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Adequate Audio Power in the Home

JAMES MOIR*

A discussion of the factors affecting the power required for satisfactory reproduction of typical program material and the methods of calculating it.

ESTIMATES OF THE AUDIO POWER required to produce adequate loudness from the domestic loudspeaker are characterised by a very wide divergence of opinion even among authorities, figures ranging from 100 milliwatts to 50,000 milliwatts (50 watts) having been quoted by different writers. It is interesting to examine the problem and to attempt to produce some reliable data. As a preliminary it is necessary to clear our ideas as to what is meant by the 'audio power' for it is evident that the same basic power may be expressed in several ways. Thus the same amplifier may be quoted as having an output of ten or twenty watts both figures being accurate statements of the performance.

Expressing the Power

In a mains frequency power circuit the supply voltage and current have the substantially sinusoidal waveform of Fig. 1 and without ambiguity the power dissipated as heat in a resistance load of R ohms will be given by $(0.707 V)^2/R$ where V is the peak value of the applied voltage. To eliminate the necessity of always multiplying the meter indication by 0.707, commercial meters used in the heavy engineering field are sealed to indicate, not the peak value, V , but the *rms* (root mean square) value $v = 0.707 V$. Within the usual engineering tolerances the value of voltage or current will be indicated quite accurately by ordinary commercial meters and the reading will be independent of the physical size of the meter.

The multiplying factor, 0.707 applies only to a sinusoidal waveform but in the communications field sine waves are generally confined to test equipment, speech and music signals having the much "spikier" waveform indicated by Fig. 2. There is no equivalent numerical factor relating peak and rms values that can be applied to such irregular waveforms and thus the output of an amplifier may be expressed either in terms of its peak power, V^2/R , or as rms power $(0.707 V)^2/R$ the latter figure being the power dissipated as heat in a resistor of R ohms by a sinusoidal voltage having the

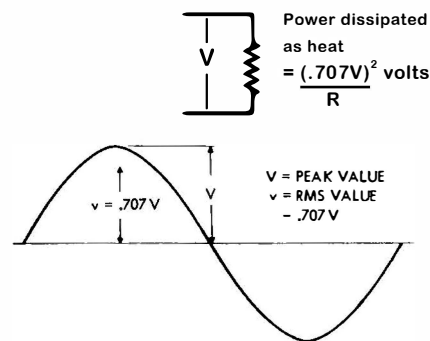


Fig. 1. Relation of peak and rms values of voltage for a sine wave.

same peak voltage as the speech wave. It should be appreciated that this is *not* the rms power in the speech wave but a figure which may be perhaps ten times higher.

On sinusoidal waveforms the rms power will only be *one half* (ie $(0.707)^2 = 0.5$) the peak power and thus the same amplifier may be rated in either peak power or rms power, the peak

power figure being twice the rms power figure. As there is a fixed ratio between the two ratings there appears to be no good reason for departing from the practice of quoting the rms power output the standard practice in other engineering fields.

Measuring the Power

There need be no ambiguity in measuring the power output of an audio amplifier for sinusoidal test signals can be employed and special meters are not required, though it should be noted that the power specification is meaningless unless the distortion level is also quoted.

However our present interest is not in what power an amplifier *can* deliver but in what power it *does* deliver when used in the home. This is a much more troublesome problem, for speech and music waveforms are irregular, and have a high ratio of peak to rms power due to the intervals between words or phrases when no signal is present. Heating (a function of the rms voltage 0.707

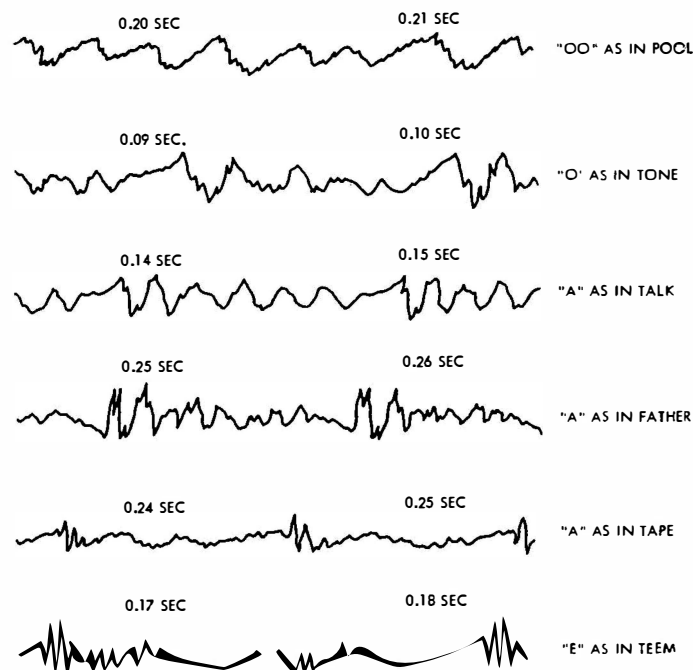


Fig. 2. Waveforms of typical vowel sounds. (From Fletcher, "Speech and Hearing.")

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TABLE I

	Preferred Maximum Sound Level db above 10^{-16} watts/cm ²					
	Public Musicians			Programme Engineers		Engineers
	Men	Women		Men	Women	
Symphonic Music ..	78	78	88	90	87	88
Light Music	75	74	79	89	84	84
Dance Music	75	73	79	89	83	84
Speech	71	71	74	84	77	80

V) is of little consequence in either amplifiers or loudspeakers and in consequence it is more reasonable to measure the peak values of signal voltage and express the speech power in terms of its peak value, V^2/R .

The measurement of the peak voltage of such irregular waveforms is by no means easy. Pointer-type meters of any kind have movements of sufficient inertia to prevent them reading peak values and the indications may easily be in error by a factor of ten times. Large well damped meters of high nominal accuracy invariably have heavy moving systems and are particularly inaccurate when used to "measure" audio voltages. Measurements using pointer-type instruments of the programme voltage across, into a loudspeaker are therefore completely valueless. Three types of instrument are in current use for measuring sound power, the sound-level meter, the high-speed level recorder and the cathode-ray oscillograph.

The sound-level meter has the disadvantage of a pointer-type meter but as the mechanical constants of the meter are closely specified the error due to instrument inertia may be roughly estimated. A typical meter may give readings that are below true peak by 20 db, the error being small when the signal is steady and rising to 20 db on speech signals where the gaps between words and sentences may be comparatively long.

The high-speed level recorder employs a tube-operated servo system to drive the pointer and will generally indicate values that are 5-10 db below true peak readings.

The cathode-ray oscilloscope has no significant error due to inertia and can indicate true peak values on the most complex waveform, but care must be taken to operate with sufficient brightness to show up the faint high-speed traces characteristic of peaks of short duration.

Failure to indicate whether peak or rms power is being quoted and the use of unsuitable power measuring equipment undoubtedly accounts for differences of from 10 to 100 times in the amount of power thought to be necessary for domestic reproduction. This is a large error but even greater discrepancies can occur if the maximum loudness is not carefully specified.

What Constitutes Adequate Loudness

Difference of opinion as to what constitutes "adequate loudness" is responsible for considerable discrepancies between writers' estimates and the importance of clearing the air will be fairly obvious when it is realised that a difference of 10 db in specifying the maximum loudness level thought to be desirable will result in a change in the required amplifier output power of ten times. Published figures seem to indicate that the differences of opinion embrace a power range of something nearer 40 db (a power difference of 10,000 to 1) so it is absolutely necessary to have our thoughts clear on this point.

At first sight it appears reasonable to approach the problem by reviewing the volume ranges encountered in original speech and music on the assumption that "a perfect reproduction" will require the same volume range. The most difficult case, an original performance by a large symphony orchestra may involve a power ratio of 80 db (100 million to 1) but this range is generally only encountered for a few tenths of a second in several hours, a more frequently occurring range being nearer 74 db.

At the receiving end it is reasonable to assume that the listener should adjust his volume control to bring the *minimum* signal to somewhere near the room noise level and as an average value for the domestic noise level is about 40 phon it implies that peak levels in the region of 114 db (or phon) are required. Though this appears to be a very reasonable deduction, experience suggests that it is wise to make a check and this has been done both in England and in America. The B.B.C. have made a very careful study of the sound levels preferred by their monitoring staff and by the general public and Table I lists some of their data taken from a paper by Somerville and Ward.

In these tests the listeners were provided with a high-quality reproducer system of ample power handling capacity and were asked to set the loudness to the level they considered preferable. The acoustic level at a point about 18 inches from the listener's head was then checked with a standard type of sound-level meter. It is surprising to note that none of the listeners wished to have sound levels greater than 90 phon a re-

sult supported by similar tests in America which indicated a preference for levels about 8-9 phon lower than the B.B.C. results suggest.

Sound levels approaching 114 phon occur in concert halls and there is not the least evidence that these are anything but satisfying, but the available evidence does suggest that these levels are not optimum in the home. The reason for this difference is not clear, but in the writer's experience a level of 110 phon sounds "louder," though "smaller" and more oppressive in a small room than the same level in a concert hall.

A major discrepancy between the various estimations of "power required" may thus be attributed to the choice of maximum loudness thought desirable. An estimate based on the very reasonable assumption that concert-hall loudness levels are necessary in the home will suggest a power some at least 20 db (100 times) higher than another estimate based on achieving only the maximum preferred loudness level of 90 phon. As it will be seen from Table I that the general public only require a maximum loudness level of about 80 phon, a "logical" engineering estimate of the power necessary will be about 30 db (1000 times) higher than is really required.

This preference for lower levels in the home is providential because some consideration for the neighbours is necessary. In flats, terraced houses or houses built in pairs, a house-to-house insulation of 55-60 db can be achieved fairly easily by simple building techniques but science and the average builder are not yet in close touch, with the result that 45-50 db is the figure more usually achieved in semi-detached pairs of houses having a 9-in. party wall. Peak sound levels in the region of 110 phon will result in the neighbours enjoying *your* choice of programme at a level of 70-80 phon and while this may be just tolerable in the early evening when their own noise level is in the same region as your own it must become a little annoying to them when later in the evening their own noise level has dropped to something nearer 30 phon.

Acoustic Power Requirements

The next steps in the enquiry are to make an estimate of the actual acoustic

TABLE II

Maximum Loudness Levels produced by typical sound sources in domestic surroundings.

Small Upright Piano	
Maximum in normal playing	— 72 db
Player asked to play a "loud" selection	— 82 db
Player asked to play "as loudly as possible"	— 90 db
Speech	
Boy normal speech	— 60 db
Man " " "	— 65 db

TABLE III

Acoustic Power required to produce given loudness levels in a room of 1540 ft³ and reverberation time of 0.5 sec. Computed from Eq. (7) of Appendix.

80 db	.00036 watt	(.36 milliwatts)
90 db	.0036 "	(3.6 milliwatts)
100 db	.036 "	
110 db	.36 "	
120 db	3.6 "	

power required to produce the loudness levels thought necessary, and then to examine the electro-acoustic conversion efficiency of loudspeakers for this will enable the electrical power requirements to be predicted.

The actual acoustic power required to produce acceptable loudness levels is very small indeed. A first approximation to the figure can be obtained by considering the data on the acoustic power required for normal conversation. The most reliable data, that of Sivian, Dunn, and White indicates that the instantaneous maximum power rises to about 700 microwatts (0.7 milliwatt) when making an impassioned speech to a large audience. About 5 per cent of speakers will produce powers five times higher than the figure quoted, making their acoustic output 3-5 milliwatts. Declamatory speech of this kind would be intolerably loud in domestic surroundings, rather suggesting that the maximum acoustic power required for any purpose is not likely to rise much above 5 milliwatts. Data is available on the acoustic output of most of the common instruments but it is not particularly useful as an indication of domestic requirements as all the figures refer to tests in which the instrument was played as loudly as possible. A concert grand, played loudly, has a power output of about 350 milliwatts but experience suggests that even a small upright piano can be intolerably loud in a small room. In my own room a small upright piano played by a moderately competent player produced the loudness levels shown in Table II and it is perhaps significant that normal playing gave maximum levels of 72 phon with a level of 90 phon reached when the player was asked to produce the absolute maximum output. It should be noted that readings were taken when the sound level was reasonably steady and the absolute peak levels are therefore likely to exceed the meter readings by only 4-8 phon.

Calculation of Sound Power Requirements

In the appendix it is shown that the acoustic power required to produce a sound level of 100 db can be computed from

$$P = .0000116 V/T \text{ watts}$$

where V is the room volume and T is the reverberation time. Applied to one of my own rooms having a volume of 1540 cu. ft. and a reverberation time of

0.5 second it suggests that the power shown in Table III will be required for levels of 80-120 db, the power required for 100 db being computed from the equation directly, and being modified by a factor of ten for each 10 db change in level. The suggested maximum requirement of 90 db is reached with an acoustic power of only 3.6 milliwatts, a figure that is in substantial agreement with the power deduced from that produced by a human speaker at maximum output.

Objection has been raised to any formula that suggests that the power required is inversely proportional to the reverberation time, on the score that the bursts of energy in speech are so short that room reflections do not have time to reinforce the direct sound from the speaker. It has therefore been suggested that the power required should be computed on the assumption that the loudness is entirely due to the direct sound. The calculation is not difficult but it does require a knowledge of the polar diagram of the loudspeaker over the frequency range.

A sound wave leaving the speaker will diverge in the form of a solid cone with

TABLE IV

Electrical Power required to produce a loudness level of 80 db from three typical speakers.

A—17-in., 17,000 gauss magnet.

B—12-in., high-fidelity type, 14,000 gauss.

C—8-in., radio receiver type, 8,000 gauss.

Speaker	Sound Level db	Voice Coil Power mw	Electro-acoustic Efficiency, percent
A	80	9.5	3.8
B	80	55	.66
C	80	240	.15

the speaker at the apex but the angle of divergence will be a function of frequency, being greatest at low frequencies (180 deg. if the speaker is in the centre of one wall) and decreasing as the frequency increases until it is down to something near 25 deg. at 5000 cps. There is therefore some difficulty in fixing an effective average angle for the whole of the audio frequency range. Power, loudness and intelligibility are not linearly proportional to bandwidth, a fact that increases the difficulty in fixing an average angle for the whole frequency range. In spite of these difficulties it has been claimed that power requirements computed on the assumption that there is no gain in loudness from the reverberant sound, do give good agreement with measurement.

The earlier discussion suggests that the maximum acoustic power required in domestic surroundings is only in the region of 3-5 milliwatts but in the absence of data on the electro-acoustic efficiency of typical loudspeakers it is

difficult to translate the acoustic power requirements into electrical power to be provided by the amplifier.

Electro-acoustic Efficiency of Loudspeakers

There is very little published data on the conversion efficiency of loudspeakers, partly because of the difficulty of measurement but also because any single figure can be misleading and liable to misinterpretation. In these measurements to be described, the figure quoted as the efficiency was determined by measuring the electrical power input to a loudspeaker operating on ordinary programme in the normal living room and simultaneously measuring the loudness level in the room. Care was taken to observe steady values and from this data the acoustic power output was calculated. The efficiency is the ratio

$$\frac{\text{Acoustic power} \times 100.}{\text{Electrical power}}$$

With domestic approval a sound-level meter, oscilloscope and oscillator were set up in the dining room as shown in Fig. 3 and several listening and watching sessions enjoyed. As a first check some co-operative members of the family were asked to adjust the loudness to their liking and as it was found that the levels chosen were in good agreement with those obtained by the B.B.C. (Table I) it was assumed that nothing was seriously amiss. The procedure then employed for the power measurement tests was to set up the CRO and sound-level meter in close proximity to enable both meter and CRO to be viewed simultaneously and to mark the tube face each time the meter peaked to 80 db. After a few attempts it was possible to draw two parallel lines on the tube face defining the maximum deflections produced when the sound-level meter reached this figure. A Promenade Concert provided valuable test material, as it was possible to watch the meter on one phrase and check the CRO deflection when the phrase was repeated a second or so later. Music also has the advantage that complex tones are held for sufficient time to provide a steady deflection on the meter, thus eliminating any argument about the contribution of the

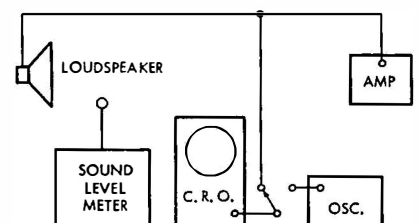


Fig. 3. Schematic arrangement used for audio power measurements.

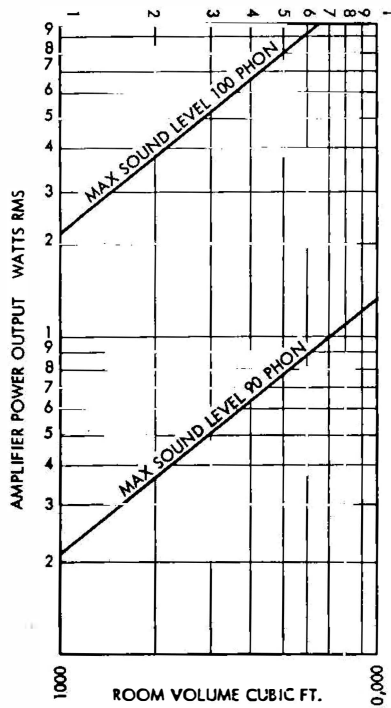


Fig. 4. Curves of power required for two sound levels in relation to room volume.

reverberant sound to the total loudness. Audience applause is equally effective for this purpose. The room was in semi-darkness and a bright trace employed to avoid missing sharp peaks of short duration.

Having defined the CRO deflection characteristic of a sound level of 80 db, the CRO was then switched to the calibrated oscillator and the rms voltage corresponding to the deflection noted. Three hours checking with three different loudspeakers provided some interesting data which is reproduced in Table IV.

As the input power to each of the speakers was adjusted to produce an acoustic level of 80 db in the room, it is assumed that the acoustic power produced is the same for all, a reasonable but not a precision conclusion, in view of the different frequency characteristics inherent in speaker units of such widely varying quality. Column 3 indicates the power in the voice coil computed on the assumption that the effective resistance of the voice coil is equal to its d.c. resistance. Column 4 contains figures for the electro-acoustic efficiency computed from the measured electrical input to the speaker on the assumption that the acoustic power output is given by Eq. (7) in the Appendix, corrected to a sound level of 80 phon.

Speaker A is a large 18-in. cone speaker having a 2½-in. voice coil working in a gap having a flux density of 17,000 gauss. Speaker B is a standard type of unit typical of the better quality 12-in. high-fidelity units, while speaker C is typical of the cheaper 8-in. units included in radio receivers.

Speaker B, typical of the units being

used by most high fidelity enthusiasts only requires an input of about 55 milliwatts to produce a sound level of 80 db and a power of 0.55 watt to produce 90 db. If concert-hall levels of 110 db were required in domestic enclosures a power of 55 watts would be necessary but this speaker would have to call for help from at least four of its fellows if this power was to be handled.

Though a horn loaded unit was not tested it is known that electro-acoustic efficiencies of 20-40 per cent can be reached, enabling the concert hall level to be obtained for an input of about 1½ watts. As evidence of this, some recent measurements in a 700-seat theatre having a volume of 120,000 cu. ft. showed that the feature film was being regularly run with a maximum electrical input to the loudspeakers of less than one watt.

The 18-in. speaker is shown to have an efficiency twenty times that of the cheap radio speaker but this is insufficient to justify its use where cost is of importance, for acoustic power can generally be produced more cheaply by the combination of a small speaker and a large pentode, than by an expensive speaker and a small triode.

It is convenient to have available for ready reference curves relating to room volume, sound level, and electrical power required. Figure 4 provides this information based on the assumptions that

1. The acoustic power is computed from Eq. (7).
2. A loudspeaker efficiency of 1 per cent is obtained.
3. The optimum reverberation time relation of Fig. 5 is approximated in all cases.

In the majority of rooms above 2000 cubic feet the reverberation times of Fig. 5 are approximated, but in smaller houses current constructional methods appear to give a reverberation time of about half a second almost regardless of the furnishing scheme.

After reviewing the results obtained it appears that there is great opportunity for difference of opinion in estimating the power required to produce adequate loudness in small rooms. An experimenter measuring the power that gives him adequate loudness will find it to be in the region of 50 milliwatts if he uses a CRO, perhaps 5 milliwatts if he uses a high-quality rectifier voltmeter, and something less than 1 milliwatt if he has an rms-reading thermal meter. A devotee of Aristotle preferring meditation rather than experiment might be excused if he based his calculations on the assumption that the loudness level found desirable in concert halls would prove to be equally desirable in the home. He would then produce a figure approaching 40-50 watts, but if this was thought to be insufficiently impressive, he could with all honesty quote the same power as 80-100 watts peak, i.e. peak volts times peak current. A difference in estimate as great as 100 watts to .001 watt must be a record for an honest difference of opinion in the engineering field.

Though the reason is probably psychological the preference for reduced maximum loudness levels in the home is not understood and should form an interesting subject for further study.

APPENDIX

If it is assumed that "loudness" is related to the steady-state sound intensity the power required to produce any specified intensity can be computed from the standard exponential relation between sound-energy density and the time interval during which power is being supplied to the enclosure. The sound-energy density in ergs/cc at any time t secs. after the power is turned on, is given by

$$E = \frac{4P}{CS_a} (1 - C^{-CS_a t / 4V}) \quad (1)$$

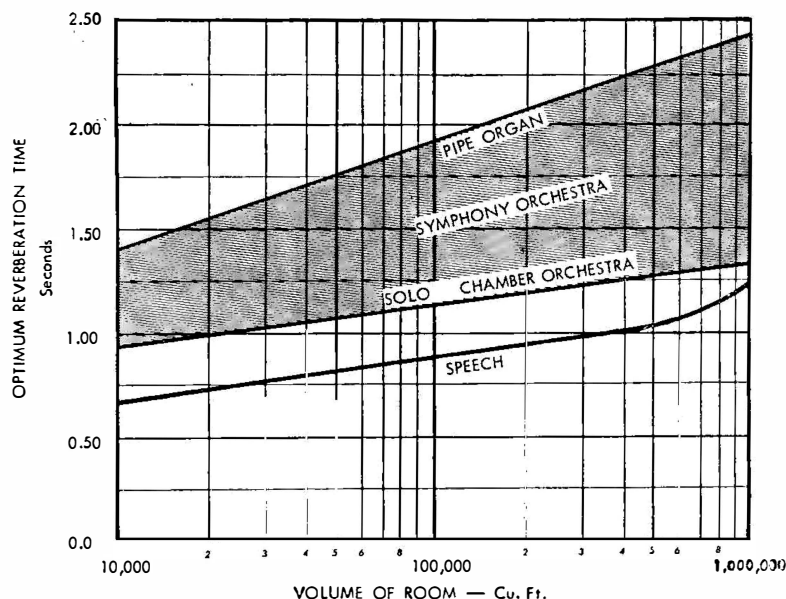


Fig. 5. Curve showing optimum reverberation time in relation to room volume.

where

P = rate of emission of the source,
ergs/sec.
 C = velocity of sound, cm/sec.
 S = total surface area of absorbing
surfaces, sq. cms.
 α = average coefficient of absorption
of all surfaces.
 V = total volume of room, cu. cms.

When steady state conditions are reached, theoretically after infinite time, but practically after T secs. where T is the reverberation time of the enclosure, the bracketed term is equal to unity and the sound energy density is given by

$$E = \frac{4P}{CS\alpha} \quad (2)$$

It is more convenient to have a relation involving the reverberation time T and the volume of the enclosure V rather than S and α and this can be obtained from the normal Sabine relation for reverberation time $T = kV/S\alpha$, from which $S\alpha = kV/T$. Substituting kV/T for $S\alpha$ in Eq. (2) gives

$$E = \frac{4PT}{CkV} \quad (3)$$

from which the source power in Ergs/sec. is given by

$$P = \frac{CkVE}{4T} \quad (4)$$

If some standard intensity is adopted, the arithmetic is simplified and as 100 db is a convenient figure this will be inserted. It corresponds to a sound intensity of 10^{-6} watts/sq. cm. and a sound energy density of 3×10^{-4} ergs/cu. cm. Substituting this value in Eq. (4) and including all constants, the acoustic power in watts required from the source to produce a maximum intensity of 100 db is given by

$$P = \frac{3.4 \times 10^4 \times 16 \times 10^{-4} \times 3 \times 10^{-4}}{4 \times 10^7} \times \frac{V}{T} \quad (6)$$

$$= 4.1 \times 10^{-10} V/T$$

or converting to ft. units

$$P = 1.16 \times 10^{-5} V/T = .0000116 \frac{V}{T} \text{ watts} \quad (7)$$

For any loudness level other than 100 db the power required will be doubled for each 3 db increase in intensity that is considered necessary. The threshold of pain is reached at an intensity level of about 120 db requiring a power 100 times that given by the equation and presumably fixing the absolute maximum value of power that anybody might ever consider necessary.

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