Decibel annoyance reduction of low-frequency blast attenuating windows

Paul D. Schomer
U. S. Army Construction Engineering Research Laboratories, Champaign, Illinois 61820

Edmond Buchta and Karl-Welhelm Hirsch
Institute für Lärmschutz, Düsseldorf, Federal Republic of Germany

(Received 27 June 1990; accepted for publication 15 November 1990)

In this study, the acoustical benefits of improved, blast noise reducing retrofit windows are determined using the methods of paired-comparison testing with panels of subjects. The results show that the retrofit windows reduce the received indoor C-weighted SEL by about 7 dB. The retrofit windows result in about a 14-dB improvement in terms of community response. Further, a regression line is fit to the indoor measured blast CSEL and their correspondingly equivalent control noise ASEL. The slope of this line is 2.5, indicating that a 1-dB change in CSEL corresponds to about 2.5-dB change in control ASEL. This corresponds to the result one would get if one used loudness to describe both indoor signals instead of describing the control (indoors) using ASEL and the blast (outdoors) using a variety of descriptors such as peak, CSEL or FSEL, etc.

PACS numbers: 43.50.Qp, 43.50.Pn, 43.50.Jh, 43.55.Ti

INTRODUCTION

The two major noise sources that cause environmental problems for the U.S. Army are helicopters and large weapons such as artillery, tanks, and demolition.[1] These large weapons produce blast sounds which are particularly troublesome to deal with. The Army has instituted the Installation Compatible Use Zone Program (ICUZ) as their means to work closely and cooperatively with communities near to Army installations. The ICUZ program is patterned after the Federal Aviation Administration (FAA) Part 150 program (commercial airports)[2] and the Department of Defense (DoD) Air Installation Compatible Use Zone Program (AICUZ) for military airfields.[3] In these programs, one method used to mitigate noise problems is the retrofit of existing houses and design of new dwelling units so as to better shield occupants from the noise. For fixed-wing aircraft, this takes the form of increased noise reduction capability from outdoors to indoors. For common community sources such as fixed-wing aircraft, it is the middle frequencies that are primarily reduced so as to reduce the audibility of the noise.

Noise reduction structural designs that work for fixed-wing aircraft do not work for blast noise because the sound spectra are different and because blast noises create rattles. Noise-excited rattles have been shown to be a major problem when dealing with the blast noise generated by large weapon fire.[4–6] Also, these blast noises contain primarily low frequencies, having little energy above about 200 Hz.[7] So, to shield residents from blast noise, it is necessary to design and retrofit dwelling units so as to rattle less when excited by large blast sounds and to better insulate from the very low frequencies characteristic of these sounds. Researchers at the U.S. Army Construction and Engineering Research Laboratories[8,9] and other researchers for the German Ministry of Finance[10] have been studying methods to better shield residents from the effects of blast sounds.[11] Also, the U.S. Army Construction Engineeering Research Laboratory has systematically studied the role rattles play in human and community response to noise.[12–14] These studies used the method of paired comparison to systematically test subjective response to the presence or absence of rattles in otherwise similar blast sound environments.

The German studies included a large pilot retrofit program in which about 100 homes received improved blast noise attenuating windows. These studies included pre- and post-window installation surveys. The survey results indicated that the retrofit windows produced a large benefit in terms of reducing annoyance and dissatisfaction with blast noise for large guns. However, only the population receiving retrofit windows, at no cost to them, participated in both surveys. Thus there could be a bias in these results. So, the more controlled method of paired comparison tests[8,9,12,13] was used to test the benefits provided by the retrofit windows. These tests were performed on site in Grafenwöhr, Federal Republic of Germany and used local residents, most of whom had not received new windows.

The purpose of the tests reported here was to systematically measure subjective response to blast noise with retrofit windows as compared to the original windows. As an additional purpose, using the same controlled, paired comparison tests in two countries will, in future studies, facilitate the cross-cultural comparison of human response to blast noise.

I. GENERAL APPROACH AND TEST CONDUCT

A. Approach

This study was performed using paired comparison tests in a similar fashion to earlier studies.[8,9,12,13] Here, juries of test participants were placed in two similar, occupied houses on the same street with one intervening house. For the first part of the study, house 1 had old windows and house 2 had retrofit windows. For the second part of the study, house 1 received new, retrofit windows, and the windows in house 2 remained the same retrofit windows used in the first part of the study. Juries of subjects drawn from the local area occupied the living room of each house. Most of these subjects had not received new windows. C-4 plastic explosives set off about 1.2 km from the houses provided the blast sound stimuli; loudspeakers in each test house produced the white noise, control stimuli. As in earlier studies, subjects were merely asked to choose which of each pair of noises was more annoying or bothersome and to rate their difficulty in selecting one of the sounds from the pair. The Appendix illustrates the English version of the machine read test form. This form was translated and printed in German for this study.

The general approach is explained in more detail in Schomer.[8,9,12,13] Figure 1 shows the form of typical data expected from the experiment for a single blast noise level. As in Refs. 13 and 14, we plotted one curve for each blast level and each part of the study. There were two nominal blast charge sizes: 2 and 0.5 kg. Thus there were two outside-the-house peak, flat-weighted blast sound-pressure levels that were nominally 112 and 120 dB; the "low," and "high" levels, respectively. Each blast level was plotted separately in a figure containing "the percent of respondents finding the blast noise more annoying" versus the ASEL of the control noise. Thus each figure yields a pair of levels (outdoor peak flat-weighted blast level and indoor control ASEL) at the point at which 50% of the subjects perceived the blast noise to be more annoying than the control white noise, and 50% perceived the blast noise to be less annoying. These are taken to be the equivalency points, that is, points at which the blast noise is equivalent to the control noise in terms of response.

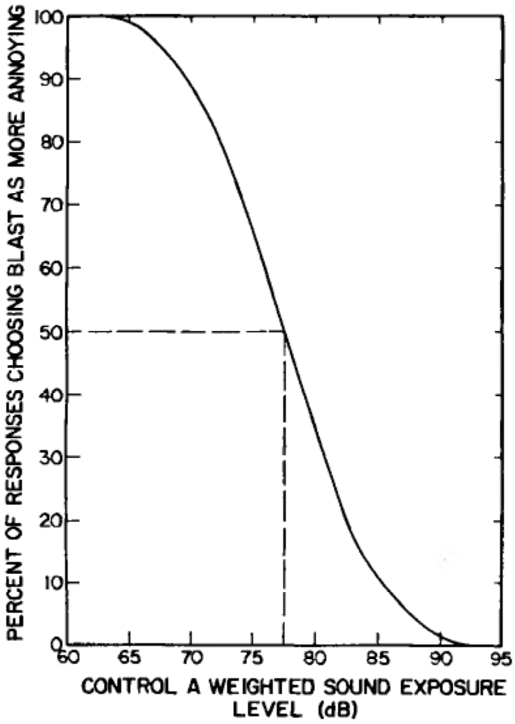

FIG. 1. The expected form of the data. For a fixed blast level (e.g., peak, flat-weighted, outdoor sound pressure level of 122 dB), the plot shows the percent of respondents indicating the blast as the more annoying of the test sound pairs as a function of the comparison white noise ASEL. In this example, the curve indicates the equivalency between the 122-dB peak, flat-weighted outdoor blast and the indoor white-noise ASEL of 62 dB.

The data yield eight such pairs of points; two houses, by two parts, by two blast levels.

As a generality, the data in Fig. 1 should assume a sigmoid shape. At low enough white-noise control levels, 100% should find the blast noise more annoying; and at high enough control levels, 100% should find the control noise more annoying. But we are trying to fit a straight line to these curves. As a practical matter, nearly all the data lie between 15% and 85%, which is the linear region of the sigmoid curve. Also, to the extent that the data are symmetrical, then the 50% point is properly located even if the linear regression could be performed in a more exact manner. To test the concept of transformation to a linear curve, the percent data were converted to z scores (the equivalent mathematical process to plotting the data on normal probability paper) and regression lines were fit to these z scores. With these transforms, the equivalency point is shifted to $z = 0$.

B. The test site layout

Figure 2 shows the test site layout. The house between the two houses was used as the assembly point for the subjects. Here, they received instruction and test forms. The written instructions were translated by native German researchers and the oral instructions were given by native Germans. The subjects were located in the living room of each test house. These living rooms included a large window and glass door that looked out on the backyard and faced the blast site at an angle of about 45 deg. Figure 3 shows the old door and window at house 1. The only difference between the first part and the second part of the study was the retrofit of improved windows to house 1.

There were six primary positions within the living room, and so, typically, five subjects participated in a test session. The loudspeakers for producing the control white noise were located as shown in the Fig. 4. Substantially (typically ± 1 dB), the same control noise level was produced at each of the subject positions.

C. Subject selection

Subjects were recruited from the entire Grafenwöhr area. The residents of the house between the two test houses

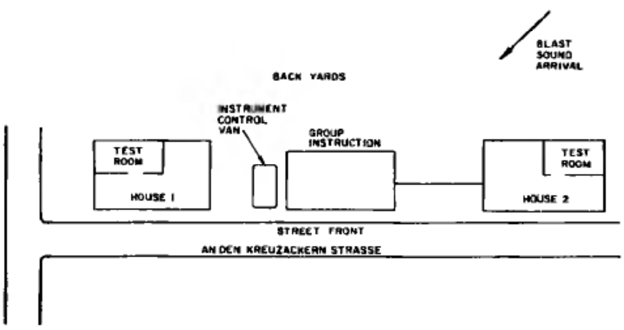

FIG. 2. The test site layout including houses 1 and 2 and the intervening house where subjects were assembled and given instructions. The blast came from the direction indicated by the arrow. The subjects were in the living rooms of the houses. These living rooms fronted the backyards and faced the incoming blast (arrow). This figure also indicates the position of the instrument van where the control stimuli were generated and where all the measurement instrumentation was located.

FIG. 3. (a) The original window and glass door at house 1; (b) the retrofit window and glass door at house 2.

were paid to recruit subjects. They did this by word-of-mouth and through local and newspaper notices. Every effort was made to develop a diverse subject body that would include both young and old, male and female, etc. Table I lists the breakdown of subjects by age and sex.

D. The control stimulus

The control stimulus was a 200- to 1500-Hz band of white noise. The instrumentation and signals are exactly those described in Refs. 13 and 14. The amplitude versus time envelope of the control stimulus was chosen so that it would be temporally similar to a blast noise, and the overall level of each control stimulus in a pair of signals was adjusted under computer control by means of a programmable step attenuator. Each high level blast had six corresponding white noise levels, which differed from one another by about 4 dB; each low level blast had five corresponding white noise levels, which differed by about 5 dB. These control levels were selected separately for each house configuration and blast level. They were chosen in an attempt to have the results such that the corresponding 50-50 equivalency point (Fig. 1) would occur in the middle of that control noise range.

The computer-controlled noise generation equipment and the measurement equipment were operated from the instrument van noted in Fig. 2. All of the equipment and the van were shipped to Germany, and the operators were the

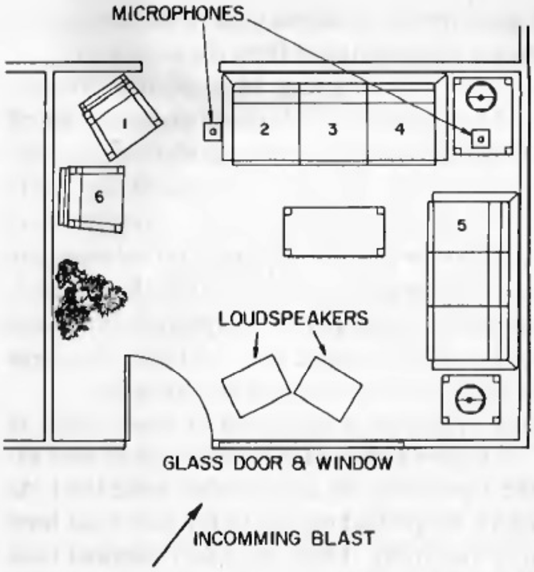

FIG. 4. A plan diagram of a typical living room (the two test houses were more or less mirror images of one another. The locations of the subjects, microphones, accelerometer, and control noise loudspeakers are indicated.

TABLE I. Demographics of subjects participating in study.

Test	Age group <20	21–30	31–40	41–50	51–60	≥61
1985	6	22	18	6	3	0
1986	17	31	13	4	4	3
1987	12	35	29	14	4	2
1988 (without rattle)	19	37	8	2	1	1
1988 (with rattle)	25	20	7	2	0	1

Test	Sex M	F	Occupation Student	Other
1985	27	28	16	39
1986	32	40	35	37
1987	53	43	28	68
1988 (without rattle)	42	26	50	16
1988 (with rattle)	28	27	37	18

same technicians and engineers that operated the equipment at the earlier studies in the United States.

E. Data measured

The primary blast source measurement was made with a B&K type 4921 outdoor microphone system located outside and about 5 cm from the center of the large window. There were always two microphones indoors as shown in Fig. 4. These were placed between subjects at ear height and on either side of the room. These served to show that the blast source and the control stimulus were presented at the correct, test-design levels.

There were also measurements of window acceleration. All of the acceleration levels were so low as to be not-at-all or only barely perceptible.

F. Study procedure

There were new test subjects each day. Prior to testing, they were assembled at the house in-between the two test houses where they received general instructions about the study and specific written instruction sheets. A German researcher remained with the subjects throughout the test. The test period began with several practice comparisons. Subjects had to decide which was more bothersome or annoying, the first or second noise in a pair. They also indicated on a 5-point scale how difficult it was to decide which was more annoying; but, in every case, subjects were required to decide which of the two sounds was more annoying. After the practice comparisons the regular test commenced. On days when test time permitted, each subject completed one full set of responses in each house.

Each pair of sounds consisted of four distinct segments: (1) listening to the first sound; (2) a short period of quiet; (3) listening to the second sound; and (4) a period of quiet for choosing the more annoying or bothersome sound and marking the answer sheet. Each signal pair sequence took about 10 s to complete.

G. Experimental design

The study was randomized by (1) blast level, (2) control level, (3) order of presentation (blast or control first), and (4) sequence of presentation. There were two blast levels: "high" and "low." There were six different control levels used with the "high" blast signals, and five control levels used with the "low" level blasts. Thus there was a total of 11 signal pairs. Each signal pair consisted of a blast signal and a computer-generated control signal. During a test session, each subject judged each signal pair four times; twice with the blast being the first signal in the pair and twice with the control being first. Thus each subject responded 44 times during a given test session. The data were gathered in groups of 11 signal pairs. Each group of 11 contained all of the possible signal pairs but in an apparently random order. Each of the four groups of 11 differed from one another, but the latter two groups (22 signal pairs) were identical to the first two groups except for the order of presentation. For example, if, for signal pair 1, the blast was presented *first* and was "high level" and the control was 70 dB, then signal pair 23 (1 plus 22) also consisted of a "high level" blast and a control of 70 dB, but the blast was presented *second*.

TABLE II. Control ASEL found equivalent in terms of annoyance to the blast stimulus for each location, blast size, and test period. The approximate error limits in decibels (in parentheses) come from the 95% confidence limits as shown in Fig. 5.

		Control ASEL (dB)	
Blast size	House	Before	After
Low	1	62.8 (2.5)	49.2 (2.8)
Low	2	36.6 (7.5)	43.5 (2.0)
High	1	76.1 (1.5)	64.0 (4.8)
High	2	50.8 (9.5)	52.8 (1.9)

II. DATA REDUCTION AND RESULTS

A. The basic response data

The various sets of data accumulated during this study included the subjects' responses, measured CSEL near the subjects, and the flat-peak SPL, C-peak SPL, FSEL, and CSEL just outside the test house. A separate plot was made for each blast level and test house configuration. In all, there were eight plots, two for each part of the study and for the two houses. Table II lists the equivalency points in terms of the ASEL of the control signal found equivalent to the blast stimulus. These all come from figures similar to Fig. 5. In these figures, percents (finding the blast sound more annoy-

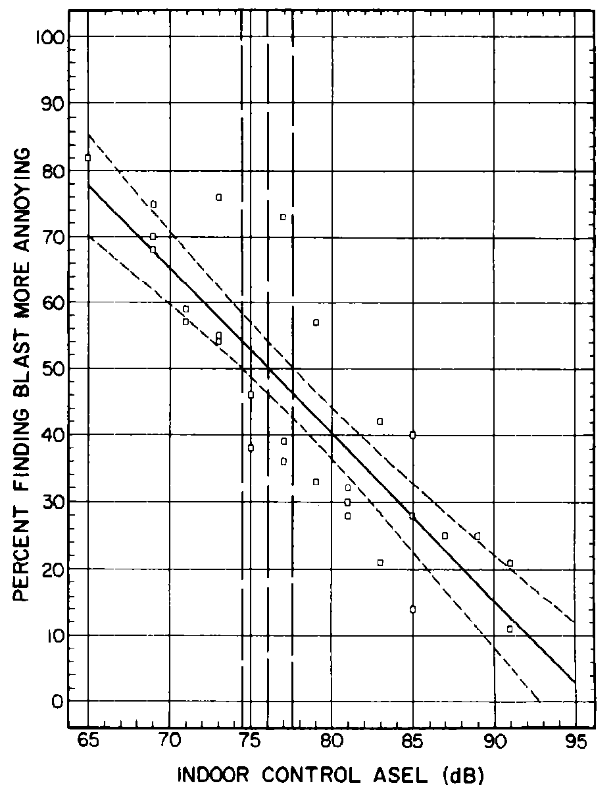

FIG. 5. Typical data curve. The percent finding the blast more annoying versus the ASEL of the control stimulus. This curve is for house 1 before retrofit of the new windows and using the high blast level. A regression line is fit to the data and the 95% confidence limits are shown. Eight of these figures were produced, one for each study condition.

TABLE III. Measured outdoor and indoor acoustical levels and the equivalent indoor control level for each location, blast size, and test period.

			Outside				Inside	
Blast size	House	Time period	Peak	Flat SEL	Flat CSEL	CSEL delta	Blast CSEL	Control ASEL
Low	1	before	110	97	89.4	13.5	75.9	62.8
		after	114	99	92.7	21.3	71.4	49.2
Low	2	before	115	102	91.4	21.8	69.6	36.6
		after	117	101	93.7	25.9	67.8	43.5
High	1	before	118	104	96.9	14.5	82.4	76.1
		after	121	106	99.3	21.1	78.2	64.0
High	2	before	122	107	99.0	23.8	75.2	50.8
		after	124	108	100.4	26.2	74.2	52.8

ing) have been plotted versus the ASEL of the control. Linear regression is used to fit a line to the data. The error limits in Table II come from the calculated limits as shown in Fig. 5. The dashed lines show the 95 percent confidence intervals and are used to find the error bounds given in Table II. As discussed below, the large error bounds for the low blast levels in house 2 result from the sounds being very quiet and difficult for the subjects to judge.

In gathering the data, care was taken to see that the control signal level range was such that the 50% point was included in the middle of the range and that little data was at 0% or 100%. As indicated in the introduction, the percent data were transformed to *z* scores and regression analysis was also used to fit lines to these transformed data. In this study, the transformation of the percent data to *z* scores did not improve the analysis. On average, the correlation coefficients for the linear regressions did not improve with the transformation of the percents to *z* scores. Five of the eight correlation coefficients increased by a maximum of 0.02 and the other three decreased. So for the sake of brevity, the *z*-score analysis has been omitted.

B. Comparison with measured sound levels

Table III shows the measured indoor and outdoor CSEL in each house during the two halves of the study. These data are energy averages of the individual events. This table also lists the outdoor peak-flat SPL and flat SEL. There was a systematic difference in the outdoor levels of a couple of decibels between house 1 and house 2. Overall, the new windows provided about a 7-dB improvement in C-weighted sound insulation, but they do not appear to be quite as good as the retrofit windows in house 2. However, the 7-dB figure is in substantial agreement with what was measured as an overall average for the 100 houses retrofit during the pilot project.[15]

Table III also lists the corresponding ASEL control levels found equivalent to the various blast levels. First, one notes that the shift at house 2 corresponds directly to the small change in blast levels—sound propagation conditions changed a little. So, overall, the conditions during the two halves of the study are very similar. Second, it is clear from the data from the first part that the windows in house 2 (retrofit) are much better than the windows in house 1 (old). Finally, comparing the first and second halves for house 1 shows quantitatively that the 5-dB indoor change in CSEL (the windows improve by 7 dB but the blast levels are 2 dB higher so the net change is 5 dB) corresponds to a 14-dB improvement in judged response.

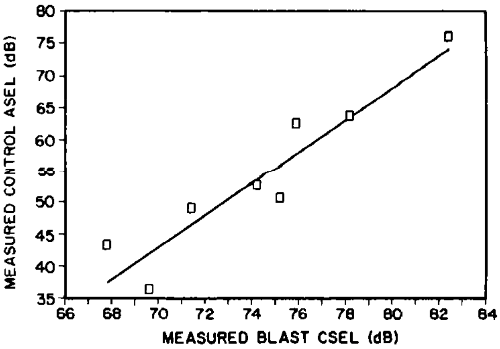

FIG. 6. The indoor measured blast CSEL and corresponding equivalent control ASEL for each location, blast size, and test period are plotted. A regression line is fit to the data. The equation for this line is: ASEL = 2.5·CSEL − 132, so a 1-dB change in CSEL corresponds to a 2.5-dB change in the correspondingly equivalent control level.

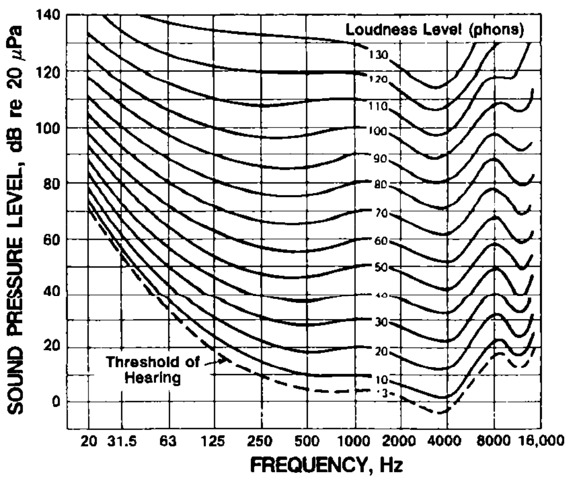

FIG. 7. Classical loudness curves.[16] In the middle frequencies (250 to 4000 Hz) these are parallel curves spaced about 10 phon apart. But in the 30- to 40-Hz range and at the (indoor) sound levels characteristic of this experiment, each decibel change in level corresponds to about a 2-phon change in loudness level.

C. Discussion

Figure 6 plots the last two columns from Table III: the indoor blast CSEL and equivalent control noise ASEL. One can note the somewhat increased scatter to the data at low sound levels where it is very difficult for the subjects to make judgments. A regression line is fit to these data and the results indicate that each decibel improvement in C-weighted sound isolation (to large blasts) is worth about 2.5 dB in reduced annoyance. Since the blast energy peaks at about 30 to 40 Hz, this is similar to the result one would expect to get from a loudness calculation. Figure 7 shows classical loudness curves.[16] In the middle frequencies (250 to 4000 HZ), these are parallel curves spaced about 10 phon apart, but, in the 30- to 40-Hz range at the sound-pressure levels (SPL) characteristic of this experiment the curves are spaced about 5 phon apart. Specifically, for narrow-band sounds around 32 Hz, a 62 dB SPL corresponds to 20 phon and a 72 dB SPL corresponds to 40 phon; a difference of 10 dB in SPL corresponds to a difference of 20 phon in loudness level. So loudness level may be appropriate to describe public reaction to large-amplitude, low-frequency blast sounds.

III. CONCLUSIONS

The major conclusion from this study is that the retrofit windows are highly effective in providing enhanced sound isolation for blast noise. The conduct of the experiment shows that this result is acoustical in nature since the subjects in this study had not received free retrofit windows. The data clearly show that the windows provide about a 14-dB improvement in terms of reduced annoyance.

The results appear to indicate that the major underlying factor in noise annoyance is loudness. Clearly, a loudness type of function explains how a 5-dB change in CSEL (where the energy peaks in the 30- to 40-Hz range) might correspond to a 14-dB change in annoyance. This result is also consistent with similar results found with helicopters.[17]

The results are highly significant. The decibel offsets are large and statistically significant, the number of subjects overall is close to 50, and each subject makes 44 judgments.

APPENDIX

Figure A1 shows an example of the machine-read data form in English. Only the top half of the form is shown for the sake of brevity.

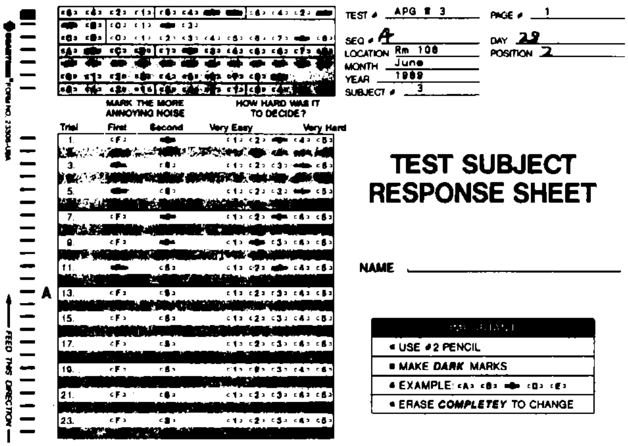

FIG. A1. The top half of the machine read data form (in English). Headings on these forms are normally machine printed prior to the test. This example is from a subsequent study performed at Aberdeen Proving Grounds, MD. All of the heading information except *sequence*, *day* and *position* were printed prior to study execution (the subject's name has been erased from this example).

[1] George Luz *et al.*, "An analysis of community complaints to noise," J. Acoust. Soc. Am. **73**, 1229–1235 (1983).

[2] Federal aviation regulations, Part 150, Sec. 8, Washington, DC.

[3] "Air Installations Compatible Use Zones (AICUZ)," Department of Defense Instruction 4165.57, July 1973, revised November 8, 1977.

[4] P. N. Borsky, "Community reactions to sonic booms in the Oklahoma City area," Aerospace Med. Lab. Rep. No. AMRL-TR-65-37, Wright–Patterson Air Force Base, Ohio (1965).

[5] P. D. Schomer, and R. D. Neathammer, "Community reaction to impulsive noise: A final 10-year research summary," U.S. Army Construction Engineering Research Laboratory, Tech. Rep. No. N-167, Champaign, Il (1985).

[6] *Ibid.* Ref. 3.

[7] P. D. Schomer *et al.*, "Statistics of amplitude and spectrum of blasts propagated in the atmosphere," J. Acoust. Soc. Am. **63**, 1431–42 (1978).

[8] P. D. Schomer *et al.*, "Mitigation of the building vibration and rattle induced by blast noise: Development of a test facility and systematic investigative procedures," U.S. Army Corps of Engineers, CERL Rep. N-87/25, Champaign, IL (1987).

[9] P. D. Schomer *et al.*, "Expedient methods for rattle-proofing certain housing components," U.S. Army Corps of Engineers, CERL Rep. N-87/24, Champaign, IL (1987).

[10] The German Federal Ministry of Finance is responsible for the program to soundproof houses in the vicinity of airports. Under this proposed program, houses would also be soundproofed in the vicinity of major military training areas where the noise from large guns was a problem.

[11] E. Buchta, "Pilotprojekt für passive Schallschutzmassnahmen am Truppenübungsplatz Grafenwöhr," Institut für Lärmschutz for Bundesminister der Finanzen (1989).

[12] P. D. Schomer and R. D. Neathammer, "The role of helicopter noise-induced vibration and rattle in human response," J. Acoust. Soc. Am. **81**, 966–976 (1987).

[13] P. D. Schomer and A. Averbuch, "Indoor human response to blast sounds that generate rattles," J. Acoust. Soc. Am. **86**, 665–673 (1989).

[14] P. D. Schomer and B. D. Hoover, "A-weighting—It does not work indoors for helicopter or large gun noises; noises with low frequencies and large amplitudes," INTER-NOISE 89, 853–858 (1989).

[15] *Ibid.* Ref. 11.

[16] ISO/R 226-1969, "Pure-tone frequency response of the ear," (International Organization for Standardization, Switzerland, 1969).

[17] *Ibid.* Ref. 14.