Choice of frequency weighting for the evaluation of weapon noise

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This paper describes a laboratory study to choose an appropriate frequency weighting network for predicting the annoyance caused by the noise from small, medium, and large weapons. The results indicate that the annoyance of all three weapon types is the same if the blasts are heard at identical A-weighted SEL's. On the other hand, equal C-weighted SEL's result in large differences in annoyance between the weapon types. The implications of these results for outdoor noise criteria depend on the assumption concerning window condition. If one assumes that people hear the blasts predominantly through open windows, then A-weighted criteria should be appropriate for all the weapon types without any correction (penalty or bonus) for weapon type. On the other hand, if the blasts are heard predominantly through closed windows a penalty of about 5 dB should be applied to the outdoor levels of the large weapons to account for the poorer low-frequency attenuation of the windows.

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INTRODUCTION

Establishing community criteria for weapon noise is obviously a difficult task as the annoyance is influenced by a host of psychoacoustical and sociological factors. Community reaction is commonly assessed in social surveys carried out in the vicinity of military training grounds.[1–3] Nevertheless, the psychoacoustical aspects may also be studied through laboratory experiments, provided that the reproduction system is made sufficiently realistic. Laboratory experiments have the obvious advantage of expediency. They also offer more controlled test conditions which may reduce unwanted effects present in social surveys (e.g., bias of the persons interviewed concerning the training grounds). This paper concentrates on laboratory experiments designed to answer one particular question: Which frequency weighting network (notably A or C) is more suited for describing the annoyance from small, medium, and large weapons? Formulated differently, can a single weighting network be employed to describe the annoyance of all three weapon sizes? Initial results were presented in Refs. 4 and 5.

The question of frequency weighting has received considerable attention in the literature. Most studies, however, have concentrated on the annoyance of specific weapon types or sizes rather than comparing one type directly with another. A short summary of past findings is given below. The discussion is limited mainly to the annoyance of impulsive noise and leaves the comparison of impulsive to transportation noise (although obviously important in establishing noise limits) open.

The use of A weighting has been employed in a number of countries for the evaluation of gunfire sounds from small arms,[1,6,7] whereby a correction for the added annoyance of impulse sounds is normally included. On the other hand, a number of investigators have recommended the use of C weighting for measuring and evaluating the noise from large weapons such as detonations or the firing of cannons.

In an early paper, Schomer cites social surveys on sonic boom (Edwards Air Force Base and Oklahoma City) where it was found that annoyance was related to sound-induced vibrations and rattling in buildings.[8] Since C weighting does not significantly attenuate the low frequencies, it provides a good correlation with rattling, hence annoyance. In addition (see, for example, Ref. 3), the C-weighted L_{eq} or CDNL of sonic booms and artillery noise is found to be approximately equivalent in annoyance to the identical A-weighted L_{eq} of transportation noise. In a later article Schomer also points out the practical advantages of performing blast measurements with C weighting since at long distances (for example 5 miles) the spectrum of blast noise is dominated by frequencies below 200 Hz.[9]

In a later article Schomer and Averbuch again emphasize the importance of rattling in relation to annoyance.[10] The study was performed in a special test house furnished with various objects which could rattle. The blast sounds were produced by a very large shake table. The authors found that the influence of rattles is greatest for quiet blasts but as the blasts get louder the rattle adjustment decreases.

Bullen *et al.* present the results of social surveys performed in the vicinity of an artillery range (105- and 140-mm guns).[2] They report that the best estimator of reaction is the accumulated peak level (unweighted) but the differences in correlation to annoyance between this measure and $L_{eq(A)}$ or $L_{eq(C)}$ are not significant at the 0.05 level. One of their analyses suggests that the strength of overall noise reaction depends on the audible component of the noise, rather than the low-frequency component which causes house vibration or rattling of windows. In the same article the authors compare these results with those of a previous study in the vicinity of the Hornsby rifle range. Thus the authors strive to relate the annoyance caused by sounds produced by small versus large firearms. They find that the accumulated peak level yields the best agreement (the smallest difference) between the two studies. Concerning the A and C weighting their data implies that the optimal frequency weighting is intermediate between the A and C weightings (but much closer to C).

Buchta *et al.* describe the results of social surveys in the vicinity of five military training areas.[11] The main source of noise was cannon fire. The authors find that the perception of vibration and startle reactions have a large influence on annoyance. For cannon fire, C weighting correlates only slightly better with annoyance than A weighting but offers a technical measurement advantage at large distances. On the other hand, comparing the results with an earlier study of rifle and pistol ranges they conclude that the annoyance of rifle and pistol fire is approximately the same as that of cannon fire when the A-weighted level of the rifle/pistol equals the C-weighted level of the cannon fire. This statement holds for the level "substantially" annoyed. At higher levels of annoyance the curves are displaced by about 5 dB, i.e., the annoyance of rifles is 5 dB greater than that of the cannons when the A-weighted level of the rifle/pistol equals the C-weighted level of the cannon fire.

Although the authors of Refs. 2 and 11 attempt to relate the annoyance of artillery and rifle (or pistol) sounds their comparisons are based upon *separate* field studies of the two weapon types. Their conclusions must be regarded with caution since systematic differences between studies (differences in population, shooting schedules, etc.) are unavoidable.

Thus, the goal of the present study was to provide a direct comparison of the annoyance of different weapon types under controlled laboratory conditions. The experimental conditions of this study did not allow an investigation of rattling. The work of Schomer and Buchta indicates that rattling contributes significantly to annoyance. However the degree of rattling that actually occurs in houses exposed to blasts depends on many factors such as the blast strength and frequency spectrum as well as the house and window construction. Thus with respect to general weapon noise criteria the role of rattling is not yet clear. It is unlikely, for example, that medium-sized weapons or large weapons firing smaller charges induce rattling. Furthermore the degree of rattling undoubtedly depends on distance from the weapon. To summarize, when rattling actually occurs, it is evidently an important factor, but considering the various weapon-distance-construction combinations rattling is probably limited to a minority of situations.

I. METHOD

A. Laboratory installation

The investigations were performed in a simulated living room environment. With the help of appropriate room furnishings and the installation of two free-standing gypsum walls, a suitable reverberation time (0.5 to 0.7 s between 125 and 4000 Hz and rising to approx. 1 s at 31 Hz) was obtained. A mock window, illuminated from the rear with an outdoor scene, contributed to the simulation.

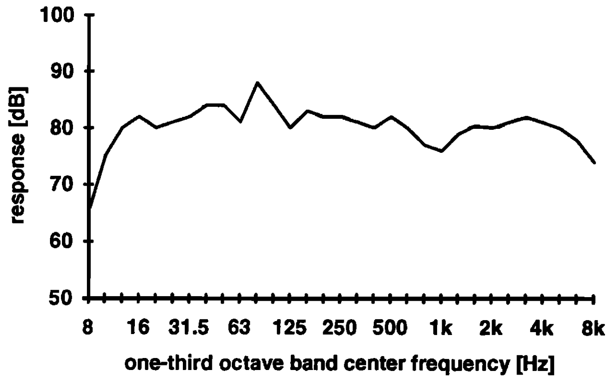

FIG. 1. Frequency response over the entire system, measured near the subjects' ears.

The main problem lay in developing a loudspeaker system capable of reproducing the high levels and very low frequencies present in the noise from large weapons. Four 18-in.-diam woofers (EV, Type EVX-180) with a free-air resonance frequency of 20 Hz were employed. A key feature of the system was the method of mounting these woofers. As is well known, with a closed-box system a good low frequency response requires a large enclosure. Indeed in order to maintain the very low resonance frequency of these 18.-in. woofers, the enclosure would have filled up a large portion of the test room. The solution was to mount the loudspeakers, unbaffled, in a wall of the test room (hidden behind a curtain). In this way the entire adjoining room could serve as the enclosure. A further advantage of mounting the loudspeakers in a wall was the added realism: The sound appeared to come from outdoors. The system was completed with a 12-in. midrange speaker (EV type EVM-12) and a horn (EV type HR-90, driver type DH 1012-A). The woofers were driven by a power amplifier having a maximum power rating of 2500 W. With the help of equalization the frequency response of the system was optimized. Figure 1 shows the frequency response finally achieved.

The weapon noises stemmed from field measurements in the vicinity of military training areas. The signals were stored digitally using an audio workstation with 18-bit AD and DA converters. The workstation was also programmed to control the presentation and random ordering of the signals and to store the subjects' responses, i.e., their potentiometer settings (see Sec. I D). A muting signal with a frequency of 19 kHz was mixed with each test signal. This controlled relays located at the output of the power amplifiers. Thus the loudspeakers were activated only for the duration of the test signal.

Thanks to the outstanding bass response and high level capability, the reproduction of weapon noise, including cannon blasts was quite realistic. These sounds were not only heard but "felt" in the whole body.

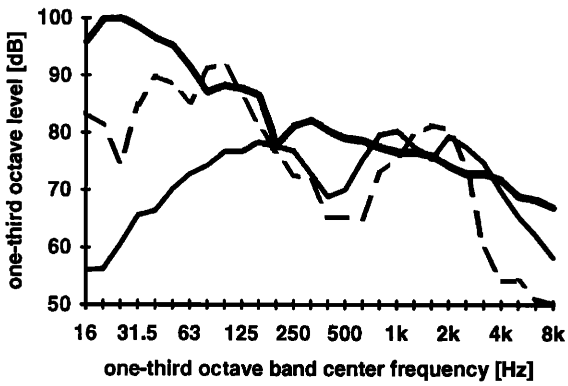

FIG. 2. Spectra for the cannon blast (solid thick line), the antitank missile (dashed line) and the rifle (solid thin line).

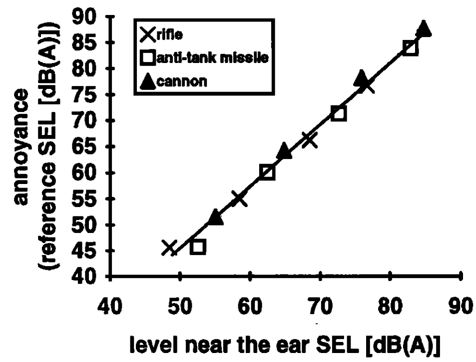

FIG. 4. Annoyance of the stimuli as a function of the indoor A-weighted SEL for the situation windows open. The regression line (mean responses) is presented; the R-square value over these points approaches 1 (0.99).

B. Acoustical stimuli

The *test stimuli* included the sounds of cannon blasts (Howitzer M109), antitank missiles and rifles, thus covering the range from large to small weapons. The frequency spectra of the original field recordings are given in Fig. 2. These recordings were made at distances of 50 m (rifle), 200 m (antitank missile) and 400 m (cannon) from the weapons. The dips at 250 and 500 Hz seen in the frequency spectra are due to the ground impedance and are typical for source and/or receiver locations close to the ground.

The stimuli presented corresponded to four distances from the weapon. These distances were simulated by broadband attenuation (geometric spreading) and additional high frequency attenuation (atmospheric and ground-effects losses). In the tests the acoustical conditions for an opened and also for a closed window were simulated. This required an appropriate modification of the original signals. The respective transfer functions employed for the two conditions are given in Fig. 3. For the case "windows closed" the curve is the decibel sum of the sound isolation of a double glazed window (typical for Swiss windows) plus the transfer function from outdoors to within the room.

The *reference sound* for the comparison consisted of synthetically generated noise (pink noise with a low-pass filter set at 800 Hz) lasting 2 s. The rise time was 600 ms, the decay time 1000 ms. To add realism as well as to mask any remaining clicks or hum in the system a low-level ambient noise (distant road traffic noise) was introduced for the duration of the experiments. A level of 37 dB(A) (measured in the test room) was chosen for the condition "windows open," resp. 27 dB(A) for the condition "windows closed."

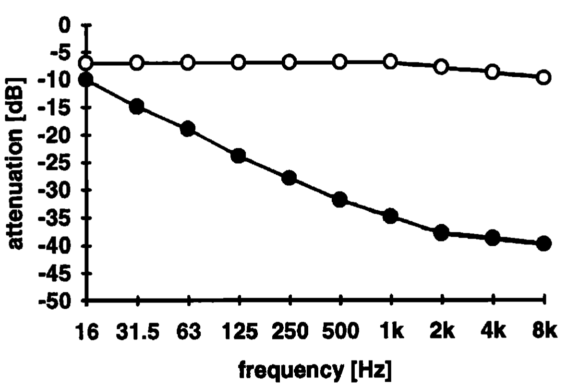

FIG. 3. Transfer function for the condition "windows open" (empty circles) and "windows closed" (filled circles).

C. Subjects

A total of 51 persons took part in the experiments, 40 males and 11 females. They ranged in age from 20 to 61 with a mean age of 40 years. The subjects had no prior experience with this kind of experiment.

D. Scaling method

For the main body of the experiment the method of adjustment was employed. The subjects had the task of adjusting the level of the reference noise until it was considered to be equally annoying as the test noise. They were permitted, by pressing the appropriate button, to alternate between the test and reference noise at will. The adjustment of the reference noise was accomplished with a potentiometer. In order to avoid a visual clue, the zero setting was altered randomly for each comparison. In addition the magnitude estimation method was employed, involving an eleven-point noise thermometer. On this scale, "0" represented no annoyance and "10," strong annoyance. As the two methods yielded practically the same results this paper will deal exclusively with the method of adjustment. A comparison of the results of the two methods may be found in Ref. 4.

E. Experimental design and procedure

Four different levels corresponding to different distances for each of the three test signals (cannon, antitank missile and rifle) were presented for the condition "windows open" and two levels for the condition "windows closed." For the cannon these distances varied from 800 m up to 5000 m, for the antitank missile 400 to 3000 m, and for the rifle 200 to 1400 m.

The subjects were given a brief hearing test at frequencies 125 to 8000 Hz prior to the experiments to screen out persons with hearing losses greater than 20 dB. They were asked to imagine themselves being at home in their living room. Appropriate to the living room setting the subjects were asked to rate the degree of annoyance, instead of

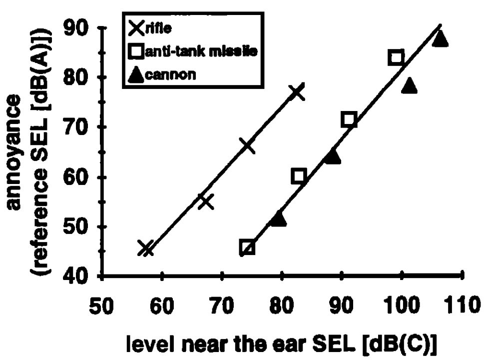

FIG. 5. Annoyance of the stimuli as a function of the indoor C-weighted SEL for the situation windows open. The regression lines (mean responses) are presented; the R-square values over the rifle points, resp. the medium and heavy weapons are 0.98 and 0.96.

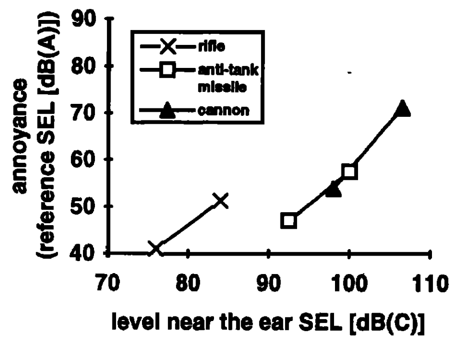

FIG. 7. Annoyance of the stimuli as a function of the indoor C-weighted SEL for the situation windows closed. The lines simply connect related points.

merely loudness. In order to create a situation in which the noise could interfere with an activity the subjects were asked to "try to relax between the sequences during the experiment, thumb through the magazines on the table." The experiment lasted 50 to 80 min. All stimuli were presented in random order. The pace of the experiment was determined by the test subjects themselves.

II. RESULTS

A. Condition "windows open"

The annoyance of the various sounds for the condition "windows open" is shown in Fig. 4 as a function of the A-weighted SEL. In this and the following figures only the A- or C-weighted SEL values are employed. The corresponding maximum values (FAST) may be obtained from the SEL values simply by adding 7 dB. It is emphasized that all levels presented in the graphs were measured near the subject's ears, i.e., in the test room. The annoyance values in the figures (y axis) are all mean values of the responses of the 51 subjects.

The points of Fig. 4 indicate that the annoyance for all three stimuli lies almost on the same line, i.e., different stimuli presented with the same A-weighted SEL evidently produce the same annoyance regardless of whether they stem, for example, from a cannon or a rifle. The line shown represents the regression with respect to the above-mentioned mean values.

Figure 5 employs the same data as Fig. 4, this time however plotted in terms of the respective C-weighted SEL values. Here the data are clearly divided into two separate categories: (a) the cannon and antitank missile and (b) the rifle. This implies that identical C-weighted levels at the ears for large and small weapons result in different degrees of annoyance.

The responses of the test subjects were to a first approximation normally distributed with a standard deviation in the order of 7 dB. Considering that each point on the graphs represents a mean value from the responses of 51 subjects, the standard error of the mean typically amounts to about 1 dB ($7/\sqrt{51}$). This indicates that the separation of the two categories for C weighting in Fig. 5 is statistically significant. The R-square values for the two lines approach 1 and are given in the figure. If the mean values for all the weapon types were used to form a single regression line, the R-square value of this line would fall to 0.74. This value is clearly much lower than the corresponding value for A weighting (see Fig. 4).

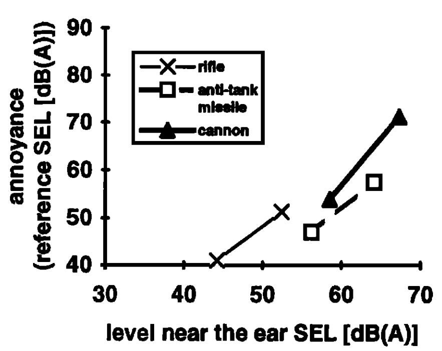

FIG. 6. Annoyance of the stimuli as a function of the indoor A-weighted SEL for the situation windows closed. The lines simply connect related points.

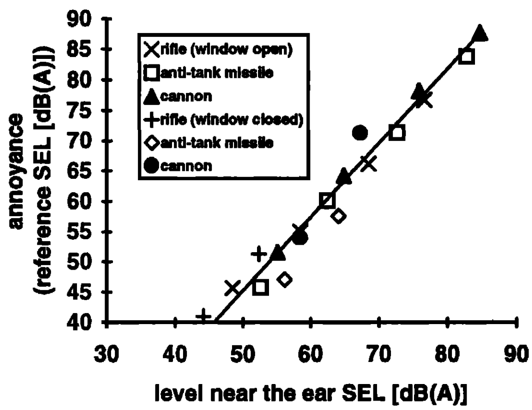

FIG. 8. Annoyance of the stimuli as a function of the indoor A-weighted SEL for the situation windows open and windows closed. The regression line (mean responses) is presented; the R-square value over all points approaches 1 (0.96).

B. Condition "windows closed"

As mentioned above, experiments were also performed with noise levels as would be expected in the test room with closed windows. The original stimuli were therefore provided with a typical window insertion loss (Sec. I B). For each of the three weapon sounds, only the two respective highest levels were used here since with windows closed the two lower levels ere hardly audible (e.g., ≤34 dB(A), resp. 50 dB(C) for the rifle and ≤48 dB(A) resp. 72 dB(C) for the cannon, measured indoors).

The ensuing annoyance curves are shown in Figs. 6 and 7 as a function of A- and C-weighted SEL, respectively. As before, the abscissa gives the measured indoor levels near the subjects' ears. With A weighting (Fig. 6) it is seen that the data for the different noise types again fall more or less onto one line or its extension. With C weighting the data are again separated into two lines.

C. Overall results

Finally the entire body of data—with windows open and windows closed—is plotted together as a function of the A-weighted SEL (Fig. 8). Despite the variety of levels and spectra of the test sounds all the data once again bunch quite closely around a single line.

III. DISCUSSION

The results indicated that the annoyance due to all of the impulse sounds correlates well with the A-weighted level, *as measured indoors* (in the test room, near the subjects' ears). Indeed, this holds true regardless of whether the stimuli pass through an open or a closed window.

A. Consequences for outdoor criteria

Until now the data have been presented as a function of the indoor levels, i.e., the levels measured near the ears of the test subjects. However, noise criteria normally specify a measurement point *outdoors*. With the help of transfer functions such as in Fig. 3 the indoor levels may be converted to corresponding outdoor levels. With windows open, the transfer function is essentially frequency independent and involves merely a shifting of the abscissa in Figs. 4 and 5. Thus, if the noise levels are measured outdoors and the windows are open, the A-weighted levels of all the weapons still correlate just as well with annoyance. Stated more generally, assuming that the blasts are heard through open windows the use of A-weighted noise criteria with the measurement point outdoor would preclude the necessity of introducing a correction (penalty or bonus) for small, medium or large weapons.

On the other hand, the transfer function for closed windows is frequency dependent. As a result, for identical *outdoor* A-weighted levels of the cannon blast and the rifle shot, the A-weighted level of the cannon (as heard through the closed windows) will be higher than that of the rifle. The magnitude of this difference is a function of the spectrum of the blast and the transfer function of the window. It amounts to about 5 dB for double-glazed window constructions as typically employed in Switzerland. As an example, if the outdoor A-weighted SEL is 80 dB for cannon as well as for rifle blasts then the indoor levels through a closed double-glazed window will lie typically in the range of 50 to 55 dB(A) for the cannon and 45 to 50 dB(A) for the rifle. The cannon blast will therefore be judged more annoying.

B. Comparison with previous studies

As mentioned above, the experiments reported upon here are restricted to a direct comparison of the annoyance of small, medium and large weapons. Thus, based on these experiments, we cannot establish annoyance relationships to other types of noise. This latter subject has been investigated in numerous studies. In recent field-laboratory experiments, for example, Schomer *et al.*[12] study the annoyance of small arms with respect to two control sounds (reference sounds), namely wheeled vehicles and artificially generated noise. They find that the prediction of annoyance of the small arms requires an impulsive noise penalty, whose magnitude however depends on the type of control sound. Furthermore the annoyance for large blasts increases at a greater rate than that of the control sound (a slope of 2).

In the above-mentioned article, the results for small and large weapons are presented separately. For small arms, the authors employ A weighting and for large blasts C weighting. Indeed, in cases where people are exposed mainly to only one weapon category, say, artillery weapons, then the evaluation of annoyance may be performed equally well with A or C weighting, i.e., both weighting networks yield practically the same correlation with annoyance. This was observed in both the studies of Bullen *et al.* and Buchta *et al.*[2,11] On the other hand, the question of A or C weighting becomes important if one attempts to create unified noise criteria for both large and small weapons. Combining his studies of artillery ranges and rifle ranges, Bullen *et al.* conclude that the optimum weighting network lies between the A and C weighting but much closer to C weighting. As the overall annoyance in his work is based on an unknown combination of the annoyance experienced (1) indoors with windows closed, (2) indoors with windows open, and (3) outdoors, it is not possible to relate these findings quantitatively to those of the present study.

Buchta *et al.*, combining the results of different studies, find that the annoyance of cannon fire, measured outdoors with C weighting, is as great or almost as great as the annoyance of rifle fire having the same A-weighted level.[11] Even accounting for the frequency-dependent window attenuation, this remains in discrepancy with the present findings.

As mentioned earlier, the authors of Refs. 2 and 11 arrive at their conclusions based upon *separate* fields studies for the small and large weapon types. Thus, the possibility of systematic differences between the studies cannot be ruled out. On the other hand, the influence of rattling was excluded from our laboratory experiments. Under conditions where rattling occurs, increased annoyance would be expected, i.e., our experiments may then underestimate the annoyance of large weapons.

The work of Vos and Veltman offers a good opportunity for comparing results with ours since their experiments are likewise based on data collected under controlled laboratory conditions.[13] In a simulated home environment they investigated the startle response and annoyance for impulse sounds produced by a 7.62-mm gun and a 155-mm howitzer. They find [compare their Fig. 1(b) and (d)] that the annoyance caused by the small and large weapon hardly differ from one another when presented at comparable indoor levels as measured with dB(A, IMPULSE). This is in agreement with our findings that dB(A) is a good measure of annoyance. [For single blasts the difference between dB(A, IMPULSE) and A-weighted SEL is a constant normally amounting to about 10 dB.]

IV. CONCLUSIONS

Laboratory experiments indicated that the annoyance of single blasts of large, medium, and small weapons is closely correlated to the A-weighted SEL as heard by the subjects, i.e., measured indoors, near the subjects' ears. Implications for community noise criteria with the measurement point outdoors depend on the assumption of window condition (open or closed). If the blasts are assumed to be heard predominantly outdoors or through open windows then the A-weighted SEL measured *outdoors* should be a good predictor of annoyance. Assuming closed windows, however, a penalty of about 5 dB(A) should be applied to the measured outdoor level of the large weapon blast to compensate for the poorer low-frequency attenuation of windows. The influence of rattling was not included in these experiments and warrants further study.

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