other Health Effects

Other deleterious effects of noise on human health have been claimed, including nausea, headaches, instability, sexual impotence, anxiety, and general stress. No conclusive evidence as to the validity or extent of these effects is available. Miller concludes that "the evidence support(s) that, if noise control sufficient to protect persons from ear damage and hearing loss were instituted, then it is unlikely that the noise of lower level and duration resulting from this effort could induce non-auditory disease" [7.4]. The U.S. Environmental Protection Agency (EPA) has taken a similar position.

Infrasound and Ultrasound

Infrasound is generally considered to be sound in the frequency range from 0.1 Hz to 20 Hz, whereas ultrasound encompasses those sounds with frequencies above 20 kHz. Relatively little is known about the effects of infrasound and ultrasound on

humans, except that it is evident that people are much less sensitive to infrasound and ultrasound than they are to sounds in the normal frequency range.

In the past few years, the press has publicized the presumed hazards of infrasound. These include affecting the balance mechanism of the ear, producing fatigue or nausea, and creating a condition similar to drunkenness. Available experimental evidence indicates that these presumptions are unfounded. Johnson, in his recent survey of the subject, claims that infrasound at levels below 130 dB is quite innocuous [7.5]. Infrasonic levels of 140 dB are considered safe for the crew of the Apollo rocket. In the infrasonic range of 150 to 153 dB, humans can feel the abdominal and chest walls moving, but large animals have been exposed to levels as high as 172 dB with no discernible effect. Johnson summarizes the effects of infrasound as follows:

Whole Body Effects - Start noticing adverse subjective effects past 150 dB. Tolerance limit not reached. Middle ear pressure buildup starts at 130 dB as well as voice communication modulation.

Respiration - Definite effect once 166 dB is reached.

Vestibular - No effect identified on human subjects at levels as high as 155 dB. Effect on animals does occur occasionally, but at very high sound pressure levels.

Auditory - A small amount of TTS has occurred for exposures longer than 20 minutes, but generally a level below 150 dB is not expected to produce adverse results if the exposure duration is less than 30 minutes.

When the alleged hazards of infrasound are considered, it should be borne in mind that fluctuations in pressure on the order of 125 dB occur naturally on a windy day [7.6]. A man jogging encounters a 90-dB infrasonic exposure simply because of barometric pressure variations as his head changes altitude [7.5]. These exposures are harmless, even though exposure to the same sound levels in the audible frequency range would be considered hazardous.

Ultrasound is attenuated very rapidly in the air, so exposures to humans are rare. However, no adverse effects have been observed at exposures below 105 dB [7.7].

Whole-Body Vibration

Whole-body vibration can affect the comfort and working efficiency of those exposed to it. If sufficiently intense, it can also affect health.

Human adults are most sensitive to vibration in the head-foot direction in the frequency range around 7 Hz, because in this range, the viscera resonate in the thoracic cavity. Exposure limits, established on the basis of comfort, are in the range of 0.5 to 25 m/sec. Further details are given in Sec. 7.2.

SECONDARY EFFECTS

Speech Interference

Noise can "mask" other sounds, making them inaudible to listeners. Masking is a complicated process, for man has a formidable ability to "hear out" or distinguish one sound in a medley of sounds.

One of the more important effects of masking is the way in which it restricts the intelligibility of speech. The amount of speech interference present in a given situation is governed by three principal factors:

- . Vocal effort of the talker
- . Noise level of the environment
- . Distance between listener and talker.

Other factors also influence speech interference to a lesser extent. They include familiarity of the talker and the listener with the language, the amount of redundancy in the speech material, and reverberant characteristics of the acoustical environment. These other factors, although important in specific situations, are generally not considered in determining the amount of speech intelligibility in noisy environments.

A relationship between communicating distance, noise level, and vocal effort was established by Beranek [7.8] and presented later in modified form by Webster [7.9]. The result of this relationship is shown in Fig. 7.4, where adequate intelligibility is taken to be the understanding of 90% of the key words in sentence material.

Figure 7.4 shows that two people should be able to communicate with normal vocal effort at a distance of about 10 feet against a noise background with a level of 55 dB(A). Recent studies involving traffic noise indicate that variable speech-interference effects associated with the time-varying character of such noise is well accounted for by the L_{eq} measure of the noise.

Sleep Interference

The effects of noise on sleep cannot be stated as precisely as the effects of noise on speech intelligibility, partly because of the highly complex nature of sleep itself. There is as yet no universal agreement as to what constitutes "sleep disturbance," for the sleep disturbance process involves aspects of sound other than its physical properties. At one extreme, a mother can be awakened by a faint cry of her child; at the other extreme, soldiers can sleep through continuous artillery fire. Thus, the

FIG. 7.4. NECESSARY VOICE LEVELS AS LIMITED BY AMBIENT NOISE FOR SELECTED DISTANCES BETWEEN TALKER AND LISTENER FOR SATISFACTORY FACE-TO-FACE COMMUNICATION.

Note: Along the Abscissa Is The Noise Level. The Ordinate Is Distance, And The Parameter Is Voice Level. At Levels Above 50 dB(A), People Raise Their Voice Level, As Shown By The "Expected" Line, If Communications Are Not Vital, Or By The "Communications" Line If Communications Are Vital.

meaning conveyed by a sound is extremely important in its ability to awaken.

Some evidence of the effects of sound level on sleep is available from laboratory studies. The laboratory studies do not indicate precise noise levels that interfere with the sleep process. Rather, a broad span of levels ranging from 40 to 80 dB(A) (measured indoors) can have varying amounts of effects on people's sleep. Figure 7.5, taken from a summary of laboratory studies on sleep interference caused by brief sounds (under 3 minutes [7.1]), illustrates this point. Figure 7.5 shows that levels near 70 dB(A) have been found to waken only 10% to 20% of one subject group in a particular experiment. In contrast, in a different experiment, levels of 40 dB awoke 55% of the people from a specific sleep stage.

A suggested "threshold" for sleep disturbance caused by noise is 35 dB(A). This arbitrary level is often recommended for bedrooms by acoustical consultants. However, we are aware of no studies that indicate that steady sounds below 40 dB(A) interfere with sleep.

Most of the tests relating to the effects of noise on sleep have utilized individual noise events, such as aircraft flyovers or truck passbys, which intrude above the background noise. These short, intrusive sounds may disrupt sleep more than a steady noise of equal level. It has been suggested by some researchers that steady, periodic, or rhythmic background sounds may improve the quality of sleep [7.1]. Indeed, some products advertised as aids to sleeping simply produce steady sounds that mask the brief, disturbing sounds that might otherwise disturb sleep.

FIG. 7.5. AWAKENINGS TO SOUND FROM VARIOUS LABORATORY AND QUESTIONNAIRE STUDIES (From Ref. 7.1).

Note: The Horizontal Axis Gives The Approximate A-Weighted Sound Level [dB(A)] Of The Noise. The Curves Labeled "Awakening" Are From Normally Rested Young Adults Who Were Sleeping In A Laboratory And Were Moderately Motivated To Awake In Response To Sound. The Percentage Of Awakening Responses Will Depend Not Only On The Intensity Of The Sound But Also On The Definition Of "Awakening", The Motivation Of The Subject To Awake In Response To Sound, And The Sleep Stage (I, II, III, IV, Or I-REM) When The Stimulus Is Presented.

Astronauts, sleeping in space vehicles, report disturbance from intermittent, irregular noises. A higher, steady noise to mask out these intermittent sounds is being considered for the space shuttle project during which astronauts may spend as long as a month in space.

Since the generally accepted threshold for sleep disturbance [35 dB(A)] is lower than that for any other noise effect, attention often focuses on sleep interference in environmental controversies concerning noise. Recent examples of such controversies involving the energy technologies include 765-kV transmission lines [7.10] and construction of nuclear power plants [7.11].

Clearly, more research is needed on the effects of noise - particularly steady noises - on human sleep.

Annoyance

Sleep and speech interference, interference with TV and radio listening, interference with relaxation, and other activity-interference phenomena owing to noise presumably result in annoyance on the part of the hearers.

Annoyance caused by noise is measured by conducting attitude surveys of people exposed to noise. Recently, T.J. Schultz completed a comprehensive study of 19 such surveys conducted in nine different countries [7.12]. From 12 of these surveys, he deduced a "universal response curve" relating the percentage of persons reporting they are highly annoyed by noise to the noise level. This curve, together with the results from the 12 surveys, is shown in Fig. 7.6.* The curve has the equation:

* The average of the other seven surveys is essentially the same.

FIG. 7.6. SUMMARY OF NOISE-ANNOYANCE DATA FROM 12 SOCIAL SURVEYS.

Note: The Heavy Curve, An Empirical Fit To The Data, Has The Equation Shown In The Text [7.12].

$$\%H.A. = 0.8553 L_{dn} - 0.0401 L_{dn}^2 + 0.00047 L_{dn}^3 .$$

Schultz's work provides the best current (1977) information for predicting community annoyance owing to noise. It supercedes similar results published by the U.S. EPA in 1974 [7.13].

Impulsive sounds are generally considered to be more annoying than steady sounds of the same continuous, A-weighted energy level. The controversy surrounding the proposed U.S. development of a supersonic transport in the late 1960's led to extensive studies of the attitudes of communities to sonic booms [7.14,7.15]. From this data base, criteria have been developed for annoyance caused by impulsive sounds based upon the 24-hour C-weighted energy equivalent level of the impulse. These criteria are described in Sec. 7.2.

Complaints

In some instances, members of a community exposed to noise will complain about it in the hopes of initiating corrective action. Complaints presumably result from intensive and extensive annoyance caused by noise in a community, although the complainants may not be those most exposed to the noise.

Over the years, several procedures have been developed to predict the complaint potential of a new noise intrusion into a community. These procedures are described in Sec. 7.2.

7.1.2 Wildlife, domestic, and laboratory animals

In view of the difficulty of observing animals and the diversity of species that might be affected, it is not surprising that relatively little is known about the effects of noise on

domestic animals and wildlife. Of what has been published on the subject, much is deficient either zoologically or acoustically. Only rarely - except in laboratory studies of the auditory functions of animals - are these two disciplines combined.

Studies of the effects of noise on animals can be divided into three broad categories: effects on wildlife, effects on domesticated (farm) animals, and effects on laboratory animals. Fletcher adopted these classifications in his comprehensive literature survey of the subject in 1971, and much of the material below is drawn from his work [7.16].

Wildlife

Table 7.1 summarizes what has been reported about the effects of noise on wildlife.

As with men, the effects of noise on wildlife can be divided into physiological (hearing) impairment and activity interference. The former is quite rare, perhaps because wildlife would tend to leave the area where such intense noise exposures occurred. Activity interference is presumably much more common.

Acoustic masking by noise is the most likely source of activity interference for wildlife. Many animals use acoustic signals for detection of prey or predators, locating young, and establishing territoriality, and for mating calls [7.17]. Noise can interfere with all of these functions. Animals such as bats, which have highly developed acoustic functions, could be particularly affected [7.18], although it has been found that bats are resistant to jamming [7.19]. Similarly, one would suspect that songbirds would be susceptible to noise interference, although most studies have shown that, other than a

TABLE 7.1. EFFECTS OF NOISE ON WILDLIFE — SUMMARY
(After Fletcher [7.16]).

Class	Family or Genus	Effect	Noise Source	Level	References (See end of Table)
MAMMALS	Rats and mice	— decreased nesting near sound source — death at very high levels	—	60 to 140 dB	Sprock, Howard and Jakob (1967)
	Norway rats and mice	Aversion to sound	Pulsed ultrasound	—	Greaves and Rowe (1969)
	Gray whales	Reversed direction of movement	Killer-whale sounds	—	Cummings (1971)
	White whales	Prevent river migration	Tones, noise, and killer-whale sounds	—	Fish and Vania (1971)
	Bats	Histophysiological changes in pineal gland and supraoptic nucleus	Bell	60 dB	Miline, Devercerski and Kastic (1969)
	Bats	Driven out of nuclear power station	Dog whistles	—	Hill (1970)
	Rabbits, deer, and some birds	Repelled	"Av-Alarm" (a commercial device)	—	Crummett (1970)
	Sea Lions	Death	Underwater explosion	—	Fitch and Young (1948)
	Reindeer	"Disturbed"	Power-line hum	—	Klein (1971)
BIRDS	California Brown Pelican	Death, if head is underwater	Underwater explosion	—	Fitch and Young (1948)
	Unspecified	Repelled	Own distress calls	—	Langowski, Wight, Jacobson (1969)
	Starling	Flocks dispersed	Own distress calls	—	Pearson, Skon and Corner (1967) See also Thompson, Grant, Pearson and Croner (1968a) and 1968b); see also Block (1966)
	Japanese Quail	Increased song frequency and level	—	63 dB	Potash (1972a)
	Unspecified	No disturbance	Aircraft	75 to 96 dB	DOI EIS on Big Cypress Swamp Jetport
FISH	Unspecified (school)	Driving and changes in direction of school	Ship noise	—	FAO Fisheries Report No. 16 (1968)
	Goldfish	"Locomotion patterns"	—	80 dB	Malar and Kleere-koper (1968)
	Unspecified (with air bladders)	Death, but others do not leave area	Explosion	—	Aplin (1947)
INSECTS	Indian meal moth	Reduction in emergence from larval stage	—	—	Kirkpatrick and Harepin (1965)
	Indian meal moth and flour beetles	Little effect	—	70 to 134 dB	Lindgren (1969)
	Indian meal moths	Ceased movement	"Loudspeaker, bells and whistles"	—	Tsao (1969)
	Corn earworm moths and Mediteranean flour beetles	Reduced longevity	Pulsed ultrasound	65 dB	Cutkomp (1969)
	Locusts	Flying response	—	80 dB	Shulov (1969)
	Honeybees	Cessation of movement	—	107 to 119 dB	Frings and Little (1957)
	Mole midges	Attracted to sound	—	13 to 18 dB above ambient	Frings and Frings (1959)

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startle reflex that is usually habituated, birds are more responsive to the information content of interfering acoustic signals.*

Studies by the U.S. Department of the Interior for the Big Cypress Swamp Jetport indicated that jet-aircraft flyovers producing noise levels in the range of 75 to 97 dB did not flush or disturb birds underneath [7.20]. Indeed, travelers have noted that flocks of birds and small mammals seem to live on the grounds of major jetports in the United States, a location certainly too noisy for human residences.

Leitner is presently studying the effects of noise from the Geysers geothermal facilities in California on wildlife in the area. Though these studies are not yet complete, preliminary results indicate that there is "no significant effect" from the rather intense noise existing there [7.21].

In general, the published studies of the effects of noise on wildlife reveal great gaps in our knowledge. Important species (such as those on the endangered list) have been ignored. Many studies have been directed at wildlife control rather than wildlife protection. Acoustic or biological information is missing. Studies have not been performed in the natural habitat, or have not been long enough to detect possible slow but permanent changes in ecological balance. There is clearly a need for further research in this area.

On the effects of noise on wildlife, the U.S. EPA has stated [7.13]:

* Fletcher's summary indicates that almost all studies of the effects of sounds on birds were concerned with acoustic means for dispersing birds from farm fields, airports, etc. Historically, the success of such efforts has been mixed.

Considerable research needs to be accomplished before more definitive criteria can be developed. The basic needs are:

- More thorough investigations to determine the point at which various species incur hearing loss.
- Studies to determine the effects on animals of low-level, chronic noise exposures.
- Comprehensive studies of the effects on animals in their natural habitats. Such variables as the extent of average reactions, physiological changes, and predator-prey relationships should be examined.

Until more information exists, judgments of environmental impact must be based on the existing information, however incomplete. The most simple approach is to assume that animals will be at least partially protected by application of maximum levels identified for human exposure.

In a critique of U.S. EPA research plans, the Office of Technology Assessment stated [7.22]:

Wildlife populations can be disturbed significantly in mating, reproduction, and other behavior by the noise from construction (e.g., Alaska pipeline), off-the-road vehicles (e.g., south-west desert), transportation (SST's, cars), and other sources. Aquatic organisms, like whales and dolphins, can also be substantially disturbed by noise ... Research may be needed on effects of noise on wildlife because none now exists within the Federal establishment,* despite its importance to the survival of wildlife populations. Animals do not sense noise in the same way as humans do. Rather, they respond to a different set of frequencies, and often in different and more dramatic ways. Regulations controlling the noise generated by machines adequate for human protection may not be adequate for wildlife (e.g., off-the-track vehicles).

* This statement is not strictly true. Dr. Leitner's work is funded by DoE and NSF, and the U.S. Forest Service has also supported a small amount of work in this area. The USAF has supported a number of studies of the effects of aircraft noise and sonic booms on farm animals.

Domestic Animals

Somewhat more attention has been paid to the effects of noise on farm and other domesticated animals, perhaps because of their commercial importance. However, Fletcher states, "experimental controls and adequate response measurement techniques have been lacking ... (and) ... it is difficult to compare the effects of noise on one type of domestic animal with effects found in other domestic animals."

A summary of some of the published studies of the effects of noise on domestic animals is given in Table 7.2. In general, although some of the noise exposures were intense, the effects observed were minor, probably because farms are often very noisy places. For example, sound levels have been reported in chicken houses ranging from 75 to 83 dB(A); in pig pens from 84 to 103 dB(A); and in cow barns from 59 to 64 dB(A) because of the vocal activity of the animals themselves and of associated farming machinery.

Laboratory Animals

Laboratory animals have been used extensively to study the physiological effects of intense sounds, particularly on the auditory systems of small mammals. This work will not be discussed here. A summary through 1970 is given by Fletcher [7.16].

7.1.3 Effects of noise on structures and sensitive equipment

In structures, vibration can produce stresses intense enough to cause immediate failure. Typical examples are the cracking of plaster by nearby blasting activities and the shattering of

TABLE 7.2. EFFECTS OF NOISE ON DOMESTIC ANIMALS — SUMMARY
(After Fletcher [7.16]).

Family or Genus	Effect	Noise Source	Level	References (See end of Table)
Swine	No significant effect	Aircraft	120 to 135 dB	Bond, Winchester, Campbell and Webb (1969)
Swine	Increased pulse rate, motion	300 to 600 Hz	130 dB	Bond (1963)
	No effect	700 to 5000 Hz	100 to 120 dB	Bond (1970)
	Activity, then in- difference	Baby pig squeal	100 dB	Bond (1970)
Swine (young cas- trated males)	Aldosteroidism; "severe" water and sodium reten- tion	—	93 dB	Bugard (1960)
Milk cows	No difference in milk production	Aircraft		Parker and Bayley (1960); Casady and Lehman (1966)
Cows	Did not give milk during stimuli	Exploding paper bags	—	Bond (1956)
Cows	Decrease in milk production	Motorboat noise	—	Oda (1960)
Cows	"Mild reaction"	Sonic boom	0.75 to 2.6 psi	Bond (1956)
Hens (fertilized eggs)	No effect	—	120 dB	Stadelman (1958a)
Hens (fertilized eggs)	No effect	Sonic boom	0.75 to 1.25 psi	Bell (1970)
Hens	No effect on egg production	Traffic noise	95 dBC	Kagan and Ellis (1974)
Hens	Greatly diminished brooding	—	120 dB	Stadelman (1958a)
Hens (baby)	No effect on chick growth	Aircraft Noise	80 to 115 dB	Stadelman (1958a) Stadelman (1958b) Stadelman (1958b)
Turkeys	Broodiness interrupted	Jet aircraft noise	110 to 135 dB	Jeannoutot and Adams (1961)
Mink	Increased litter size Curiosity, no panic	Sonic booms	0.5 to 2.0 psi	Travis, Richard- son, Menear and Bond (1968)
Mink	No effect	Sonic booms	—	Bell (1970)

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windows by sonic booms from supersonic aircraft. Continuous vibration exposures at lower levels can also produce failures, usually caused by fatigue; these generally occur when some resonance of the structure is excited.

Structural responses to ground vibration from blasting are considered in Ref. 7.23, and exposure caused by airborne blasts are given in Ref. 7.24.

CHABA has recommended that continuous exposures to noise be limited to 130 dB and to vibration to 2 inches per second for structural safety [7.25]. See Sec. 7.2.2.

When sensitive equipment is to be exposed to intense sound and vibration, it is common to test such equipment beforehand in a simulated dynamic environment in order to qualify the equipment for use under actual conditions. Test specifications, for example [7.26], exist for these purposes.

7.2 Regulations, Practices, and Guidelines Regarding Noise

Noise regulations, practices, and guidelines that provide noise limits are attempts to judge the effects of noise on people in terms of the practical costs and benefits of a noise reduction or regulation effort. Such documents exist both for familiar noise sources and for acoustic noise in general. It is instructive, therefore, to examine these documents for their pertinence to the developing energy technologies.

Modern noise regulations generally set quantitative noise limits that are believed to be enforceable, technically and economically feasible, and sufficient to protect the public health and welfare. Regulations are legal requirements and are intended to withstand the rigors of a court test.

Recommended noise practices are formulated by professional societies, industrial groups, and/or trade associations. Often called "standards,"* these recommended practices are advisory and their use is purely voluntary. A good noise practice is developed with attention to technical and economic feasibility. However, the beneficiary of the practice may not necessarily be the public health and welfare. Potential enforceability need not be a consideration in a practice, though some recommended practices have subsequently been adopted by government agencies as regulations.

Noise guidelines represent desiderata, or goals, as to what would constitute an acceptable noise impact. Such guidelines are often based solely upon considerations of public health and welfare, without consideration of technical or economic feasibility, or of enforceability.

Such guidelines are often adopted as standards when they constitute the goal of a regulatory program. However, in the absence of regulatory intent, the use of guidelines is voluntary.

Some regulations, practices, and guidelines draw a distinction between primary and secondary limits or standards. Familiar examples are the primary and secondary standards for certain air pollutants. The achievement of primary standards is considered to be important for the protection of public health or safety. The additional achievement of more stringent secondary standards is considered to be beneficial to the public welfare for esthetic or other reasons not related to health. Analogous primary and secondary goals exist in the noise field, although they are not often referred to as such.

* "Standards" in this context are not to be confused with legal or regulatory standards that may be established by government agencies as the goals of a regulatory program.

7.2.1 Primary (health) regulations

Employee Noise Exposure Regulations

Under the Walsh-Healey Public Contracts Act and subsequently under the Occupational Safety and Health Act of 1971 [7.27], the U.S. Department of Labor has established regulations limiting the exposure of employees to noise in the workplace [7.28].* These are commonly referred to as the "OSHA Noise Regulations."

The present occupational noise regulations state, in essence, that an employee shall not be exposed to a noise level higher than 90 dB(A) continuously during his 8-hour workday. Exposures to more than 90 dB(A) are permitted for periods of less than 8 hours/day according to a formula that allows for a 5-dB(A) increase for each halving of exposure time. The limit is 115 dB(A); no exposure is permitted above that level. Impulsive sounds may not exceed 140-dB peak.

The occupational noise regulations are based upon a body of data indicating that prolonged (i.e., 8 hours/day, 5 days/week, 50 weeks/year, for 30 to 40 years) exposures to intense continuous noise can cause some people to suffer a loss of hearing sensitivity (i.e., "hearing damage"). See Sec. 7.1.1. The nominal 90-dB(A) limit is also based upon considerations of technical and economic feasibility.

The OSHA Noise Regulations are now being reviewed. EPA, which believes that the limit should be 85 dB(A), is presently engaged in a disagreement with DOL on this matter. EPA also

* The regulation of occupational noise exposures in coal and other mines derives from different authority, but the exposure limits are substantially the same. Regulations for mines are promulgated by the Mine Safety and Health Administration recently established in the Department of Labor.

argues that the escalation formula should allow a 3-dB(A), rather than a 5-dB(A), increase in noise levels with a halving of exposure time.

Members of the President's Council on Wage and Price Stability, on the other hand, state that any workplace noise limit would be inflationary and unjustified.

The EPA "Levels" document [7.13] (see Sec. 7.2.2) includes a guideline level of 70 dB(A) L_{eq} for continuous 24-hour exposure [usually equivalent to an L_{eq} of 75 dB(A) for an 8-hour workday exposure] to protect against hearing damage "with an adequate margin of safety." This guideline, of course, does not take into consideration technical or economic feasibility.

USAF (ERDA) Noise Exposure Regulation

U.S. Air Force Regulation 161-35 establishes limits for hazardous noise exposure to USAF personnel [7.29]. This regulation is presently undergoing revision by the USAF and may soon become obsolete. However, it has for some years been employed as an in-house policy by ERDA and its predecessor, the AEC. In substance, the USAF Regulation establishes the following:

- . Noise-exposure limits for hearing preservation that are similar in concept to those of OSHA, but more stringent. They start at 84 dB(A) [rather than 90 dB(A)] for an 8-hour exposure, and they have a doubling rate of 4 dB. Ear protection must be worn by personnel whose noise exposure exceeds these limits.

Without ear protection, exposure is not permitted to ultrasonic sounds exceeding 85 dB in any 1/3-octave band.

- . Noise limits for whole-body exposure to personnel wearing ear protection, as follows:

<u>Frequency Band</u>	<u>Limit</u>
1-12.5 Hz (infrasonic)	150 dB in any 1/3-octave band
16-80 Hz	145 dB in any 1/3-octave band
Audible range	150 dB(A)
12.5k-40 kHz (ultrasonic)	150 dB in any 1/3-octave band

- . Noise exposure limits for "performance" purposes, based upon the need for speech communication in various interior spaces.
- . Requirements for audiometric testing of noise-exposed personnel.
- . Procedural and recordkeeping requirements.

Technically, USAF Regulation 161-35 is a very good document. Its application by DoE may be somewhat cumbersome, however, because of its military tone. The procedural parts of the regulation are not likely to be applicable to DoE organizations. The regulation does not address noise exposure to communities surrounding operating facilities or to wildlife.

Limits for Exposure to Impulsive Sounds, Recommended by CHABA

CHABA has developed suggested limits for human exposure to impulsive sounds (up to 100 pulses/day) [7.3] to avoid human hearing damage. These limits, shown in Fig. 7.7, are in terms of the peak overpressure of the pulse and its duration. Because of their greater effective duration, caused by reflections from room boundaries, pulses heard indoors are generally considered more damaging than those heard outdoors. Thus, the limits for indoor exposures (i.e., B-durations) in Fig. 7.7 are more stringent than those for outdoor exposures (A-durations).

FIG. 7.7. SUGGESTED LIMITS FOR HUMAN EXPOSURE TO IMPULSIVE SOUNDS TO AVOID HEARING DAMAGE (After CHABA [7.3]).

Note: The A-Duration Is The Duration Of The Initial Peak Over-Pressure Pulse And Is Generally Controlling For Pulses Heard Out Of Doors. The B-Duration Is The Cumulative Durations Of The Initial Pulses Plus That Of All Significant Reflected Pulses. It Is Generally Of Importance For Exposures Indoors.

7.2.2 Secondary (public welfare) regulations, policies, and guidelines

Federal Legislation

Federal regulatory efforts directed at noise in the community derive principally from two acts: The "National Environmental Policy Act of 1969" [7.30] and the "Noise Control Act of 1972" [7.31]. The former requires "A detailed statement on ... the environmental impact of ... major federal actions." This requirement has been interpreted to include noise impacts.

The Noise Control Act of 1972, administered for the most part by the U.S. EPA, is more specific. This Act:

- . Directs Federal agencies to comply with environmental noise regulations at all levels of government (see Sec. 4 of the Act);
- . Requires the identification and publication of certain noise information, including information on "the levels of environmental noise, the attainment and maintenance of which in defined areas under various conditions are requisite to protect the public health and welfare with an adequate margin of safety" (see Sec. 5);
- . Authorizes the regulation of noise produced by products and the noise labeling of products (see Secs. 6, 8, 9, and 10);
- . Authorizes the EPA to contribute to the regulation of noise from aircraft (see Sec. 7), railroads (see Sec. 17), and trucks (see Sec. 18);
- . Provides for research, technical assistance, and public information, including "technical assistance to State and local governments to facilitate their development and enforcement of ambient noise standards ..." (see Sec. 14).

It is unlikely, under this authority, that the U.S. EPA will specifically regulate noise from fixed sources, such as energy

facilities, in the foreseeable future.* However, the agency has provided information on the acceptability of noise [Sec. 5(a)(2)], and has assisted state regulatory efforts [Sec. 14(2)], and will probably continue and increase these services.

Two documents of particular significance have grown out of this Federal effort: the EPA Levels document and the CHABA EIS Guidelines. Although neither is a regulation, both provide authoritative information upon which state and local regulations could be based.

EPA Levels Document 550/9-74-004

Under the Federal Noise Control Act of 1972, the Environmental Protection Agency was required to "publish information on the levels of environmental noise, the attainment and maintenance of which in defined areas under various conditions are requisite to protect the public health and welfare with an adequate margin of safety." This report, published in March of 1974 [7.13], is entitled "Information on Levels of Environmental Noise Requisite to Protect the Public Health and Welfare with an Adequate Margin of Safety," and is known as the "Levels" document. It represents the consensus of recognized acoustical experts throughout the world, and includes a summary of major prior studies that led to the conclusions presented.

The Levels document should be viewed as a guideline. The document states that it is not a regulation or standard. Cost and technical feasibility were not considered in its preparation. However, the document claims that "One of the purposes of this document is to provide a basis for judgment by states and local

* Indeed, the Act states that "...primary responsibility for control of noise rests with State and local governments" [Sec. 2(2)(3)].

governments as a basis for setting standards," together with considerations of cost, feasibility, etc.

The Levels document contains two kinds of information pertinent to the question of noise impact from energy facilities. These are:

- . The guideline limits for noise levels described in the main body of the report
- . The cause-and-effect relationships (i.e., criteria) for noise exposure summarized in the appendices of the report.

These two areas of applicability are discussed below.

EPA Guideline Limits

The EPA guideline limits are listed in their entirety in Table 7.3. Of particular interest to energy facility siting are those levels identified for "Residential with outside space and Farm Residences":

Indoor L_{dn}	45 dB(A)
Outdoor L_{dn}	55 dB(A)

Note from the table heading that these are yearly energy-average values.

The justification for these levels is quoted in part from the document:

The level identified for the protection of speech communication is an L_{eq} of 45 dB within the home in order to provide for 100% intelligibility of speech sounds. Allowing for the 15-dB reduction in sound level between outdoors and indoors (which is an average amount of sound attenuation that assumes partly open windows),

TABLE 7.3. YEARLY AVERAGE EQUIVALENT SOUND LEVELS IDENTIFIED AS REQUISITE TO PROTECT THE PUBLIC HEALTH AND WELFARE WITH AN ADEQUATE MARGIN OF SAFETY, IN dB(A) [7.13].

	MEASURE	INDOOR			OUTDOOR		
		Activity Interference	Hearing Loss Consideration	To Protect Against Both Effects	Activity Interference	Hearing Loss Consideration	To Protect Against Both Effects
RESIDENTIAL WITH OUTSIDE SPACE AND FARM RESIDENCES	L_{dn} $L_{eq}(24)$	45	70	45	55	70	55
RESIDENTIAL WITH NO OUTSIDE SPACE	L_{dn} $L_{eq}(24)$	45	70	45		70	
COMMERCIAL	$L_{eq}(24)$	NA	70	70	NA	70	70
INSIDE TRANSPORTATION	$L_{eq}(24)$	NA	70	NA			
INDUSTRIAL	$L_{eq}(24)$	NA	70	70	NA	70	70
HOSPITALS	L_{dn} $L_{eq}(24)$	45	70	45	55	70	55
EDUCATIONAL	L_{dn} $L_{eq}(24)$	45	70	45	55	70	55
RECREATIONAL AREAS	$L_{eq}(24)$	NA	70	70	NA	70	70
FARM LAND AND GENERAL UN-POPULATED AREAS	$L_{eq}(24)$				NA	70	70

this level becomes an outdoor L_{eq} of 60 dB for residential areas. For outdoor voice communication, the outdoor L_{eq} of 60 dB allows normal conversation at distances up to 2 meters with 95% sentence intelligibility.

Although speech-interference has been identified as the primary interference of noise with human activities and is one of the primary reasons for adverse community reactions to noise and long-term annoyance, the 10 dB nighttime weighting (and, hence, the term L_{dn}) is applied to give adequate weight to all of the other adverse effects on activity interference. For the same reason, a 5-dB margin of safety is applied to the identified outdoor level. Therefore, the outdoor L_{dn} identified for residential areas is 55 dB.

A summary of the effects associated with achieving an outdoor day-night sound level, also quoted from the document, is given in Table 7.4.

The Levels document indicates that about 90 million people in the United States presently live in noise environments exceeding an L_{dn} of 55 dB(A). Thus, achieving such a goal for the whole population would be quite difficult. However, Appendix D states:

The levels of environmental noise that are associated with annoyance depend upon local conditions and attitudes. They cannot be clearly identified in terms of the national public health and welfare. The only levels which can be so identified are the levels which are required to assure that speech communication in the home and outdoors is adequate in terms of public health and welfare. Lower levels may be desirable and appropriate for specific local situations.

Guidelines for EIS Preparation

CHABA has prepared for the EPA a report entitled "Guidelines for Preparing Environmental Impact Statements for Noise" [7.25]. Of particular interest in this report are a method for assessing

TABLE 7.4. SUMMARY OF HUMAN EFFECTS IN TERMS OF SPEECH COMMUNICATION, COMMUNITY REACTION, COMPLAINTS ANNOYANCE AND ATTITUDE TOWARDS AREA ASSOCIATED WITH AN OUTDOOR DAY/NIGHT SOUND LEVEL OF 55 dB(A) re 20 MICROPASCALS [7.13].

Type of Effect	Magnitude of Effect
Speech - Indoors	100% sentence intelligibility (average) with a 5-dB margin of safety
- Outdoors	100% sentence intelligibility (average) at 0.35 meters
	99% sentence intelligibility (average) at 1.0 meters
	95% sentence intelligibility (average) at 3.5 meters
Average (i.e., residential urban) Community Reaction	Noise evident; 7 dB below level of significant "complaints and threats of legal action" and at least 16 dB below "vigorous action" (attitudes and other nonlevel-related factors may affect this result)
Complaints	1% dependent on attitude and other nonlevel-related factors
Annoyance	17% dependent on attitude and other* nonlevel-related factors
Attitudes Towards Area	Noise is essentially the least important of various factors

*This is no longer considered correct. See Sec. 7.1.1.

the impact of noise on an exposed population and a method of screening projects for the necessity of preparing a noise impact statement. The assessment method is based upon the use of yearly average L_{dn} , and takes into consideration the generally accepted effects of noise on people (i.e., annoyance, speech interference, hearing loss). The impact of a high noise level on a small number of people is assumed equivalent to the impact of a lower noise level on a larger number of people. The properties of sound intensity and of the number of people exposed are combined mathematically through the use of a weighting function. The result is a single measure indicating the number of "equivalent fully exposed" people.

The weighting function, Fig. 7.8, is of interest. It is derived from the annoyance relation of Fig. 7.6 plus consideration of hearing damage risk at levels of above 75 dB(A). Notice that 1 person exposed to an annual L_{dn} of 75 dB(A) is equivalent to 4 people exposed to 60 dB(A), to about 10 people exposed to 53 dB(A), and to about 20 exposed to 50 dB(A).

The CHABA screening procedure is summarized in Fig. 7.9, in which both scales are in terms of yearly average L_{dn} . This figure graphically illustrates the requirements for noise impact analysis that are described in detail in the report.

The CHABA guidelines include criteria for human exposure to infrasound, ultrasound, impulsive sounds, and vibration.

Infrasound exposures of 1 minute or less are suggested to be limited to 120 dB in the range from 0.1 to 5 Hz, and to $[120 - 30 \log \frac{f}{5}]$ dB in the range from 5 to 20 Hz. Exposures of more than 1 minute but less than 100 minutes should be reduced from the 1-minute limit by $10 \log t$, where t is in minutes. Exposure at levels 20 dB or more below the 1-minute limit are regarded as having no impact, regardless of exposure times.

FIG. 7.8. NOISE IMPACT WEIGHTING FUNCTION PROPOSED BY CHABA [2:25].

FIG. 7.9. SCREENING PROCEDURE RECOMMENDED BY CHABA TO DETERMINE THE NEED FOR, AND REQUIREMENTS OF A NOISE ENVIRONMENT DOCUMENTATION (NED) [7.25].

Ultrasound exposures should be limited to 105 dB. Exposures above this limit should be "individually evaluated based upon specific research studies."

Impulsive sounds are to be rated for community annoyance potential on the basis of a C-weighted day-night average sound level observed on the "slow" scale of a standardized Sound Level Meter.* The proposed noise-impact annoyance rating criterion is illustrated in Fig. 7.10.

Vibration and shock criteria are proposed by CHABA for situations involving (1) human work efficiency and annoyance and (2) potential damage to structures. This work is based principally on existing and proposed ISO Standards [7.32]. Recommendations for residential areas are given in Fig. 7.11, and corrections for other conditions are listed in Table 7.5. Additional criteria are given for structural damage caused by blast waves in the air and in the ground [7.33]. The possibility of structural damage exists when peak overpressures exceeding 130 dB or peak accelerations above 0.5 m/sec^2 occur.

Noise Abatement and Control Standards of the Department of Housing and Urban Development (HUD)**

HUD has established standards for determining the suitability of noise levels in and around residences. These standards are described in HUD Circular 1390.2, "Noise Abatement and Control: Departmental Policy, Implementation Responsibilities, and Standards," dated August 4, 1971 [7.35]. The HUD standards differ from others in that they are not directed at limiting the noise

* It is stated that, empirically, the meter reading will be 20 to 26 dB(C) below the instantaneous peak value of the impulse.

**The HUD Noise Standards are referenced for use in NRC (AEC) Regulatory Guide 4.2 concerning environmental impact reports for nuclear power plants [7.31].

FIG. 7.10. NOISE-IMPACT ANNOYANCE RATING CRITERION FOR IMPULSIVE SOUNDS, AS PROPOSED BY CHABA [7.25].

FIG. 7.11. VIBRATION CRITERION FOR RESIDENTIAL AREAS (After CHABA [7,28]).

TABLE 7.5. CHABA's BASIC THRESHOLD ACCELERATION VALUES FOR ACCEPTABLE VIBRATION ENVIRONMENTS [7.25]. (See also Fig. 7.11.)

Daytime is 7 am to 10 pm. Nighttime is 10 pm to 7 am. All values are meters/sec²

Type of Place	Time of Day	Continuous Intermittent rms Acceleration	Impulsive Shock Excitation Peak Acceleration
Hospital operating rooms and other such critical areas	Day	0.0036	0.005
	Night	0.0036	0.005
Residential	Day	$\frac{0.072}{\sqrt{t}}$	$\frac{0.1}{\sqrt{N}}$
	Night	0.005	0.01
Office	Anytime	$\frac{0.14}{\sqrt{t}}$	$\frac{0.2}{\sqrt{N}}$
Factory and Workshop	Anytime	$\frac{0.28}{\sqrt{t}}$	$\frac{0.4}{\sqrt{N}}$

t = duration seconds of vibration, for durations greater than 100 sec, use t as 100 sec.

N = is the number of discrete shock excitations that are one sec or less in duration. For more than 100 excitations, use N=100.

immissions of some source; rather, they are directed at determining the suitability of a residence from the point of view of noise emissions, regardless of the noise sources affecting the residence.

The purpose of the HUD noise policy, as stated in the policy circular, is:

It is the finding of the Department of Housing and Urban Development (HUD) that noise is a major source of environmental pollution which represents a threat to the serenity and quality of life in population centers. Noise exposure may be a cause of adverse physiological or psychological effects as well as economic losses. Accordingly, it is the purpose of Departmental policy to call attention to this threat, to encourage the control of noise at its source in cooperation with other Federal departments and agencies, to encourage land utilization patterns for housing and other municipal needs that will separate uncontrollable noise sources from residential and other noise-sensitive areas, and to prohibit HUD support to new construction on sites having unacceptable noise exposures.

HUD has established noise limits in three areas:

- . External noise levels on the residential site
- . Noise levels within residential structures
- . Sound transmission properties of walls and floors between dwelling units of multifamily structures.

In the first area - external noise levels - a potential residential site is classified in one of four categories on the basis of a continuous 24-hour measurement of noise at the site. The categories are:

Acceptable

Discretionary - Normally Acceptable

Discretionary - Normally Unacceptable
Unacceptable.

The standards that form the basis for this classification are listed in their entirety in Table 7.6. Note the parenthetical remarks, which indicate the increasing complexity of obtaining approval for sites in the "Unacceptable" category.

The criteria for the "Acceptable" category are so quiet that, in practice, such low sound levels are almost never measured. Certainly in urban and suburban areas where most HUD-assisted residences are built, it would be very difficult to find such quiet sites. As a result, most HUD-approved residential sites fall into the "Discretionary - Normally Acceptable" category.

Along heavily travelled roads, the requirements of the "Discretionary - Normally Acceptable" classification are often difficult or impossible to satisfy. In these situations, it is customary to amend the site layout and building designs in an attempt to satisfy the HUD interior noise exposure limits, and then to use the building structures themselves to screen traffic noise from outdoor living areas. The applicable HUD interior noise limits are given in Table 7.7.

HUD also sets lower limits on the noise-reduction properties of interior partitions between dwelling units in multifamily structures. These "acoustic privacy" limits are considered desirable to maintain the livability of the residences.

TABLE 7.6. HUD EXTERNAL NOISE EXPOSURE STANDARDS FOR NEW CONSTRUCTION SITES [7.35].

General External Exposures dB(A)	Airport Environs	
	CNR Zone*	NEF Zone*
Unacceptable Exceeds 80 dB(A) 60 min per 24 hr Exceeds 75 dB(A) 8 hr per 24 hr [Exceptions are strongly discouraged and require a 102(2)C environmental statement and the Secretary's approval.]	3	C
Discretionary - Normally Unacceptable Exceeds 65 dB(A) 8 hr per 24 hr Loud repetitive sounds on site [Approvals require noise attenuation measures, the Regional Administrator's concurrence and a 102(2)C environmental statement.]	2	B
Discretionary - Normally Acceptable Does not exceed 65 dB(A) more than 8 hr per 24 hr		
Acceptable Does not exceed 45 dB(A) more than 30 min per 24 hr	1	A

*Composite Noise Rating (CNR) and Noise Exposure Forecast (NEF) are methods for rating the cumulative effects of aircraft noise.

TABLE 7.7. HUD STANDARDS FOR INTERIOR NOISE EXPOSURES (FOR NEW AND REHABILITATED RESIDENTIAL CONSTRUCTION [7.35]).

(NOTE: The standards listed below are performance standards. The means required for achieving them will depend on, among other things, the external noise levels, the equipment and layout used in the building, and the noise attenuation characteristics of the building's floors and walls. These standards assume open windows unless other provision is made for adequate ventilation.)

ACCEPTABLE

Sleeping Quarters. For the present time, HUD field personnel should consider existing and projected noise exposure for sleeping quarters "acceptable" if interior noise levels resulting from exterior noise sources and interior building sources, such as heating, plumbing, and air conditioning:

- do not exceed 55 dB(A) for more than an accumulation of 60 minutes in any 24-hour period, and
- do not exceed 45 dB(A) for more than 30 minutes during nighttime sleeping hours from 11PM to 7AM, and
- do not exceed 45 dB(A) for more than an accumulation of eight hours in any 24-hour day.

Other Interior Areas. HUD personnel should exercise discretion and judgment as to interior areas other than those used for sleeping. Consideration should be given to the characteristics of the noise, the duration, time of day, and planned use of the area.

Federal Highway Administration (FHWA) Noise Standards and Procedures

FHWA has established noise standards for new highways. Unless special waivers are granted, these standards must be met in order for the project to be eligible for Federal aid partici-

TABLE 7.8. FHWA DESIGN NOISE LEVEL/ACTIVITY RELATIONSHIPS [7.36].

Activity Category	Design Noise Levels – dB(A) $L_{eq}(h)$ or $L_{10}(h)$	Description of Activity Category
A	57 (Exterior) 60 (Exterior)	Tracts of land in which serenity and quiet are of extraordinary significance and serve an important public need, and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose. Such areas could include amphitheaters, particular parks or portions of parks, or open spaces which are dedicated or recognized by appropriate local officials for activities requiring special qualities of serenity and quiet.
B	67 (Exterior) 70 (Exterior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, picnic areas, recreation areas, playgrounds, active sports areas, and parks.
C	72 (Exterior) 75 (Exterior)	Developed lands, properties or activities not included in categories A and B above.
E	52 (Interior) 55 (Interior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

pation. The noise standards are contained in FHWA Federal Aid Highway Program Manual (FHPM 7-7-3), dated 14 May 1976 [7.36].

The standards of FHPM 7-7-3, shown in Table 7.8, are in effect a noise regulation for new highways. The limits "represent a balancing of that which may be desirable and that which may be achievable." It is stated that "noise impacts can occur even though the design noise levels are achieved. Highway agencies are urged, therefore, to strive for noise levels below the values in Table 7.8 where lower levels can be achieved at reasonable cost, without undue difficulty, and where benefits appear to clearly outweigh the costs and efforts required."

Procedures for predicting highway noise are well established. They depend upon the traffic volume and speed, truck/auto mix, and highway design parameters. Furthermore, traffic noise is the biggest noise problem in the United States today, in terms of the number of people impacted.

The computation of traffic noise for comparison with the FHWA standards must be based upon worst-case conditions. Typically, this means traffic conditions that will occur only a few hours per year, for a projected traffic volume many years in the future. The noise exposure computed can be either the hourly L_{eq} or the hourly L_{10} .

Note, in Table 7.8, there are limits for both exterior and interior noise levels. The exterior levels apply to "outdoor areas which have regular use," whereas the indoor limit applies to those "situations where no exterior noise-sensitive land use or activity is identified."

Prediction of Community Response to Noise Intrusions

A number of empirical procedures have been developed to predict community response (i.e., complaints) to noise intrusions. Although such methods might appear to reduce a complex sociological issue to quantitative prediction, they do not because several undefined factors must be used in applying any of the procedures. A great deal is left to the judgment of the technicians using the practice.

The appendices of the EPA Levels document contain a number of cause-and-effect relationships (i.e., criteria) that allow evaluation of the effects of various noise levels. One of these criteria is the prediction of community response to noise intrusions, a procedure based upon past experience with community reaction to noise. These experiences are illustrated in Fig. 7.12, where each point indicates a particular case history.

The normalized L_{dn} on the lower abscissa of Fig. 7.12 is the actual magnitude of the L_{dn} of the intruding noise, adjusted by the factors listed in Table 7.9.

Alternatively, the upper horizontal scale, which is based on the difference between the L_{dn} of the intruding noise and the L_{dn} of the ambient, can be used. In this case, the corrections of Table 7.9 for "Outdoor Noise Level Measured in the Absence of Intruding Noise" should not be applied.

Note that by this procedure some community reaction ("sporadic complaints") can be expected when the L_{dn} of the intrusion equals the L_{dn} of the preexisting ambient. Serious community reaction ("threats of legal action") becomes probable when the new noise intrusion exceeds the ambient by 10 dB(A) or more. On the other hand, the scatter among the individual case

FIG. 7.12. COMMUNITY REACTION TO INTRUSIVE NOISES OF MANY TYPES AS A FUNCTION OF THE NORMALIZED OUTDOOR DAY/NIGHT SOUND LEVEL OF THE INTRUDING NOISE [7.13].

TABLE 7.9. CORRECTIONS TO BE ADDED TO THE MEASURED DAY/NIGHT SOUND LEVEL (L_{dn}) OF INTRUDING NOISE TO OBTAIN NORMALIZED L_{dn} . SEE FIG. 7.12 [7.13].

Type of Correction	Description	Amount of Correction to be Added to Measured L_{dn} in dB
Seasonal Correction	Summer (or year-round operation) Winter only (or windows always closed)	0 - 5
Correction for Outdoor Noise Level Measured in Absence of Intruding Noise	Quiet suburban or rural community (remote from cities and from industrial activity and trucking) Normal suburban community (not located near industrial activity) Urban residential community (not immediately adjacent to heavily traveled roads and industrial areas) Noise urban residential community (near relatively busy roads or industrial areas) Very noisy urban residential community	+10 + 5 0 - 5 -10
Correction for Previous Exposure and Community Attitudes	No prior experience with the intruding noise Community has had some previous exposure to intruding noise but little effort is being made to control the noise. This correction may also be applied in a situation where the community has not been exposed to the noise previously, but the people are aware that bona fide efforts are being made to control the noise. Community has had considerable previous exposure to the intruding noise and the noise maker's relations with the community are good. Community aware that operation causing noise is very necessary and it will not continue indefinitely. This correction can be applied for an operation of limited duration and under emergency circumstances.	+ 5 0 - 5 -10
Pure Tone or Impulse	No pure tone or impulsive character Pure tone or impulsive character present	0 + 5

histories is 5 dB(A), equivalent to two level ranks on the Community-Reaction Scale.

A similar procedure, ISO-R-1996, has been adopted by the International Standards Organization [7.37]. This procedure is somewhat more conservative than the EPA's, and it has been specifically disapproved by the U.S. delegation to the ISO.

State and Local Noise Regulations

Many states now have noise laws and/or energy-facility siting regulations that apply to noise, and other states have such laws pending (see Fig. 7.13). For example, applicable regulations now exist in California, Oregon, Washington, Minnesota, Ohio, Illinois, Georgia, Maryland, New Jersey, and Massachusetts. Regulations are pending in New York, Connecticut, and Kentucky. The technical and legal caliber of these regulations varies widely from state to state, as does the enforcement skill and capability. Almost all regulations set octave-band levels and/or dB(A) limits; or, alternatively, require the submission of data in such terms. Where enforcement exists, personnel trained to use standardized acoustic instrumentation and terminology are employed.

It is common for state noise regulations to set limits that vary with time of day [like the 10-dB(A) penalty in L_{dn}] and with land use. The most stringent limits exist for nighttime in residential areas. Temporal averaging, as in L_{eq} and L_{dn} , is rare in state noise regulations because of the instrumentation and enforcement difficulties associated with such averaging. Some, like the Minnesota regulation, involve averaging over a brief period, such as an hour.

STATE	TYPE OF REGULATION	
	Noise Limits for Fixed Sources	Environmental Energy Facilities Sites
California		X
Oregon	X	
Washington	X	
Minnesota	X	X
Ohio		X
Illinois	X	
Maryland	X	
Georgia	X	
New Jersey	X	
Massachusetts	X	
New York	PENDING	X
Connecticut	PENDING	
Kentucky	PENDING	

FIG. 7.13. SOME STATES WITH NOISE REGULATIONS APPLICABLE TO ENERGY FACILITIES.

There are hundreds of local municipal noise ordinances in the United States [7.38]. About three-quarters of these are anti- nuisance laws with no objective acoustic limits, and lawyers advise us that such ordinances are difficult to enforce. The remaining 25% are mostly zoning (land use) regulations, with some motor-vehicle noise laws or building codes. Quantitative limits, when imposed, are in terms of dB(A) or octave-band levels.

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8. POTENTIAL NOISE-CONTROL PROBLEMS OF THE DEVELOPING ENERGY TECHNOLOGIES

8.1 Introduction

The noise-control problems of the developing energy technologies are summarized in this section. This discussion leads directly to the recommendations presented in Sec. 1 for future Department of Energy activities that will mitigate these problems.

A qualitative summary of the major noise sources, paths, and receptors of the developing energy technologies is given in Table 8.1. (Quantitative details have been given in Secs. 5, 6, and 7.) In most cases, the sources are conventional. In no instance does any technical noise-control problem present a serious limitation to the development of any of the energy technologies considered. In most cases, the solution of specific noise problems that might occur in the future can be achieved by the application of conventional noise-control technology at that time.* An example is the process-plant noise resulting from growth of coal gasification and liquefaction activities in this country.

Premature emphasis on potential noise problems of many developing technologies would only encumber, and perhaps delay, the effort to solve the more significant engineering and financial limitations that must be overcome in bringing such programs to fruition. The few areas where technical research on noise analysis and control appear justified in supporting DoE's basic missions have been singled out for recommendation in Sec. 1.

* See, for example, Refs. 8.1 through 8.3.

TABLE 8.1. QUALITATIVE SUMMARY OF PRINCIPAL NOISE SOURCES, PATHS, AND RECEPTORS IMPORTANT TO THE DEVELOPING ENERGY TECHNOLOGIES.

	Principal Noise Sources										Principal Paths			Principal Receptors			
Energy Technology	Diesel Engines (4)	Pump and Compressors (2)	Other Machinery	Burners (2)	Jets	Valves and Piping (2)	Fans (2)	Trains (4)	Motor Vehicles (4)	Cooling Towers (2)	Air	Ground Vibration	Water	Workers (5)	Nearby Residences (6)	Wildlife	Other
Coal Conversion and Utilization																	
Mining																	
Surface (4)	X		X						X		X			X		X	
Deep (3)		X	X				X					X		X			
Preparation (3)	X		X								X			X	X	X	
Gasification																	
Surface		X	X	X		X	X			X	X			X	X	X	
In-situ		X	X			X				X	X	X		X	X	X	
Liquification																	
Surface		X	X	X		X	X			X	X			X	X	X	
In-situ		X	X			X				X	X	X		X	X	X	
Transportation (4)	X					X		X	X		X	X		X	X	X	
Direct Combustion (7)		X	X	X	X	X	X			X	X			X	X	X	
Waste Disposal (4)	X		X					X	X		X			X	X	X	
Oil Shale																	
Mining and Crushing (3)	X		X					X	X		X			X	X	X	
Retorting																	
Surface		X	X	X		X	X			X	X			X	X	X	
In-situ		X	X			X				X		X		X	X	X	
Waste Disposal (4)	X		X					X	X		X			X	X	X	
Oil and Gas																	
Advanced Fracturing	X	X	X			X					X			X	X	X	
Secondary/Tertiary Recovery	X	X	X	X	X	X				X	X	X		X	X	X	
Offshore Operations	X	X	X			X					X		X	X			X (Note 1)
Eastern Devonian Shales	X	X	X			X						X		X	X	X	
Methane Stripping from Brines		X	X			X				X	X	X		X	X	X	

TABLE 8.1. (Cont.)

	Principal Noise Sources										Principal Paths			Principal Receptors			
Energy Technology	Diesel Engines (4)	Pump and Compressors (2)	Other Machinery	Burners (2)	Jets	Valves and Piping (2)	Fans (2)	Trains (4)	Motor Vehicles (4)	Cooling Towers (2)	Air	Ground Vibration	Water	Workers (5)	Nearby Residences (6)	Wildlife	Other
Conservation																	
Buildings (6)																	X (benefit to occupants)
Machinery (including appliance efficiency)		X		X		X	X			X	X				X		X (occupants)
EHV/UHV Power Transmission											X				X(8)	X	
Geothermal (8)	X	X	X		X	X			X		X			X	X	X	
Advanced Systems																	
Wind			X				X				X				X	X	
Ocean Thermal Energy Conversion		X	X			X					X		X	X			X (Note 1)
Fusion																	
Auxiliaries and Support		X	X			X				X	X	X		X	X	X	

☐ = Area where further technical work by DoE is recommended (see Ch. 1).

- Notes:
1. National defense implications of underwater noise produced should be investigated.
 2. When lumped together, these constitute what is referred to herein as "process-plant noise."
 3. The Bureau of Mines, U.S. Dept. of the Interior, sponsors noise-control research in this area.
 4. The Department of Transportation sponsors noise-control research in this area.
 5. The National Institute of Occupational Safety and Health and the Occupational Health and Safety Administration sponsor noise-effects research in this area.
 6. The Office of Noise Abatement and Control of the Environmental Protection Agency sponsors research in this area.
 7. The Edison Electric Institute sponsors some work in this area.
 8. DoE presently sponsors noise studies in this area.

8.2 Applicable Ongoing Research

Table 8.1 also shows several areas where Federal and private organizations are presently sponsoring research on noise. These are listed in greater detail in Table 8.2. Such research could provide information for the solution of noise problems that DoE may encounter. Thus, it is probably unnecessary for DoE to pursue research activity in these areas -- although it is certainly advisable for DoE to monitor such research for results applicable to DoE's needs.

It should be noted that most Federally sponsored noise research has been concentrated in two areas:

- . The health (i.e., hearing damage) hazards of occupational exposures
- . Analysis and control of community noise impacts from transportation vehicles: aircraft, motor vehicles, and trains.

Relatively little work has been done by Federal agencies on the analysis and control of steady noise impacts on communities and wildlife from such fixed sources as mining and drilling operations, process plants, fans, cooling towers, etc. Such work would probably fall within the area of interest of the Office of Noise Abatement and Control (ONAC) of the Environmental Protection Agency. However, this office operates with a limited budget against a very tight regulatory time schedule. ONAC is not likely, in the foreseeable future, to sponsor research on noise from fixed industrial sources.

8.3 Classes of Possible Noise-Control Problems

The possible noise-control problems that DoE may encounter in the future can be classified in three general areas:

TABLE 8.2. SOME CURRENT NOISE RESEARCH PROGRAMS SPONSORED BY FEDERAL AND PRIVATE ORGANIZATIONS.

Subject	Sponsoring Organization
Effects of Noise on health of workers	<ul style="list-style-type: none"> • National Institute of Occupational Safety and Health (NIOSH) • Occupational Health and Safety Administration (OSHA)-Regulatory
Control of Noise of Mining Machinery	<ul style="list-style-type: none"> • Bureau of Mines, Department of the Interior • Mining Enforcement and Safety Administration (MESA), Department of Labor - Regulatory
Analyses and Control of Construction Noise	<ul style="list-style-type: none"> • Construction Engineering Laboratories, U.S. Army • Environmental Protection Agency, Office of Noise Abatement and Control (EPA/ONAC) • Department of Transportation, Federal Highway Administration (DOT/FHWA)
Analyses and Control of Motor Vehicle Noise	<ul style="list-style-type: none"> • Department of Transportation EPA/ONAC-Regulatory
Rail Transportation Noise	<ul style="list-style-type: none"> • EPA/ONAC-Regulatory
Aircraft Noise	<ul style="list-style-type: none"> • Department of Transportation Federal Aviation Administration (DOT/FAA) • EPA/ONAC • National Aeronautics Space Administration (NASA)
Jet, rocket, and other aerodynamic noise sources	<ul style="list-style-type: none"> • NASA
Corona audible noise	<ul style="list-style-type: none"> • Electric Power Research Institute (EPRI) • DoE (including Bonneville)
Community annoyance due to low-level sounds (corona and transformer noise)	<ul style="list-style-type: none"> • DoE (at NBS) • EPRI
Interference of noise with speech	<ul style="list-style-type: none"> • EPA/ONAC • NASA
Electric Power Plant Noise: Prediction, Assessment, and Control	<ul style="list-style-type: none"> • Edison Electric Institute (EEI)

- . Occupational noise exposures exceeding prescribed limits
- . Community noise exposures leading to complaints about noise and possible legal action
- . Environmental-impact questions and issues involving noise from proposed energy activities.

Because of their importance to the timely completion of many of DoE's programs, these three classes of problems are discussed in greater detail in the following pages.

8.3.1 Excessive occupational exposures

From a technical point of view, noise problems involving excessive occupational exposures are the most tractable because the acceptable exposure limits are clearly prescribed by regulation for private industry and by Executive Order for Federal agencies. Furthermore, the solution is frequently as simple as requiring the use of ear protection and limiting exposure times. When these solutions are not possible, engineered noise control almost always yields suitable -- if much more costly -- solutions.

8.3.2 Public noise complaints

Public noise complaints following the start-up of a new industrial facility almost always result from engineering oversights during the design of the facility - and they may add up to a costly sociological oversight. Overlooking noise control leads to expensive retrofit and to legal and regulatory delays. Moreover, it sensitizes and alienates the noise-impacted community. The result may be overdesign of the ultimate noise-control treatment that could have been avoided if the problem had been handled during initial facility design.*

* See Secs. 5.1.5 and 5.5.3 for some typical examples of such problems.

Furthermore, the word gets around. The next time such a facility is proposed, noise impact may be treated as an environmental issue out of proportion to its significance.

8.3.3 Environmental impact issues

Perhaps the most difficult of all noise "problems" are those that must be treated in environmental impact proceedings related to proposed energy facilities. Depending upon the particular regulatory procedures (usually determined by state and local regulations), lengthy delays can be encountered while adversaries argue conflicting views of the magnitude and acceptability of noise impacts. Unanswered questions may be raised, spawning hasty and inefficient research, the result of which may only be further questions. A classic example is the recent series of hearings on proposed 765-kV transmission lines in New York State mentioned in Secs. 5.5.3 and 7.1.1. The delay caused by these hearings now (1978) exceeds three years, and noise has been a major issue.

This type of noise problem often arises because the parties involved do not have a common definition of acceptable and unacceptable noise exposures. It is rare to find noise becoming a major environmental issue when there is common agreement (such as a local noise ordinance or a written Federal policy that will be complied with) as to the limit of acceptable noise exposure.

It is clear from these classifications of potential noise problems that many such problems are not amenable to solution by technical research. Rather, the likelihood of their occurring can be minimized by certain procedural actions. Thus, the conclusions of this study include certain suggested procedural actions as well as selected technical research programs.

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APPENDIX A: GLOSSARY

Acceleration

Acceleration is a vector that specifies the time rate of change of velocity [1].

Note 1: Various self-explanatory modifiers such as peak, average, rms are often used. The time interval must be indicated over which the average (for example) was taken.

Note 2: Acceleration may be (1) oscillatory, in which case it may be defined by the acceleration amplitude (if simple harmonic) or the rms acceleration (if random), or (2) nonoscillatory, in which case it is designated "sustained" or "transient acceleration."

Acoustic Absorption

Acoustic absorption is the change of sound energy into some other form, usually heat, in passing through a medium or on striking a surface.

Acoustic Power

See power, sound power level.

Acoustic Scattering

Acoustic scattering is the irregular reflection, refraction, or diffraction of a sound in many directions [1].

Acoustics

(1) Acoustics is the science of sound, including its production, transmission, and effects.

(2) The acoustics of a room are those qualities that together determine its character with respect to distinct hearing [1].

Ambient Noise

Ambient noise is the all-encompassing noise associated with a given environment, being usually a composite of sounds from many sources near and far [1].

Audibility

Audibility (range of) at a specified frequency is 20 times the logarithm to the base 10 of the ratio of the sound pressure level at the threshold of tickle to that at the threshold of audibility. The unit is the decibel.

Audible sound is sound containing frequency components lying between about 15 and 15,000 Hz [2].

Background Noise

Background noise is the total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal [1].

Note 1: Ambient noise detected, measured, or recorded with the signal becomes part of the background noise.

Note 2: Included in this definition is the interference resulting from primary power supplies, that separately is commonly described as hum.

Bandwidth

See frequency band.

Band Pressure Level

A sound pressure level in a specified frequency band.

Cycle

A cycle is the complete sequence of values of a periodic quantity that occur during a period.

Continuous Spectrum

A continuous spectrum is the spectrum of a wave, the components of which are continuously distributed over a frequency region [1].

Critical Speed

Critical speed is a speed of a rotating system that corresponds to a resonance frequency of the system [1].

Damping

Damping is the dissipation of energy with time or distance [1].

Diffuse Sound Field (Reverberant Field)

A sound field in which the time average of the mean-square sound pressure is everywhere the same and the flow of energy in all directions is equally probable is a diffuse, or reverberant, sound field.

Direct Sound Field

A direct sound field is one in which energy is flowing outward from the source. The sound field very close to a source, even in a reverberant room, is a direct field. Sound fields outdoors and well removed from the ground are direct fields at all distances from the source and are referred to as "free sound fields" or "free fields."

Displacement

Displacement is a vector quantity that specifies the change of position of a body or particle and is usually measured from the mean position of rest. In general, it can be represented by a rotation vector or translation vector or both [1].

Diffraction

Diffraction is the distortion of a wave front caused by the presence of an obstacle in the sound field (see Scattering) [2].

Far Field and Near Field (Acoustic)

The acoustic fields are described in terms of wave propagation. The near field is close to the source; how far it extends depends on the wavelength of the radiated sound. Normally, the acoustic near field extends to a distance of about one-quarter of a wavelength. Sound pressure fluctuations within this distance correspond to the hydrodynamic response of the fluid to the motion of the adjacent surface. In the far field, the sound pressure fluctuations are caused by the propagation of sound waves away from the source. All measurements of sound power and source acoustic characteristics must be made in the acoustic far field.

Filter (Wave Filter)

A wave filter is a transducer for separating waves on the basis of their frequency. It introduces relatively small insertion loss to waves in one or more frequency bands and relatively large insertion loss to waves of other frequencies [1].

Free Sound Field (Free Field)

A free sound field is a field in a homogeneous, isotropic medium free from boundaries. In practice, it is a field in which the effects of the boundaries are negligible over the region of interest [1].

NOTE: The actual pressure impinging on an object (e.g., electroacoustic transducer) placed in an otherwise free sound field will differ from the pressure which would exist at that point with the object removed, unless the acoustic impedance of the object matches the acoustic impedance of the medium.

Frequency

The frequency of a function periodic in time is the reciprocal of the primitive period. The unit is Hertz (Hz) [1].

Frequency Band

A frequency band is an interval of the frequency spectrum defined between upper and lower "cut-off" frequencies. The band may be described in terms of these two frequencies, by the width of the band, and by the geometric mean frequency of the upper and lower cut-off frequencies, e.g., "an octave band centered at 500 Hz."

Hard Surface

A hard surface is a good reflector, and thus a poor absorber of sound.

Harmonic

A harmonic is a sinusoidal quantity having a frequency that is an integral multiple of the frequency of a periodic quantity to which it is related [1].

Hearing Loss (Hearing Level) (Hearing Threshold Level)

The hearing loss of an ear at a specified frequency is the amount, in decibels, by which the threshold of audibility for that ear exceeds a standard audiometric threshold [1].

Note 1: See American Standard Specification for Audiometers for General Diagnostic Purposes, Z24.5-1951. (See Section 15.).

Note 2: This concept was at one time called deafness; such usage is now deprecated.

Note 3: Hearing loss and deafness are both legitimate qualitative terms for the medical condition of a moderate or severe impairment of hearing, respectively. Hearing level, however, should only be used to designate a quantitative measure of the deviation of the hearing threshold from a prescribed standard.

Hearing Loss (Hearing Level) for Speech

Hearing loss for speech is the difference in decibels between the speech levels at which the average normal ear and the defective ear, respectively, reach the same intelligibility, often arbitrarily set at 50 percent [1].

Impulse

Impulse is the product of a force and the time during which the force is applied; more specifically, the impulse is $\int_{t_1}^{t_2} F dt$ where the force F is time dependent and equal to zero before time t_1 and after time t_2 [1].

Impact

An impact is a single collision of one mass in motion with a second mass which may be either in motion or at rest [1].

Infrasonic Frequency

An infrasonic frequency is a frequency lying below the audio frequency range [1].

Note 1: The word "infrasonic" may be used as a modifier to indicate a device or system intended to operate at an infrasonic frequency.

Note 2: The term "subsonic" was once used in acoustics synonymously with infrasonic; such usage is now deprecated.

Infrasonic (infra-audible) Sound

Infrasonic sound is sound whose frequency is below the lower pitch limit; i.e., below 15 cps [2].

Level

In acoustics, the level of a quantity is the logarithm of the ratio of that quantity to a reference quantity of the same kind. The base of the logarithm, the reference quantity, and the kind of level must be specified [1].

Note 1: Examples of kinds of levels in common use are electric power level, sound-pressure-squared level, voltage squared level.

Note 2: The level as here defined is measured in units of the logarithm of a reference ratio that is equal to the base of logarithms.

Note 3: In symbols,
$$L = \log_r (q/q_0) ,$$

where

L = level of kind determined by the kind of quantity under consideration, measured in units of $\log r$

r = base of logarithms and the reference ratio

q = the quantity under consideration

q_0 = reference quantity of the same kind.

Note 4: Differences in the levels of two like quantities q and q_0 are described by the same formula because, by the rules of logarithms, the reference quantity is automatically divided out:

$$\log_r(q_1/q_2) - \log_r(q_2/q_0) = \log_r(q_1/q_2) .$$

Line Spectrum

A line spectrum is a spectrum whose components occur at a number of discrete frequencies [1].

Live Room

A live room is a room that is characterized by an unusually small amount of sound absorption [1].

Loudness

Loudness is the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud [1].

NOTE: Loudness depends primarily upon the sound pressure of the stimulus, but it also depends upon the frequency and wave form of the stimulus.

Masking [1]

(1) Masking is the process by which the threshold of audibility for one sound is raised by the presence of another (masking) sound.

(2) Masking is the amount by which the threshold of audibility of a sound is raised by the presence of another (masking) sound. The unit customarily used is the decibel.

Microphone

A microphone is an electroacoustic transducer that responds to sound waves and delivers essentially equivalent electric waves [1].

Near Field

See Far Field.

Noise [1]

(1) Noise is any undesired sound. By extension, noise is any unwanted disturbance within a useful frequency band, such as undesired electric waves in a transmission channel or device.

(2) Noise is an erratic, intermittent, or statistically random oscillation.

Note 1: If ambiguity exists as to the nature of the noise, a phrase such as "acoustic noise" or "electric noise" should be used.

Note 2: Since the above definitions are not mutually exclusive, it is usually necessary to depend upon context for the distinction.

Noise Level [1]

(1) Noise level is the level of noise, the type of which must be indicated by further modifier or context.

NOTE: The physical quantity measured (e.g., voltage), the reference quantity, the instrument used, and the bandwidth or other weighting characteristic must be indicated.

(2) For airborne sound, unless specified to the contrary, noise level is the weighted sound pressure level called sound level; the weighting must be indicated.

Octave [1]

(1) An octave is the interval between two sounds having a basic frequency ratio of two.

(2) An octave is the pitch interval between two tones such that one tone may be regarded as duplicating the basic musical import of the other tone at the nearest possible higher pitch.

Note 1: The interval, in octaves, between any two frequencies, is the logarithm to the base 2 (or 3.322 times the logarithm to the base 10) of the frequency ratio.

Note 2: The frequency ratio corresponding to an octave pitch interval is approximately, but not always exactly, 2:1.

Octave Band

An octave band is a frequency range bounded by upper and lower frequency limits f_u and f_l , where $f_u = 2f_l$. Octave bands are usually specified by their geometric mean frequency, called the band center frequencies. The standard octave bands covering the audible range are designated by the following center frequencies: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 cycles per second (Hz). The corresponding upper and lower frequencies are 22/45, 45/89, 89/177, 177/354, 354/708, 708/1416, 1416/2832, 2832/5664, 5664/11,328, 11,328/22,656.

P

Pascal, N/m^2 pressure.

Particle Velocity

The particle velocity in a sound field is the velocity of a given infinitesimal part of the medium, with reference to the medium as a whole, due to the sound wave [1].

NOTE: The terms "instantaneous particle velocity," "effective particle velocity," "maximum particle velocity," and "peak particle velocity" have meanings that correspond with those of the related terms used for sound pressure.

Peak Level

The peak level is the maximum instantaneous level that occurs during a specified time interval. In acoustics, peak sound pressure level is to be understood, unless some other kind of level is specified [1].

Peak-to-Peak Value

The peak-to-peak value of an oscillating quantity is the algebraic difference between the extremes of the quantity [1].

Pitch

Pitch is that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high. Pitch depends primarily upon the frequency of the sound stimulus, but it also depends upon the sound pressure and waveform of the stimulus [1].

Point Source

Simple source of sound is a spherical vibrating surface of dimensions small in comparison with the wavelength of the sound produced, the displacement having the same phase at all parts of the surface [2].

Power Level (PWL)

Power level, in decibels, is 10 times the logarithm to the base 10 of the ratio of a given power to a reference power. The reference power must be indicated [1].

NOTE: In sound recording, for example, a reference electric power often used is the milliwatt, and the symbol dbm is employed to indicate both the unit of power level, the decibel, and the reference power, the milliwatt.

Pure Tone

(1) A simple tone is a sound wave, the instantaneous sound pressure of which is a simple sinusoidal function of the time.

(2) A simple tone is a sound sensation characterized by its singleness of pitch.

Random Noise

Random noise is an oscillation whose instantaneous magnitude is not specified for any given instant of time [1].

Resonance

Resonance of a system in forced oscillation exists when any change, however small, in the frequency of excitation causes a decrease in the response of the system [1].

Resonance Frequency (Resonant Frequency)

A resonance frequency is a frequency at which resonance exists [1].

NOTE: In case of possible confusion the type of resonance must be indicated; e.g., velocity resonance frequency.

Reverberant Field

The reverberant field is that part of the radiated sound field where the waves reflected from the boundaries of the enclosure are superimposed upon the incident field. The reverberant field may be called a diffuse field if a great many reflected

wavetrains cross from all possible directions and the sound energy density is very nearly uniform throughout the field.

Reverberation [1]

(1) Reverberation is the persistence of sound in an enclosed space, as a result of multiple reflections after the sound source has stopped.

(2) Reverberation is the sound that persists in an enclosed space, as a result of repeated reflection or scattering, after the source of the sound has stopped.

NOTE: The repeated reflections of residual sound in an enclosure can alternatively be described in terms of the transient behavior of the modes of vibration of the medium bounded by the enclosure.

Effective Sound Pressure Root-Mean-Square Sound Pressure [1]

The effective sound pressure at a point is the root-mean-square value of the instantaneous sound pressures, over a time interval at the point under consideration. In the case of periodic sound pressures, the interval must be an integral number of periods or an interval that is long compared to a period. In the case of nonperiodic sound pressures, the interval should be long enough to make the value obtained essentially independent of small changes in the length of the interval.

NOTE: The term "effective sound pressure" is frequently shortened to "sound pressure."

Soft Surface

A soft surface is a good absorber and thus a poor reflector of sound.

Sound Absorption

Sound absorption is the change of sound energy into some other form, usually heat, in passing through a medium or on striking a surface [1].

Sound Energy

The sound energy of a given part of a medium is the total energy in this part of the medium minus the energy which would exist in the same part of the medium with no sound waves present [1].

Sound Field

A sound field is a region containing sound waves [1].

Sound Level

A sound level is a weighted sound pressure level, obtained by the use of metering characteristics and the weightings A, B, or C, specified in American Standard Sound Level Meters for Measurement of Noise and Other Sounds, Z24.3-1944. (See Section 15.) The weighting employed must always be stated. The reference pressure is 0.0002 microbar [1].

NOTE: A suitable method of stating the weighting is, for example, "The A-sound level was 43 dB."

Sound Level Meter

Sound level meter is an apparatus for estimating the equivalent loudness of noise by an objective method [2].

In the United States, the acceptable performance of sound level meters has been standardized by the American Standards Association (American Standard for Sound Level Meters, Z24.3). Three alternate weighting networks are available in the electrical circuit to simulate the 40-dB, 70-dB, and 100-dB loudness contours of the human ear.

Sound Pressure

The sound pressure at a point is the total instantaneous pressure at that point in the presence of a sound wave minus the static pressure at that point [1].

Spectrum [1]

(1) The spectrum of a function of time is a description of its resolution into components, each of different frequency and (usually) different amplitude and phase.

(2) "Spectrum" is also used to signify a continuous range of components, usually wide in extent, within which waves have some specified common characteristic; e.g., "audio-frequency spectrum."

NOTE: The term "spectrum" is also applied to functions of variables other than time, such as distance.

Spectrum Density (Power Spectrum)

Spectrum density of an oscillation is the mean-square amplitude of the output of an ideal filter with unity [1].

Spectrum Level (Spectrum Density Level)

The spectrum level of a specified signal at a particular frequency is the level of that part of the signal contained within a band 1 cycle per second, or 1 Hz, wide, centered at the particular frequency. Ordinarily this has significance only for a signal having a continuous distribution of components within the frequency range under consideration. The words "spectrum level" cannot be used alone but must appear in combination with a prefatory modifier; e.g., pressure, velocity, voltage [1].

Transmission Coefficient

Transmission coefficient is the ratio of the sound transmitted through an interface or septum between two media, exposed to the sound field, to the sound energy incident on the interface or septum [2].

Transmission Loss

Transmission loss is the reduction in the magnitude of some characteristic of a signal, between two stated points in a transmission system [1].

Note 1: The characteristic is often some kind of level, such as power level or voltage level; in acoustics, the characteristic that is commonly measured is sound pressure level. Thus, if the levels are expressed in decibels, the transmission level loss is likewise in decibels.

Note 2: It is imperative that the characteristic concerned (such as the sound pressure level) be clearly identified because in all transmission systems more than one characteristic is propagated.

Ultrasonic Sound (Ultra-audible)

Ultrasonic sound is sound whose frequency is above the upper pitch limit. The term supersonic is now disapproved because of its use in aerodynamics as a velocity greater than the velocity of sound. Unless otherwise stated, it will be assumed that the frequency of ultrasonic (ultra-audible) sound is greater than 5,000 cps.

Velocity

Velocity is a vector that specifies the time rate of change of displacement with respect to a reference frame [1].

NOTE: If the reference frame is not inertial, the velocity is often designated "relative velocity."

Vibration

Vibration is an oscillation wherein the quantity is a parameter that defines the motion of a mechanical system [1].

Weighting (Frequency)

Weighting, or frequency, is a prescribed frequency response provided in a sound-level meter, as specified in ANSI S1.4-1975 or IEC Publications 129 or 179.

REFERENCES

1. USA Standard Acoustical Terminology [Acoustical Society of America ANSI S1.1-1971 (R-1960), New York, NY].
2. Acoustic Measurements, Leo L. Beranek (John Wiley & Sons, Inc., New York, NY, November 1950).