ECONOMIC POTENTIAL OF MINERAL-BASED INSULATING MATERIALS IN COMBATING THE NOISE PROBLEM IN RESIDENCES

By Franklin D. Cooper and Lucille M. Langlois

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CONTENTS

TABLES

ECONOMIC POTENTIAL OF MINERAL-BASED INSULATING MATERIALS IN COMBATING THE NOISE PROBLEM IN RESIDENCES

by

Franklin D. Cooper[1] and Lucille M. Langlois[2]

ABSTRACT

Three model dwelling units were redesigned to achieve specific levels of noise reduction above that provided by conventional construction. Using 1968 prices, the added costs of materials and installation were found to range from $500 to $5,000 depending upon the size of the dwelling unit and the degree of insulation. The potential aggregate expenditures for sound insulation materials are projected to reach $617 million in 1975, including about $408 million for the mineral-based materials, in 1968 constant dollars. The report includes a brief review of the mechanics and effects of sound.

INTRODUCTION

Noise, or unwanted sound, is a seemingly unavoidable part of our industrial and affluent society. In the past 20 years, new and more powerful kinds of transportation and construction equipment--jets, motorcycles, pneumatic drills--have come into general use; and increased wealth has made commonplace the acquisition of such conveniences as power lawnmowers. All of these devices make noise. As their popularity grows, more people in more places will be exposed to ever-increasing noise levels and the accompanying discomforts.[3]

The problem of increasing noise levels can be attacked in several ways: eliminating a noise or reducing sound emission to comfortable levels (stopping the noise at its source); removing the noise source from the people affected; or placing some kind of barrier between the hearer and the source of noise to

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muffle and absorb the offending sound waves. These barriers can be as simple as earplugs or as complex as complete sound control in an auditorium. So far, attempts have been unsuccessful to reduce significantly or to reduce to acceptable levels the noise emitted by modern machines. In most cases, as with aircraft engines, the noise cannot be eliminated or significantly reduced without impeding the function of the motor, nor can the source of the noise be removed. Muffling the noise at its source is also difficult, since it is awkward to insulate mobile equipment. Changes in materials or design to date have effected only minimal noise reduction, usually at a prohibitive cost (either monetarily or in terms of efficiency). Because of these various engineering problems, acoustical experts do not foresee any significant breakthroughs in the field of sound reduction in the near future. Thus, at present there is only one practical defense against most noises originating out-of-doors: erecting a barrier by means of sound insulation materials to protect homes and other structures from outside noises.

As noise levels continue to rise, the demand for additional sound protection will also grow; for, while affluence brings a greater use of noisy devices, it also brings the ability and willingness to pay for protection against noise. People can either learn to live with today's noise or pay the extra price to protect themselves from it. It is reasonable to assume, then, a growing effective demand for better protection against sound. Since at present insulation is the simplest way to obtain protection, it is also reasonable to assume that this demand will focus on materials for and methods of insulating structures against noise.

Research has shown that some of the best sound insulating materials are of mineral origin. For this reason, any increase in sound control, and its economic impact, is of special interest to the Bureau of Mines. The purpose of this report is to describe briefly the noise problem (the mechanics and measurement of sound and its impact) and to examine the various means of lowering noise levels indoors through sound insulation improvement (SII). The major part of the study consists of an economic analysis of the impact of improved sound insulation practices: their costs, projected estimates of future demand for sound insulating materials, and an overview of the effects of SII on the minerals industry.

The study is strictly limited to the increased use of sound insulation in new housing construction as a defense against outside noise. It does not concern itself with sound insulation in commercial buildings, or with the remodeling of older homes, nor does it examine the potential for sound insulation against noises produced within a home. Studies on reducing noise at its source and the social and psychological problems associated with noise and noisy environments are also outside the scope of the report. All these problems have been discussed by others.[4]

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[4]Federal Housing Administration. Impact Noise Control in Multifamily Dwellings. FHA No. 750, January 1963, 86 pp.

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SOUND AND NOISE

Acoustical Background

Sound is the result of changes in atmospheric pressure transmitted by a vibrating object. During one cycle or complete vibration of the object, the surrounding air is subjected to compression and rarefaction; these pressure changes are carried as waves from the vibrating source through the surrounding medium.

The basic form of a sound wave is a time-displacement graph that resembles a sine curve. The frequency of a sound wave indicates the number of times per second a complete cycle of the curve is traced--and to the listener, determines its pitch: the greater the frequency, the higher the pitch. The wavelength, which is the distance traveled by the sound wave in one complete cycle, varies inversely with the frequency; that is, the greater the frequency, the shorter the wavelength. The audible frequency spectrum of sound is in the range of about 15 to 15,000 cycles per second (cps).

Sound power is the acoustic energy emitted per unit of time by a sound source. The acoustic energy from a single source moves outward in all directions (if there are no intervening barriers) in a pattern roughly simulating a spherical surface. The amount of sound power per unit of area on this imaginary surface is called sound intensity, or sound pressure. The reference level of sound intensity (or sound pressure level), the decibel (dB), is equal to 10^{-16} watt per square centimeter or 0.00002 microbar. The "loudness" of a sound depends largely on its intensity or pressure, although frequency affects "loudness" as well. An increase of 6 dB indicates a doubling of sound pressure, but does not necessarily make sound twice as loud. (Degree of loudness is a subjective judgment each listener must make.) The human ear responds to a wide range of sound intensities--from a detection threshold just above 0 dB to a high of 120 dB. A normal person cannot hear sound louder than 120 dB without experiencing some pain.

Appendix A presents additional information on the physics of sound and on the definition of a decibel.

The Problem of Noise

Classifying sound as "noise" is a psychological judgment that a listener makes. Generally a noise is any annoying sound whose loudness, pitch, or other qualities are displeasing to the ear, or have an adverse emotional effect on the hearer. Although there is no standard accepted way to measure noise, probably the best measure of total response of the human auditory system to a noise is indicated on the Perceived Noise Decibel (PNdB) scale.[5] Readings on this scale indicate both the frequency spectrum and the intensity of a sound. These readings are then combined with weighting factors involving physical variables and psychological reactions. Thus, PNdB expresses not only the objective qualities of a sound but also an individual's judgment as to its "noisiness," and degree of acceptability. In this study, all measurements are expressed in terms of decibels (dB) or PNdB.

Even though noisiness, like loudness, is subjective, tests show that most people feel uncomfortable with noise levels above 70 PNdB, particularly indoors. Outdoors, most people surveyed accepted without complaint noises of 100 PNdB or more; but inside, exposure several times a day to noises of 80 PNdB or more was considered unacceptable.[6] Unfortunately, there are many modern devices which generate sound far above the normal level of acceptability. For example, a noise level well over 100 PNdB exists for about a 1.5-mile radius beyond most airport boundaries; jets produce noises of 116 PNdB and higher, while piston-powered aircraft average 102 PNdB. Decibel and PNdB ratings for some of the more common sources of noise are listed in tables 1 and 2.

TABLE 1. - Noise ratings on different scales

Source	4 ft from a large diesel engine	Factory	Piston aircraft	Jet aircraft	4 ft from a sand-blaster
Overall sound level....decibels..	108	88	110	110	116
Loudness.................sones[1]..	230	130	177	225	497
Loudness level..........phones[1]..	118	103	114	120	129
Speech interference level decibels..	99	78	83	103	107
Noisiness, perceived noise in decibels..................PNdB..	118	101	102	113	133

[1]These terms are not utilized in this report but are shown here for comparison with other studies.

Source: Lynch, Charles J. Noise Control. Internat. Sci. and Technol., v. 52, April 1966, pp. 32-41.

[5]U.S. Department of Housing and Urban Development. A Study--Insulating Houses From Aircraft Noise. November 1966, pp. 28-30.

[6]Kryter, Karl D. Psychological Reactions to Aircraft Noise. Science, v. 151, No. 3716, Mar. 18, 1966, pp. 1346-1355.

TABLE 2. - Sound intensity levels of several sound sources

Source of sound	Sound intensity, decibels
Ram-jet	180
Jet-rocket launching	175
Turbo-jet with 7,000-lb thrust	170
Four-propellor airliner at takeoff	150
Close proximity to aircraft jet-engine running at takeoff power	135
Chipping hammer, hydraulic press machine gun	130
Blaring radio	120
Jet airplane passenger ramp	117
Circular saw	116
Nearby motorcycle	111
Pneumatic jackhammer, centrifugal fan at 13,000 cfm	110
Power mower	107
Subway, maximum	104
Outboard motor	102
Nearby gunshot, loud television	100
Auto in tunnel	99
Food blender	93
Dishwasher, garbage disposer	91
Subway car	90
Conversation, failure point	85
Traffic outside Grand Central Station	81
Conversation, normal maximum	80
Garbage disposer	78
Average radio, normal conversation	70
Average television	68
Private office	65
Air conditioner fan	57
Low street noise, typical office	50
Normal home during sleeping hours	40
Quiet room	35
Comfortable level in home	30-40
Whisper	20
Person breathing	10
Threshold of hearing	0+

Sources: Elonka, Steve. Noise. Power, v. 106, No. 3, March 1962, pp. 191-206; Power, v. 106, No. 9, September 1962, pp. 186-187.

Insulation

Most conventional dwelling construction, with full thermal insulation (6 inches on the ceiling and 3 inches on the walls), offers a noise differential of about 20 PNdB between outside and inside sound levels,[7] so outside

[7] Elonka, Steve. Noise. Power, v. 106, No. 3, March 1962, pp. 181-206.

noises of 90 PNdB are tolerable when heard from indoors. But, as indicated previously, the sources of noise with sound ratings above 90 PNdB are increasing, and ordinary insulation will soon be insufficient for satisfactory sound control. "Soundproofing," or sound barrier insulation using acoustical materials in construction, will be in greater demand.

Acoustical materials, or sound barrier insulation, work in two ways to reduce sound: some--mostly nonporous materials--reflect sound waves, and others--porous insulation--absorb and muffle sound waves. The sound energy that is not reflected or absorbed is transmitted through the material; and since no acoustical material is a perfect sound barrier, we can assume that some sound, however little, will always be transmitted.

When sound strikes a relatively impervious surface, such as a concrete wall, most sound waves are reflected. Every time a sound wave is reflected, it loses energy and intensity, and so becomes less annoying; but more important, reflected sound does not pass through the barrier to disturb those behind it. An effective sound barrier is made of materials whose impedance (resistance to sound-transmitting vibrations) is greatly different from that of air. Such materials are nonresonant, and sound waves must expend much more energy than in air to transmit vibrations through these barriers. Because impedance is directly proportional to the mass of a substance, most good sound barriers are dense materials which do not vibrate easily. This is why old buildings, with thick solid walls, are relatively quiet. Modern builders, however, strive for minimum mass and more open construction, both for esthetic reasons and to conserve costly materials.

To satisfy these requirements as well as the increasing demand for improved sound insulation, builders have turned to new techniques and new materials to eliminate the need for massive sound barriers. Instead of thick solid walls, for instance, new homes have "double walls" (divided walls with an airspace between the two inner surfaces) made of nonresonant, nonporous materials. These double walls effectively reduce sound transmission without adding weight: they force sound to make inefficient energy transfers four times between different media, cutting down its power and intensity. Double walls do require more space, however, and if they are to be effective, their construction must not allow sound to be transmitted instead through the floor or ceiling (that is, acoustic coupling must be avoided). Additional noise control can be had by installing layers of porous sound-absorbing materials in the airspace between the surfaces of the two walls.

When sound is absorbed by a highly porous material such as matted glass fibers, the air inside the pores is set vibrating by the incident sound waves; a portion of the sound energy is thus dissipated by friction. The absorptive capacity of a material increases with its thickness, its porosity, and the size of the pores. There are some exceptions to this: some high-frequency sounds will penetrate even very thick barriers; and if the size of the pores becomes too large, their absorption capacity decreases. The absorption capacity of a material (the percentage of sound energy it absorbs) is expressed as the material's sound-absorption coefficient. Acoustical engineers define this coefficient, called a sabin, as 1 square foot of perfect sound-absorbing surface, or its equivalent. For example, 10 square feet of surface with a sound-absorption coefficient of 0.60 would provide 6 sabins of noise reduction. Materials that are highly impervious (nonporous) have low sound-absorption coefficients, since they reflect most sound waves. Concrete, for instance, has a sound-absorption coefficient of 0.01, while some mineral fiber compositions reach as high as 0.90.

The combination of sound-reflecting and sound-absorbing properties of insulating materials is given in terms of an overall "noise-reducing coefficient," expressed as the percentage of incident sound reflected or absorbed by the insulating material. Most common construction with simple thermal insulation affords an overall noise-reducing coefficient ranging from 0.30 to 0.55. Appendix B presents additional technical information on noise absorption and transmission and on predicted reductions in noise levels by specific building materials and components.

Mineral-Related Insulation Materials

Sound insulation is usually built into one or all of six components of dwellings: exterior walls, interior walls, ceilings, roofs, doors and doorframes, and windows and window frames. For each of these structural functions, builders can choose from a wide range of insulating materials, which vary greatly in both cost and effectiveness. Although most of these materials are multifunctional--serving for example as both thermal and sound insulation--no effort will be made here to describe all of their possible uses; only their most common or significant applications will be mentioned.

Concrete, cement blocks, and bricks, because of their high impedance and low porosity, are frequently used in exterior walls to reflect outside noises from a building. They can also be used for interior walls, to further prevent noise penetration. Similarly, acoustic plasters and plastic-coated wallboard are used in interior walls because their highly nonporous surfaces reflect rather than transmit sound. Both interior and exterior walls often are lined with mineral wools, as are ceilings and roofs. These insulating wools have high sound-absorption coefficients, and are sometimes backed by foil to reflect sound as well, thus increasing their overall noise-reducing capacity. Gypsum, which tends to reflect sound, is commonly made into wallboard, sheathing, lath, and other such components. It has the advantages of being inexpensive and fireproof, and effectively provides both thermal and acoustic insulation. Also, ceiling tiles and other cellulose products (including wallboard) generally contain some mineral filler to increase their mass, and consequently their noise-reducing capacity. These products are used on interior walls and ceilings, almost exclusively for sound control purposes. Finally, even windows today can be constructed on the same principle as the "double wall," to provide both thermal and acoustic insulation.

Table 3 lists 15 materials commonly used for acoustic insulation, 10 of which are primarily of mineral origin. The selection of specific products to be used depends on space, weight and budget limitations, exposure to weather, and fire resistance requirements.

TABLE 3. - NRC classification of acoustic materials for internal use

Type[1]	Material	NRC[2] range, 3/4-inch thick
1	Regularly perforated cellulose-fiber tile.............	0.65-0.85
2	Randomly perforated cellulose-fiber tile..............	.60- .75
3	Textured, perforated, fissured cellulose tile.........	.50- .70
4	Cellulose-fiber lay-in panels[3].........................	.50- .60
5	Perforated mineral-fiber tile.........................	.65- .85
6	Fissured mineral-fiber tile...........................	.65- .80
7	Textured, perforated or smooth, mineral-fiber tile.....	.65- .80
8	Membrane-faced mineral-fiber tile.....................	.30- .90
9	Mineral-fiber lay-in panels...........................	.20- .90
10	Perforated-metal pans with mineral fiber[3].............	.60- .80
11	Perforated-metal lay-in panels with mineral-fiber pads.	.75- .85
12	Mineral-fiber tile fire-resistive assemblies...........	.55- .90
13	Mineral-fiber lay-in panels fire-resistive units[4]......	.65- .75
14	Perforated-asbestos panels with mineral-fiber pads[5]....	.65- .75
15	Sound-absorbent duct lining[3]..........................	.65- .75

[1] These categories are the same as those utilized by the Acoustical Materials Association.
[2] Noise-reduction coefficient (proportion of incident sound absorbed and/or reflected).
[3] 1-inch thickness.
[4] 5/8-inch thickness.
[5] 15/16-inch thickness.

Source: Elonka, Steve. Noise. Power, v. 106, No. 3, March 1962, pp. 191-206.

COST ANALYSIS

Although acoustic insulation is common in commercial buildings, it is just beginning to become popular for houses, and its use there is still considered a luxury. At present--and in the near future--the cost of installing residential SII (sound insulation improvement) is high. Nevertheless, there is a growing demand for acoustic insulation in dwellings, particularly in new construction. And since many sound insulating materials are mineral-related, an increased demand can be projected for these products of the minerals industry. The remainder of this study focuses on this new market for mineral-based acoustic materials, and on its significance for the minerals industry.

Methodology

To determine the potential economic impact of SII, the probable national housing market for the next few years was simulated. Typical model dwellings of various types were devised and their construction costs estimated for different levels of sound insulation. Regional differentials in prices and construction practices were taken into account to insure that the national estimate was representative. This sample housing mix was then applied to the projections of housing starts annually through 1975 in order to approximate the probable distribution of demand for the various levels of SII and for the mineral-based materials required to provide the desired acoustic insulation.

Initially, five model dwellings were designed: an average one-story, single-family house with 1,000 sq ft of living area; a similar but slightly larger model with an area of 1,250 sq ft; a typical two-story, single-family house (1,800 sq ft); a mobile home with 500 sq ft; and a conventional one-bedroom apartment (700 sq ft). Each of the designs was varied to include plans for (a) normal full thermal insulation yielding a 20 PNdB noise reduction without soundproofing, (b) sound insulation providing total sound reduction of 25 PNdB or 5 PNdB above normal thermal insulation, and (c) sound insulation providing 35 PNdB reduction or 15 PNdB above normal thermal insulation.

The various designs were submitted to builders across the country for pricing, and the average additional cost of purchasing and installing acoustic insulation was calculated on the basis of the estimates received. Sample prices are shown in tables 4 and 5. Table 6 is an example of how these prices, which are costs to the builder, were utilized for the two-story dwelling model; the costs of SII for each of the other dwelling models were derived in the same manner. All price and cost information is based on 1968 values.

TABLE 4. - Sample prices in 1968 of some sound insulation materials

(Thousand square feet except where indicated)

Item	Range	Average
Gypsum, plasterboard, 1/2-in..................	$44- 95	$63
Gypsum, plasterboard, 3/8-in..................	38- 65	53
Gypsum, board lath, 3/8-in..................	29- 52	45
Gypsum, T&G sheathing......................	40- 75	55
Fiberboard, 1/2-in.........................	44- 87	61
Fiberboard, T&G, 25/32-in..................	80-125	104
Insulation:		
Fiberboard, 1/2-in........................	42- 95	73
Mineral wool, loose.............40-lb bag..	0.80- 2.30	1.37
Mineral wool, 3-in batts..................	40- 75	59
Glass fiber, loose..............40-lb bag..	.95- 2.30	1.55
Glass fiber, 3-in batts...................	41- 75	58
Aluminum foil, 2 layers...................	33-100	56

Source: Engineering News-Record. V. 180, No. 13, Mar. 28, 1968, p. 43.

TABLE 5. - Sample prices in 1968 of some acoustically insulated building components

Windows:	
Storm..	$1.80 to $2.60/sq ft
Double...	$6.30/sq ft.
Doors:	
Weatherstripping only..................................	$17/door
Storm door with weatherstripping.......................	$34/door
Solid core with heavy-duty weatherstripping............	$59/door
Roof: Ventilated attic space, 1/2-in gypsum boards...........	$0.40/sq ft
Exterior walls: Install new brick on concrete veneer.........	$1.40 to $2.10/sq ft
Ceilings: Install 3/4-in acoustical tile having a NRC of 0.65 or greater..	$0.85 to $1.10/sq ft

Source: U.S. Department of Housing and Urban Development. A Study--Insulating Houses From Aircraft Noise. November 1966, 58 pp.

TABLE 6. - Erected cost of components offering sound insulation improvement in an 1,800-square-foot, two-story house and garage[1]

Components and materials used	Category	Quantity needed[2]	Cost: Materials	Cost: Erection labor
20 PNdB REDUCTION (NORMAL THERMAL INSULATION)				
Exterior walls (2,440 ft^2):				
Sills and studs (framing)	Lumber	1,590 bm	$175	$260
1/2-in fiberboard	Nonmineral	2,440 ft^2	165	125
15-lb felt paper	do	2,440 ft^2	26	80
3/8-in textured plywood	Lumber	2,440 ft^2	360	537
Nails and fasteners	Nails and fasteners	290 lb	43	-
Interior walls (4,700 ft^2):				
Studs (framing)	Lumber	770 bm	85	128
0.006-in polyfilm	Nonmineral	4,700 ft^2	40	171
3/8-in plasterboard	Mineral based	4,700 ft^2	250	275
Nails and fasteners	Nails and fasteners	290 lb	43	-
Ceilings (1,800 ft^2):				
Joists and cross bracing (framing)	Lumber	2,200 bm	245	180
3/8-in plasterboard	Mineral based	1,800 ft^2	100	150
Mineral wool, loose, 450 ft^3	do	4,500 lb	146	45
Nails and fasteners	Nails and fasteners	37 lb	11	-
Roof (1,640 ft^2):				
Rafters (framing)	Lumber	1,100 bm	130	99
1-in wood sheathing	do	1,640 ft^2	198	110
15-lb felt paper	Nonmineral	1,640 ft^2	17	39
235-lb bitumen shingles	do	1,640 ft^2	150	362
Nails and fasteners	Nails and fasteners	270 lb	41	-
Windows (350 ft^2):				
Aluminum, sliding, single-strength glass	Window	21	463	463
Sills and studs (framing)	Lumber	400 bm	44	54
Nails and fasteners	Nails and fasteners[3]	-	-	-
Doors (230 ft^2):				
Outside, with hardware	Door	3	75	86
Inside, with hardware	do	10	185	220
Fasteners for 13 doors	Nails and fasteners[3]	-	-	-
Framing, sills and studs	Lumber	380 bm	45	56
Total	-	-	3,037	3,440
25 PNdB REDUCTION (5 PNdB SII)				
Exterior walls (2,440 ft^2):				
Sills and studs (framing)	Lumber	1,590 bm	$175	$260
1/2-in fiberboard	Nonmineral	2,440 ft^2	165	125
15-lb felt paper	do	2,440 ft^2	26	80
3/8-in textured plywood	Lumber	2,440 ft^2	360	537
Nails and fasteners	Nails and fasteners	330 lb	50	-
Interior walls (4,700 ft^2):				
Studs (framing)	Lumber	770 bm	85	127
1/4-in prefinished plywood	do	4,700 ft^2	425	528
3/8-in plasterboard	Mineral based	4,700 ft^2	250	275
Nails and fasteners	Nails and fasteners	290 lb	44	-
Ceilings (1,800 ft^2):				
Joists and cross bracing (framing)	Lumber	2,200 bm	245	198
3/8-in plasterboard	Mineral based	1,800 ft^2	100	150
Mineral wool, loose, 450 ft^3	do	4,500 lb	146	48
Nails and fasteners	Nails and fasteners	37 lb	13	-

Roof (1,640 ft^2):				
Rafters (framing)	Lumber	1,400 bm	165	110
1-in wood sheathing	do	1,640 ft^2	198	110
15-lb felt paper	Nonmineral	3,280 ft^2	34	50
Asbestos-cement shingles	Mineral based	1,640 ft^2	330	330
Nails and fasteners	Nails and fasteners	270 lb	41	-
Windows (350 ft^2):				
Wood, double-hung, double-strength glass	Window	21	652	770
Sills and studs (framing)	Lumber	400 bm	44	54
Nails and fasteners	Nails and fasteners[3]	-	-	-
Doors (230 ft^2):				
Outside, with hardware	Door	3	90	86
Inside, with hardware	do	10	194	220
Fasteners for 13 doors	Nails and fasteners[3]	-	-	-
Framing	Lumber	380 bm	45	56
Total	-	-	3,877	4,114
35 PNdB REDUCTION (15 PNdB SII)				
Exterior walls (2,440 ft^2):				
Sills and studs (framing)	Lumber	-	-	-
37,000 bricks plus mortar	Mineral based	-	$2,395	$4,210
3/4-in vaporproof fiberboard	Nonmineral	2,440 ft^2	280	280
4-in foilback fiberglass	Mineral based	2,440 ft^2	190	186
Nails and fasteners	Nails and fasteners	100 lb	15	-
Interior walls (4,700 ft^2):				
Studs, 2-row construction (framing)	Lumber	1,540 bm	170	230
3/8-in plasterboard	Mineral based	4,700 ft^2	250	275
3/8-in plaster applied on 3/8-in plasterboard	do	4,700 ft^2	165	485
3-in friction-fit fiberglass	do	4,700 ft^2	270	170
Nails and fasteners	Nails and fasteners	350 lb	54	-
Ceilings (1,800 ft^2):				
Joists and cross bracing (framing)	Lumber	2,200 bm	245	198
3/8-in plasterboard	Mineral based	1,800 ft^2	100	150
3/8-in plaster applied on 3/8-in plasterboard	do	1,800 ft^2	70	230
Nails and fasteners	Nails and fasteners	77 lb	14	-
Roof (1,640 ft^2):				
Rafters (framing)	Lumber	1,100 bm	130	114
1-in wood sheathing	do	1,640 ft^2	198	130
15-lb felt paper	Nonmineral	3,280 ft^2	34	50
Hand-split shakes	Lumber	1,640 ft^2	510	750
Nails and fasteners	Nails and fasteners	410 lb	62	-
Windows (350 ft^2):				
Wood, casement, 5/8-in, insulating	Window	21	1,303	994
Sills, studs, and casing (framing)	Lumber	400 bm	44	54
Nails and fasteners	Nails and fasteners[3]	-	-	-
Doors (230 ft^2):				
Outside, with hardware	Door	3	180	90
Inside, with hardware	do	10	320	200
Fasteners for 13 doors	Nails and fasteners[3]	-	-	-
Framing	Lumber	750 bm	45	70
Total		-	7,044	8,866

[1]Labor costs quoted here are base rates plus an additional 10 percent to cover fringe benefits. Materials costs allow for 10-percent wastage and loss.
[2]bm = board measure.
[3]Quantities used are negligible.

Several adjustments were made in reported costs. The labor input costs for erection and installation of each component were calculated using as a base the cost of construction labor in the first half of 1968 but with a 10-percent allowance for fringe benefits. The respective proportion of the cost of materials and the cost of directly related construction labor is assumed to be constant in any one component in all models, but not for all six different components in any one model. In other words, a glazier receives the same wage for installing similar windows in a one-story and a two-story house, but does not necessarily get paid as much as a mason or a carpenter working on the same houses. Finally, allowance was made for variations ranging to 15 percent in the local costs of materials, construction labor, and differences in construction specifications, and up to 10 percent for wastage, breakage, and loss of materials.

Given all of the final material costs and erection costs and adjustments, the approximate average basic construction costs (without acoustic insulation) of four of the five models are as follows: \$5,900 for the mobile home; \$12,500 for the one-story, 1,000-sq-ft house; \$12,500 to \$19,000 for the one-story, 1,250-sq-ft dwelling; \$35,000 for the 1,800-sq-ft, two-story house. As will be explained later, valid estimates of the cost of a single apartment unit cannot be derived. These costs include only the structure itself; no land costs are included.

In comparing the cost of SII with the basic construction costs of the five models, it was found that the additional (marginal) cost of acoustic insulation in lower priced dwellings is so high relative to total cost, that its installation appears to be economically impractical. For example, people paying less than about \$12,000 for a house are unlikely to assume an extra initial investment of roughly \$700 for 5 PNdB of SII, much less \$5,000 for 15 PNdB. Therefore, it was assumed that neither mobile homes nor houses costing less than \$12,000 would be part of the potential market for residential SII materials. Consequently, these two models were dropped from the detailed analyses of acoustic insulation practices that follow.

Sound insulation in the two remaining single-family houses will be studied as one problem, since the conditions and relative costs in both models are very similar. A separate analysis will be made of acoustic insulation in apartments since the requirements for sound control and the method used for the cost analysis are different from those involving single-family dwellings.

Besides the direct costs of purchasing and installing acoustic insulation, builders and home buyers and lessors must also consider the secondary costs of noise control. These include additional interest on mortgage payments (greater financing costs), higher insurance rates, and higher property taxes. The most significant secondary cost is likely to be the added interest payments; over a period of 25 years, an interest rate of 7 percent on the remaining balance will approximately double the cost of any initial investment. In apartments, of course, such extra costs would usually be passed on to the tenant in the form of higher monthly rentals.

It is difficult to make any general statements about the amount of these secondary costs of acoustic insulation because they will vary widely from place to place. Therefore, they have been ignored in the calculations to follow. However, their impact is clearly to increase the marginal cost of providing SII.

SII in Single-Family Dwellings

Two different house models were studied in detail to evaluate the potential for SII; one is a relatively low-priced, single-story house and the other a moderate-priced, two-story model. The two models compare as follows, in square feet:

	Two-story	One-story
Living area...........	1,800	1,250
Volume of living area[1]	15,300	10,625
Roof..................	1,600	2,200
Outside walls.........	2,340	1,380
Windows...............	[2]350	[3]190
Doors, outside........	[4]52	[4]52
Inside walls..........	4,700	1,980
Doors, inside.........	[5]175	[6]140
Ceilings..............	1,800	1,100

[1]Cubic feet.
[2]21 windows.
[3]11 windows.
[4]3 doors.
[5]10 doors.
[6]8 doors.

Table 7 details the additional cost per thousand square feet (above basic construction costs) of (1) normal thermal insulation, which ordinarily provides a 20-PNdB reduction in the noise level of a home; (2) sound insulation improvement (SII) providing a total of 25-PNdB noise reduction or 5 PNdB above thermal insulation; and (3) SII affording an overall sound reduction of 35 PNdB or 15 PNdB above thermal insulation. Table 7 classifies the types of material used, their costs, and the labor cost related to their erection. Other than doors and windows, the major types of material are wood products, mineral-based materials, and other materials. (Some materials such as plastics and bitumen shingles are classified as nonmineral-based because the value of the original mineral content is too small to be significant.) Dashes in table 7 indicate that the particular material is seldom used for sound insulation in the indicated housing unit.

It is not to be assumed--here or in any case--that the indicated differential in noise levels will always be attained by the insulation practices listed in the table. Environmental factors, such as wind direction or distance from a source of noise, produce varying sound levels which may affect the noise differential by as much as ±5 to ±10 PNdB. However, the given reductions are on the average attainable by the indicated construction methods and materials.

TABLE 7. - Construction costs for sound insulation by product in single-family dwellings[1]

Building materials	1,250 ft² living area, single-story						1,800 ft² living area, two stories					
	Normal thermal insulation		5 PNdB SII		15 PNdB SII		Normal thermal insulation		5 PNdB SII		15 PNdB SII	
	Materials	Labor	Materials	Labor	Materials	Labor	Materials	Labor	Materials	Labor	Materials	Labor
Wood products:												
Lumber, framing, sheathing, furring strips	$749	$710	$1,020	$1,080	$980	$1,173	$922	$887	$957	$915	$832	$796
Plywood (textured)	250	280	205	255	165	150	360	537	360	537	-	-
Plywood (prefinished)	-	-	-	-	-	-	-	-	425	528	-	-
Hand-split shakes	-	-	-	-	-	-	-	-	-	-	510	750
Windows[2]	243	321	341	435	683	536	463	463	652	770	1,303	994
Doors[3]	231	213	252	250	473	275	260	306	284	306	500	290
Nonmineral-based, nonwood materials:												
Felt, polyfilm, bitumen shingles[4]	207	617	40	100	60	130	233	652	60	130	34	50
Fiberboard	150	115	22	20	151	120	165	125	165	125	280	280
Mineral-based materials:												
Nails and fasteners	111	NA	111	NA	111	NA	138	NA	148	NA	145	NA
Plasterboard	175	240	210	240	180	230	350	425	350	425	350	425
Plaster (applied on plasterboard)	-	-	-	-	210	630	-	-	-	-	235	715
Mineral wool	45	15	-	-	-	-	146	45	146	48	-	-
Fiberglass products	-	-	130	90	100	85	-	-	-	-	460	356
Asbestos-cement shingles	-	-	440	340	-	-	-	-	330	330	-	-
Brick and mortar	-	-	-	-	1,395	2,647	-	-	-	-	2,395	4,210
Concrete	-	-	-	-	-	-	-	-	-	-	-	-
Concrete rebars	-	-	-	-	-	-	-	-	-	-	-	-
Total materials costs per dwelling unit	2,161	NA	2,771	NA	4,508	NA	3,037	NA	3,877	NA	7,044	NA
Total mineral-based materials only	331	NA	891	NA	1,996	NA	634	NA	974	NA	3,585	NA
Total labor cost	NA	2,511	NA	2,810	NA	5,976	NA	3,440	NA	4,114	NA	8,866
Labor for erecting mineral-based materials	NA	255	NA	670	NA	3,592	NA	470	NA	803	NA	5,706

[1] All material costs are based on 1968 prices, including 10 percent for wastage; labor costs are 1968 costs with 10 percent for fringe benefits.

[2] The one-story house has 11 windows; the two-story house has 21.

[3] Each house has 3 outside doors. The one-story house has 8 inside doors; the two-story house has 10 doors.

[4] The mineral content of these materials is negligible.

Note: A dash indicates that the given material is seldom used; NA indicates that it is not applicable.

The total additional cost for each level of sound insulation in the two houses is given in table 8. The total cost figures in part A of table 8--the sum of the component costs on table 7--were used to derive the marginal costs in part B for increasing total sound insulation from 20 to 25, and from 20 to 35 PNdB, in the two houses. Note that the marginal cost of acoustic insulation rises very rapidly. The cost of an additional 15 PNdB of sound reduction is just under 50 percent of the total basic construction cost for the one-story house, and almost 25 percent of the basic cost of the two-story model. Given such figures, it is not surprising that most lower priced houses built today do not contain much acoustic insulation.

TABLE 8. - Unit costs for insulation materials and related labor in single-family dwellings

Degree of sound insulation	One-story house (1,250 ft²)			Two-story house (1,800 ft²)		
	Materials	Labor	Total	Materials	Labor	Total
PART A--MEDIAN TOTAL COSTS (FROM TABLE 7)						
Normal thermal (20 PNdB)........	$2,161	$2,511	$4,672	$3,037	$3,440	$6,477
5 PNdB SII (25 PNdB overall)	2,771	2,810	5,581	3,877	4,114	7,991
15 PNdB SII (35 PNdB overall)	4,508	5,976	10,484	7,044	8,866	15,910
PART B--ADDITIONAL (MARGINAL) COSTS OF ATTAINING SII ABOVE NORMAL THERMAL INSULATION						
5 PNdB SII........	$610	$299	$909	$840	$674	$1,514
15 PNdB SII.......	2,347	3,465	5,812	4,007	5,426	9,433

SII in Apartments

The cost study for sound insulation in an apartment differs somewhat from that of a one-family dwelling. The basic construction cost cannot be calculated in any meaningful way for a single apartment unit. Apartment building costs are so highly aggregated that an average figure is neither accurate nor significant. The only figures that are relevant to this study are the additional costs of installing sound insulation in a new one-bedroom apartment, should the builder decide to do so.

Apartment dwellers are subjected to far more "outside" noises than are people in single-family homes. They must put up with sounds from apartments above and below and on either side, and in hallways, as well as from outdoors. Since most interior partitions, even between apartments, are thinner than exterior walls, they afford less protection against the sounds in nearby apartments. While normal external construction, as mentioned earlier, affords sound insulation of about 20 PNdB, the partitions between apartments (in ordinary construction, without acoustic insulation) provide only about half that much protection. A glance back at table 2 will show that many sounds commonly heard in apartments--radios, conversation, kitchen appliances--have noise rating above 80 PNdB. People living in apartments, then, are very frequently exposed to noise levels above the comfort limit of 70 PNdB.

Insulation between apartment units affording a 5-PNdB reduction of sound beyond normal construction practice is consequently of little or no use in apartments. For sound insulation in an apartment to be a worthwhile investment, it must provide a total noise reduction of at least 25 PNdB, or 15 PNdB of SII. The cost of "soundproofing" a standard one-bedroom apartment to provide this level of noise reduction can be approximated by redesigning the unit in much the same way that the single-family homes were redesigned. (See table 6.) Table 9 shows the major changes in construction required to attain 15 PNdB of SII in apartments. In table 10, which is identical in form to table 7, these changes are presented in terms of the kinds of materials required and of the labor needed to erect them. The marginal cost per unit is considerably lower than for single-family homes, about $290 per unit, a figure that would require only a relatively small increase in monthly rentals.

TABLE 9. - Cost of additional sound insulating materials by component in a new 700-square-foot apartment to attain a 15-PNdB SII

Component	Additional material cost in excess of normal construction cost
Walls: Exterior and corridor side--700-ft^2 total area, using 3/4-inch instead of 3/8-inch gypsum plasterboard....................................	$12
Walls: Divider between apartments--350-ft^2 total area, using 3/4-inch gypsum plasterboard nailed to furring strip on 4-inch hollow tile.	17 [1]1 ([2])
Door: Corridor--solid core instead of hollow core..	5
Doors: Balcony, metal frame--5/8-inch insulated instead of single-strength glass. Windows--90-ft^2 total area, using 5/8-inch insulated instead of single-strength glass.	22
Ceilings--700-ft^2 total area, using 1-inch gypsum plasterboard instead of 3/8-inch, nailed to furring strips.	33 [1]2 ([2])
Floor--700-ft^2 total area, using 2 inches additional reinforced concrete in the slab construction plus 3 inches glass-fiber insulation.	[3]16 [4]5 [5]40
Total....................................	153

[1]Furring strip.
[2]Nails and staples.
[3]For concrete, sand, cement, and aggregates.
[4]For reinforcing bars and rods.
[5]For glass-fiber insulation.

TABLE 10. - Construction costs for sound insulation in a new 700-square-foot apartment[1]

Building materials	700 ft² living area apartment (one-bedroom equivalent)			
	Normal thermal insulation		15 PNdB SII	
	Materials	Labor	Materials	Labor
Wood products:				
Lumber, framing, sheathing, furring strips...	$6	$10	$9	$15
Plywood (textured)........................	-	-	-	-
Plywood (prefinished)......................	-	-	-	-
Hand-split shakes..........................	-	-	-	-
Windows..	50	55	72	60
Doors..	30	40	35	40
Nonmineral-based, nonwood materials:				
Felt, polyfilm, bitumen shingles[2]............	-	-	-	-
Fiberboard..................................	-	-	-	-
Mineral-based materials:				
Nails and fasteners.........................	6	-	6	-
Plasterboard................................	40	50	102	125
Plaster (applied on plasterboard)............	-	-	-	-
Mineral wool................................	-	-	-	-
Fiberglass products.........................	-	-	40	25
Asbestos-cement shingles....................	-	-	-	-
Brick and mortar............................	-	-	-	-
Concrete....................................	48	210	64	230
Concrete rebars.............................	20	50	25	60
Total materials cost per dwelling unit....	200	-	353	-
Total mineral-based materials only........	114	-	237	-
Total labor cost..........................	-	415	-	555
Labor for erecting mineral-based materials	-	310	-	440

[1] All material costs are based on 1968 prices, including 10 percent for wastage; labor costs are 1968 costs with 10 percent for fringe benefits.
[2] The mineral content of these materials is negligible.

Market Distribution of Acoustic Insulating Materials

In the preceding section, detailed housing models were used to estimate the cost of SII in individual residential units. Data are not available on the present volume of consumption of acoustic insulation in residences, and the present size of this market cannot be estimated. But it is possible to determine the approximate composition of the markets current and future for acoustic insulating materials in houses and apartments. Total expenditures for SII can be broken down by product for each of the three models, and the percentage share of total expenditures that each product accounts for can be measured. This gives the distribution schedule of the consumption of the various acoustic materials, which can be expanded to apply to the total market for residential SII, whatever size that market may be.

Table 11 shows the approximate distribution--using present technology--of expenditures on materials for several levels of acoustic insulation. Note that mineral-based products account for perhaps half of the current market. The proportion of mineral-based products used for SII can be expected to remain constant in the near future, since sound insulation practices are not expected to change significantly. However, increased demand for residential SII will expand the total consumption of these materials. Furthermore, the proportion of mineral-based materials increases sharply as desired SII shifts from 5 to 15 PNdB, and in apartment units it accounts for two-thirds of the value of demand. Therefore, as the demand grows for higher levels of acoustic insulation, and as apartments increase in popularity relative to single-family homes, the share of mineral-based materials in the acoustic insulation market will also grow.

TABLE 11. - Percentage distribution of cost of additional materials to attain SII above normal insulation practice

Materials	1,250 ft² house		1,800 ft² house		700 ft² apartment, 15 PNdB SII
	5 PNdB SII	15 PNdB SII	5 PNdB SII	15 PNdB SII	
Wood products	44.1	25.4	45.0	19.0	2.5
Windows	12.3	15.1	16.8	18.5	20.4
Doors	9.1	10.5	7.3	7.1	9.9
Nonmineral-based, nonwood materials[1]	2.2	4.6	5.8	4.5	-
Mineral-based materials:					
Nails and fasteners	4.0	2.5	3.8	2.1	1.7
Gypsum plasterboard	7.6	4.0	9.0	5.0	29.0
Plaster	-	4.7	-	3.3	-
Mineral wool	-	-	3.8	-	-
Fiberglass products	4.7	2.2	-	6.5	11.3
Asbestos-cement shingles	16.0	-	8.5	-	-
Brick and mortar	-	31.0	-	34.0	-
Concrete	-	-	-	-	18.1
Steel reinforcing bars	-	-	-	-	7.1
Total mineral-based	32.3	44.4	25.1	50.9	67.2
Grand total	100	100	100	100	100

[1] The original mineral base of bitumens and plastic is small and has been neglected.

Source: Table 7.

PROJECTED DEMAND FOR SOUND INSULATING MATERIALS

The growth of the market for residential SII materials depends on the growth of the housing market in general, and on the increased demand for acoustical insulation to combat rising noise levels. Given these data, and the unit costs for SII components indicated in tables 4 through 10, it is possible to project the potential consumption of mineral-based acoustic insulation, and the probable value of that consumption. This can be done very simply by a series of multiplications, using the information derived in the first part of this study. Total projected expenditure for acoustic insulation is equal to the product of--total housing units projected times percentage of units with specified levels of SII times cost per unit of SII. Expenditures for various acoustic materials can also be projected by multiplying the above product by the percentage distribution of materials shown in table 11. These calculations, serving as guidelines only, can be applied to any chosen housing mix and any size housing market. It is not possible to depict the composition of the housing market in 1975, and so exact predictions of acoustic materials consumption in that year cannot be made. However, general characteristics and trends of residential construction can be gaged (such as the increased construction of apartments and rising incomes), and a reasonable projection of the 1975 housing market can be compiled.

One particular sample market for 1975 is shown in table 12. This projection is quite conservative when compared with some others, but this was done to prevent overstating the impact of residential SII on the minerals industry. The projections are all based on 1968 price levels.

TABLE 12. - Projected housing mix for 1975 and additional expenditures to attain SII above normal insulation practice[1] (1968 dollars)

Types of housing	Total units constructed (1,000's)	Units constructed using normal thermal insulation practice (1,000 units)	Units designed to attain 5 PNdB sound insulation improvement above normal insulation practice			Units designed to attain 15 PNdB sound insulation improvement above normal insulation practice		
			1,000 units	Additional direct cost, millions		1,000 units	Additional direct cost, millions	
				Materials	Labor		Materials	Labor
Mobile homes averaging $5,900 (500 ft² living area)	337.5	337.5	0	-	-	0	-	-
Apartment, one-bedroom equivalent (700 ft² living area)	525	344.0	0	-	-	181.0	27.7	25.4
One-family houses costing under $12,500 (1,000 ft² living area)	405	405.0	0	-	-	0	-	-
One-family houses costing $12,500 to $19,000 (1,250 ft² living area)	175	135.0	35.0	21.3	10.4	5.0	11.8	17.3
One-family houses averaging $35,000 in cost (1,800 ft² living area)	357.5	72.5	185.0	155.5	124.9	100.0	400.7	542.6
Subtotal	1,800.0	1,294.0	220.0	176.8	135.3	286.0	440.2	585.3

[1] Total additional projected expenditures for materials--$707.5 million; total additional projected expenditures for labor--$806.7 million.

Source: Projections by authors; costs from tables 8, 9, and 10.

Housing starts in 1967 were 1.3 million, and by 1975 are projected to reach 2 million. Although some of these housing units will not be completed in that year, it is estimated that about 1.8 million new dwellings annually will be available by the mid-1970's. Even assuming no shift in demand patterns from the present consumption of residential acoustic insulation, the demand for these materials will increase in proportion to the increase in housing starts. However, it is reasonable to expect that the demand for residential acoustic insulation will probably double by 1975, and that there will be some changes in the distribution of the housing mix.

Assuming that the projections made in table 12 are realized, we can apply our cost figures for the various models and levels of SII derived in tables 8 and 10 to determine projected additional expenditures for acoustic insulation in future dwellings. These figures are also shown in table 12. Unfortunately, given the absence of data on the number of units being constructed with SII today, it is not possible to compare future expenditures on SII with present expenditures in greater detail.

Finally, using the percentage cost distribution of the various insulating materials derived from the models (see table 11), it is possible to estimate the value of future consumption for each of the different acoustic materials. This is done in table 13. For example, using the housing mix in table 12, expenditures of $97 million can be expected to attain additional acoustic insulation of 5 PNdB in relatively small (1,250 sq ft) single-family houses by 1975. Of this total, $31 million will be used to purchase mineral-based products. These include $4 million for nails and fasteners, $7 million for gypsum plasterboard, $5 million for fiberglass products, and $15 million for asbestos shingles. Similar projections for higher levels of acoustic insulation and for larger single-family houses and apartments are also shown in table 13. Such computations can be performed for any selected housing mix, using the distribution schedule shown in table 11.

As shown in the final three columns of table 13, which compare materials demands for the selected housing mix with those for a mix with no SII, almost all of the mineral-based materials and products listed in table 13 will come into greater demand as acoustic insulation becomes more popular. The one exception is mineral wool, which tends to decrease in use as other more efficient acoustic insulating materials are substituted for it. In contrast, the most significant absolute and relative gains should be exhibited by brick and mortar, followed by asbestos-cement shingles, fiberglass products, and gypsum plaster.

On the basis of the sample housing mix chosen, it is estimated that in total an additional $408 million of mineral-based acoustic materials will be demanded annually by 1975. Roughly 10 percent of the value of these final products can be attributed to the cost of raw materials. In this case, then, the projected increase in production of raw materials in 1975 generated by increased demand for residential SII is about $41 million in 1968 dollars. Whatever the details, a significant market for mineral products is indicated.

TABLE 13. - Projected 1975 total demand for materials used to attain successively higher levels of acoustic insulation (1968 prices)

(Thousand dollars)

	Single-family houses						Apartments, 700 ft² living area per unit		For 1,075,500-unit mix		
	1,250 ft² living area per unit			1,800 ft² living area per unit					With SII as shown	Without SII	Projected additional demand for materials
SII attained, PNdB..........	0	5	15	0	5	15	0	15			
Units constructed (1,000)...	135	35	5	72.5	185	100	344	181			
Wood products:											
Lumber, framing, sheathing, furring............	101,115	35,700	4,900	66,845	177,045	83,200	2,064	1,629	472,498	463,840	8,658
Plywood, textured.........	33,750	7,175	825	26,100	66,600	-	-	-	134,450	172,450	-38,000
Plywood, prefinished......	-	-	-	-	78,625	-	-	-	78,625	-	78,625
Hand-split shakes.........	-	-	-	-	-	51,000	-	-	51,000	-	51,000
Windows..................	32,805	11,935	3,415	33,568	120,620	130,300	17,200	13,032	362,875	234,298	128,577
Doors....................	31,185	8,820	2,365	18,850	52,540	50,000	10,320	6,335	180,415	149,125	31,290
Nonmineral-based materials:											
Felt paper, polyfilm, bitumen shingles.........	27,945	1,400	300	16,892	11,100	3,400	-	-	61,037	119,523	-58,486
Fiberboard................	20,250	770	755	11,962	30,525	28,000	-	-	92,262	85,238	7,024
Mineral-based materials:											
Nails and fasteners.......	14,985	3,885	555	10,005	27,380	14,500	2,064	1,086	74,460	71,910	2,550
Plasterboard..............	23,625	7,350	900	25,375	64,750	35,000	13,760	18,462	189,222	176,750	12,472
Plaster applied over plasterboard.............	-	-	1,050	-	-	23,500	-	-	24,550	-	24,550
Mineral wool, loose.......	6,075	-	-	10,585	27,010	-	-	-	43,670	60,070	-16,400
Fiberglass products.......	-	4,550	500	-	-	46,000	-	7,240	58,290	-	58,290
Asbestos-cement shingles..	-	15,400	6,975	-	61,050	-	-	-	83,425	-	83,425
Bricks and mortar.........	-	-	-	-	-	239,500	-	-	239,500	-	239,500
Concrete..................	-	-	-	-	-	-	16,512	11,584	28,096	25,200	2,896
Concrete reinforcing steel items...................	-	-	-	-	-	-	6,880	4,525	11,405	10,500	905
Total cost of all materials............	291,735	96,985	22,540	220,182	717,245	704,400	68,800	63,893	2,185,780	1,568,904	616,876
Total cost of mineral-based materials.......	44,685	31,185	9,980	45,965	180,190	358,500	39,216	42,897	752,618	344,430	408,188

Source: Tables 7, 10, and 12.

APPENDIX A.--SOUND POWER, PRESSURE, AND INTENSITY

Sound power is the acoustic energy emitted per unit of time by a sound source. For illustration only, the acoustic energy from a simple single source moves in outward directions roughly simulating a spherical surface if there are no intervening barriers. Sound intensity, or the measure of the sound power per unit of area of this surface, equals the total sound power divided by the total area of the roughly simulated spherical surface. Sound intensity is difficult to measure directly, but it can be measured indirectly by measuring sound pressure.

The almost universal practice used for expressing sound pressure or intensity reports pressures is dynes per square centimeter, or microbars. For this purpose a logarithmic scale is used which is based on tenfold steps or ratios, known as bels (B). Normally the ratio expressed in B values equals the ratio of logarithms to the base 10 of the radiated power (overall sound level) from two sound sources. For example, an intensity ratio of $\frac{10}{1} = 1$ (B) = 10 decibels (dB) and an intensity ratio of $\log \frac{1,000}{1} = 3$ (B) = 30 dB. By general agreement, the reference level of sound intensity or sound-pressure level, the decibel, equals 10^{-16} watt per square centimeter, or 0.0002 microbar (dynes per square centimeter). Although the decibel was first used to express the ratio between two amounts of radiated power, it is now used in the acoustic field to express the ratios of sound power, sound intensity, and sound pressure. A sound-power ratio of 2:1 is 3 dB. A sound-pressure ratio of 2:1 is a power ratio of 4:1 or 6 dB. The magnitude of a sound pressure (Ps) is compared to the magnitude of a reference pressure (Pr) according to the formula:

$$\text{Decibels (dB)} = 20 \log \frac{Ps}{Pr}.$$

The human ear responds to a wide range of sound intensities. The ratio of the power of the loudest sound that a normal person can hear without pain, to the power of the weakest sound he can detect, is about 1,000,000,000,000 to 1, or 10^{12}. The logarithm to the base 10 of this ratio equals 12 expressed in bels or 120 decibels (dB). The number of decibels is actually 10 times the logarithm of the sound-power ratio.

Because the ear is sensitive to a range of pressure levels greater than 10^{12}, the use of the logarithmic scale reduces unwieldy numbers to numbers of manageable size. For example, because a 6-dB difference represents a doubling of sound pressure, a 90-dB noise has a pressure level twice as large as that of an 84-dB noise.

APPENDIX B.--SOUND ABSORPTION AND TRANSMITTANCE AND PREDICTED REDUCTION OF NOISE BY BUILDING MATERIALS[1]

The reduction of noise by sound-absorption material can be predicted with acceptable accuracy by use of the relation:

$$NR = 10 \log_{10} \frac{A_2}{A_1},$$

where NR = noise reduction of sound-pressure level, decibels;

A_1 = sound absorption in sabins before treatment; and

A_2 = sound absorption in sabins after treatment.

One sabin equals 1 square foot of a perfect sound-absorbing surface; for example, 10 square feet of surface with a sound-absorption coefficient of 0.60 would provide 6 sabins.

Some sound-absorption coefficients at 1,000 cycles per second (cps) are--

Plaster...........	0.03
Wood floor........	.07
Door (closed).....	.09
Window (closed)...	.12

The amount of noise reduction can be calculated for a room or enclosure by use of the formula:

$$NR = \log \frac{A}{T} \text{ dB},$$

where NR = noise reduction in a room or enclosure, decibels;

A = absorption of the noise by the inside surface of the room or enclosure, sabins; and

T = total sound transmittance.

By definition, the fraction of incident sound energy transmitted through a wall or partition is called its transmission coefficient (γ). This term is not so well known as the usually used transmission loss figure (TL). The relationship of γ and TL is shown as

$$TL = 10 \log \frac{1}{\gamma} \text{ dB}.$$

The noise insulation factor equals $10 \log \frac{\text{absorption}}{\text{transmittance}}$.

[1] Source: Cormack, L. J. You Can Do Something About Noise. Power, v. 3, No. 5, May 1967, pp. 79-81.

The sound transmittance loss of some building materials is--

Transmittance loss, TL in dB	Transmittance coefficient, γ
Ceiling..........40	$1{,}000 \times 10^{-7}$
Walls............41	795×10^{-7}
Windows..........26	251×10^{-5}
Doors............20	100×10^{-4}

The relationship of the transmission loss (TL) of acoustical materials in decibels (dB) and the corresponding transmission coefficients (γ) is shown in the equation

$$TL = 10 \log \frac{1}{\gamma}.$$

Transmission loss, TL in dB	Transmission coefficient, γ
20................	$1{,}000 \times 10^{-5}$
22................	631×10^{-5}
24................	398×10^{-5}
26................	257×10^{-5}
28................	159×10^{-5}
30................	$1{,}000 \times 10^{-6}$
32................	631×10^{-6}
34................	398×10^{-6}
36................	257×10^{-6}
38................	159×10^{-6}
40................	$1{,}000 \times 10^{-7}$

Note: The tabulation repeats for each 10 decibels with a change of 10 to the first power.

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