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EVALUATION OF OCCUPATIONAL EXPOSURE TO INFRASONIC NOISE IN POLAND

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Key words: Infrasound, Infrasonic noise, Acoustic measurements, Occupational exposure, Sources of infrasonic noise

Abstract. A short review of infrasound sources and effects on humans is presented. Polish standard PN-86/N-01338 and international standards ISO 7196:1995 and ISO 9612:1997 concerning the measuring techniques of infrasonic noise are described. The results of infrasonic noise measurements performed in the work environment in Poland are discussed.
The study concerned the noise emitted by 124 different types of industrial machinery, appliances and means of transport. The measurements were made in typical working conditions with reference to Polish and international standards. The sound pressure levels exceeding Polish admissible values for: (a) workers' health protection were found in 5 (4.0%) cases, (b) ensuring proper conditions for performing basic functions in observational dispatcher cabins etc. in 77 (62.1%) cases; and (c) administration premises, design offices etc. in 92 (74.2%) cases.
The admissible sound pressure levels for workers' health protection are in fact the permissible levels for hearing protection, however they do not correspond with the hearing threshold of infrasound the G-weighting characteristic is associated with. The hearing threshold of infrasound (G86 curve) was exceeded in 66.9% of all the industrial machinery and means of transport under study.

INTRODUCTION

Infrasound is defined as acoustic waves within the frequency range of 0.1 ÷ 20 Hz. Owing to its long wavelength, infrasound is less attenuated by walls and other structures, it is able to propagate over long distances, and may affect the human organism even though the latter is far from its source (2).

International Standard ISO 7196:1995 determines infrasound as sound or noise with frequency spectrum falling usually within the range of 1–20 Hz (7). Whereas Polish Standard PN-86/N-01338 limits infrasound to the frequency range of 2–16 Hz. Moreover, it introduces the definition of 'infrasonic noise'.

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Thus, the broad-band noise containing infrasonic frequencies (2 – 16 Hz) and low audible frequencies (under 50 Hz) is called infrasonic noise (23).

The infrasound which occurs in the environment may be of natural or artificial origin, mostly related to industry. The examples of natural sources are winds, storms, waterfalls, earthquakes, volcanic eruptions and other natural phenomena. The most powerful artificial sources of infrasonic waves are associated with trial nuclear explosions in the atmosphere. Infrasonic noise is commonly generated by different means of transport as well as by many industrial machinery (1,2,4,20,28).

This paper reviews the infrasound effects on humans and presents Polish and international standards concerning the measuring techniques. The results of infrasonic noise measurements performed at various workplaces in industry and transportation in order to evaluate actual exposure in the occupational setting in Poland are also presented.

EFFECTS OF INRASOUND AND INFRASONIC NOISE

It has been commonly assumed that infrasound is inaudible. Initially, the concerns about the health effects of infrasound were based on a number of alleged extra-auditory effects, such as disturbed equilibrium or an influence on the cardiovascular function. However, the experimental findings were inconsistent, and in general the effects seem to have been exaggerated (18).

Perception of infrasound is based on hearing and vibrations. The vibrations capable of inducing perception will occur only at relatively high sound pressure levels, 20 to 40 dB above the hearing threshold. Single frequencies of infrasound are not perceived as pure tones. Instead, they are described as more of a chugging or motorboating sound. The ability to hear infrasound has therefore been suggested to be based on harmonics generated by distortion in the middle and inner ear (9). The hearing threshold rises rapidly as the frequency falls, from approximately 65 dB at 32 Hz to 95 dB at 16 Hz, 100 dB at 3 Hz, and 140 dB at 1 Hz (2,9,14). Moreover, when infrasound becomes loud, it can be annoying. The annoyance associated with exposure to the audible infrasound has been the subject of a number of laboratory experiments. For example, contours of equal annoyance were determined for pure tones in the frequency range from 4 to 31.5 Hz (Fig. 1). The curves show a narrowing of the dynamic range of the ear at low frequencies. The same pattern is observed for equal loudness curves, so the annoyance of infrasound is closely related to the loudness (17,18).

One of the most conspicuous causes of the effects of annoyance caused by infrasound is pressure sensation in the middle ear. This effect begins to occur at levels between 127 and 133 dB. It is often pronounced shortly after the initiation of exposure and sometimes may also persist after its termination (4,9,14).

The adverse effects of aural pain, speech interference and temporary threshold shift (TTS), normally appear at levels from 30 to 40 dB above the hearing threshold. The threshold for aural pain is approximately 140 dB at 40 Hz and 160 dB at 3 Hz. A tympanic membrane injury may result from exposure to extremely high sound pressure levels (2,6,9,14).

Infrasound as well as low frequency sound up to 75 Hz may excite resonant oscillations in some parts of the human body, e.g. abdomen, chest and throat (4,9,14).

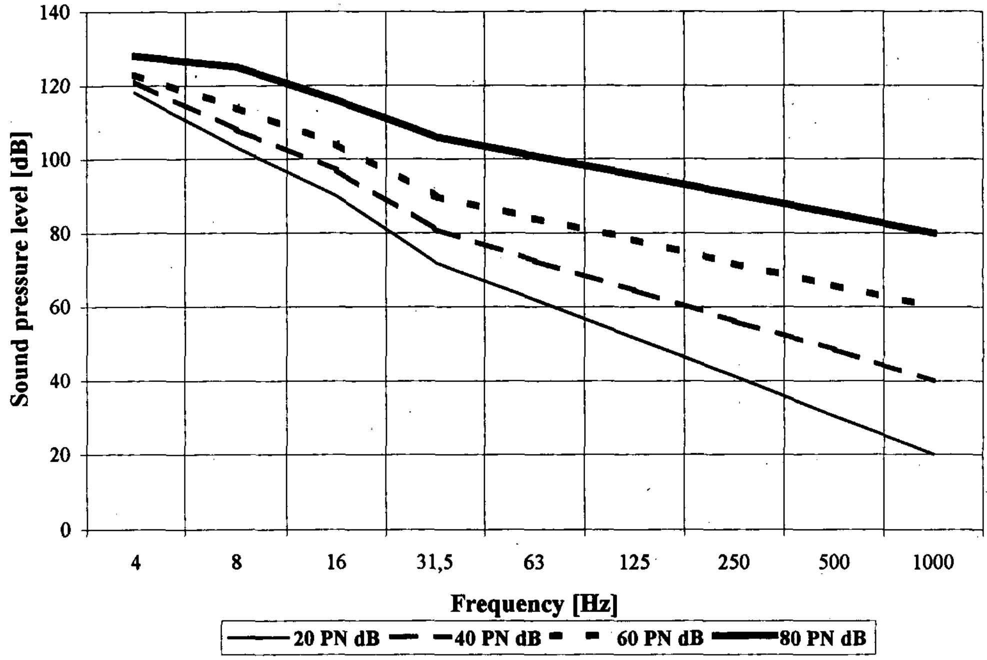


Fig. 1. Curves of equal annoyance (PN dB – perceived noisiness) (18).

An American space research project has indicated that the maximum permissible short-term exposure to infrasound should approximate 140÷150 dB. Beyond this level the chest walls of the subjects would vibrate, with a sensation of gagging and blurring of vision. The chest wall vibrations may interfere with the respiratory activity (9,14).

A close correlation exists between the exposure to infrasound, its perception, and the physiological effects. Therefore, the sound pressure levels must always be high enough to allow perception, in order to induce physiological effects. This theory has been experimentally verified in laboratory studies. Reductions of wakefulness identified through changes in EEG, blood pressure, heart activity, respiration, and hormonal production, was found to occur only when the infrasound levels exceeded the hearing threshold. Under the same conditions the deaf subjects showed no weariness (3,5,9,11–15,27).

The physiological effects observed in experimental studies often seem to reflect a general slowdown of physiological and psychological functions. The reduction in wakefulness and related physiological responses are probably to be regarded as secondary reactions to a primary effect on the central nervous system (CNS). The effects of moderate levels of infrasound are thought to be based on the correlation between the hearing perception and the resulting CNS stimulation. The participation of the reticular activating system and the hypothalamus is considered to be of great importance (3,14).

The experimental evidence of the effects associated with human exposure to infrasound derives mainly from laboratory experiments on the exposure to very high sound pressure levels of infrasound. The evidence for the effects related to moderate exposure is rather sparse and the results from different laboratory studies are not consistent. Human exposure to infrasound (infrasonic noise) in the work environment very seldom occurs at high levels; the majority of exposures are found to be moderate. Moreover, it is often concurrent with a number of other environmental factors (e.g. audible noise, vibration).

Although exposure to infrasonic noise at the levels normally experienced by man does not tend to produce any dramatic health effects, exposures above the hearing perception level may produce symptoms such as weariness, annoyance or unease.

POLISH AND INTERNATIONAL STANDARDS CONCERNING INFRASONIC NOISE

The current Polish Standard PN-86/N-01338 recommends to perform infrasonic noise measurements using 1/1 octave band filters in the 4–31.5 Hz frequency range. It also specifies the admissible values of sound pressure levels for workers' health protection and ensuring proper conditions of work at two selected categories of workplaces (Table 1) (23).

Table 1. Infrasonic noise: admissible values of the acoustic pressure levels at workplaces (exposure time – 8 h) as specified in the Polish Standard PN-86/N-01338

Admissible acoustic pressure levels (dB)	1/1 octave bands with the centre frequencies (Hz)			
	4	8	16	31.5
For health protection at all workplaces (MAI) – 1st criterion	110	**110** **137**	**110** **137**	**105*** **132****
Ensuring proper conditions for performing basic functions in observational dispatcher cabins, remote control, on premises for precise works etc. – 2nd criterion	90	90	90	85
For administration, design offices, research work, data handling etc. – 3rd criterion	85	85	85	80

* a limitation introduced by the Ordinance of the Minister of Labour and Social Policy on MAC and MAI values for agents harmful to human health in the work environment.
** maximum (short-time) permissible levels (19).

The Polish Standard PN-86/N-01338 incorporates the 3-dB equal energy rule, the same as for the audible noise. This rule allows a 3-dB increase in the permissible levels of sound pressure in 1/1 octave bands for each halving of duration.

The Ordinance of the Minister of Labour and Social Policy on MAC and MAI values for agents harmful to human health in the work environment restricts the evaluated frequency range to 8±31.5 Hz 1/1 octave bands and establishes the permissible levels for workers' health protection as maximum admissible intensity (MAI) values for infrasonic noise in the work environment (19).

International standards ISO 7196:1995 and ISO 9612:1997 recommend the use of G-weighting frequency network in order to describe infrasound (Fig. 2). Additionally, the latter of the standards allows employing 1/3 octave band filters in the frequency range up to 20 Hz. However, neither specifies the permissible levels (7,8).

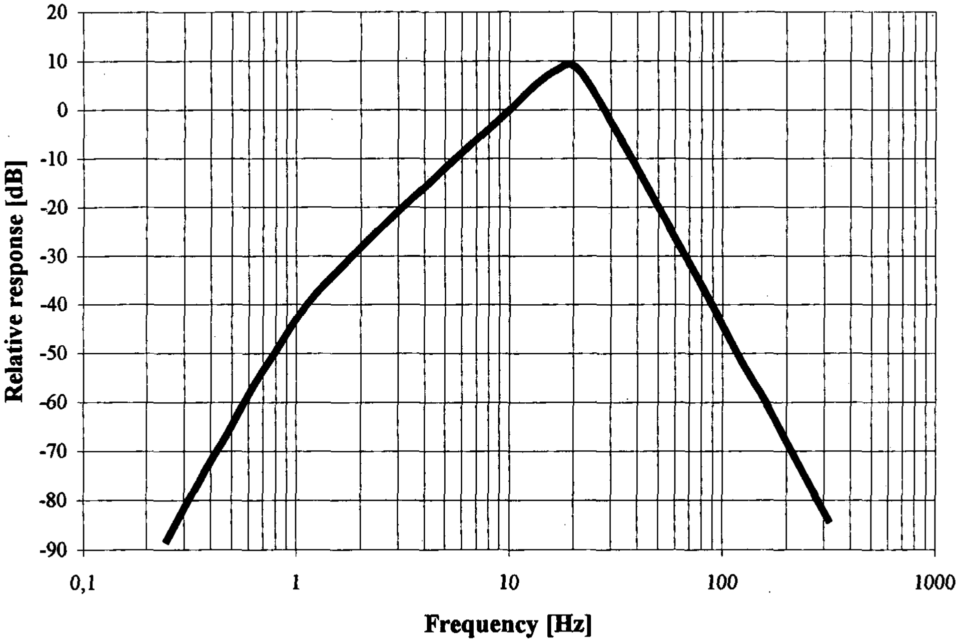


Fig. 2. G-weighting characteristic – nominal frequency response (7).

As human tolerance to infrasound is defined by the threshold of hearing perception, the frequency-weighting characteristic G has the same slope (close to 12 dB per octave) as both hearing perception threshold curves, equal loudness curves and equal annoyance curves. It is worth noting that G-weighting filter gives values that correspond well with the above mentioned subjective annoyance rating of infrasound (16). Moreover, it is assumed that the sound pressure levels found on the G86 curve* are the limit values of the hearing threshold which is exceeded in 90–95% of the population (22).

MATERIALS AND METHODS

The present study concerned the infrasonic noise emitted by 124 different types of industrial machinery and means of transport, e.g. turbogenerators, power boilers, fans, coal pulverizers, compressors, pumps, devices of petrochemistry and chemical plants, smelting furnaces, foundry devices, electric and diesel locomotives, small crafts, ferries, buses, trams, lorries, truck-tractors, road making plant, flour mill machinery etc.

The measurements were made in typical conditions of their operation and with reference to the relevant Polish and international standards. The studies were performed at well-defined stationary or non-stationary workplaces or/and around the machines or devices, sometimes at a certain altitude.

* The G86 curve is expresed as: $L_{G86} = 86 - K_G$(dB), where: L_{G86} – sound pressure level (dB), K_G – relative response of G-weighting filter (dB).

At each measuring point the following sound pressure levels were determined:

- in 1/1 octave bands in the frequency range 4÷31.5 Hz (2÷4000 Hz) – according to PN-86/N-01338,
- in 1/3 octave bands in the frequency range 1.6÷20 Hz (1.6÷5000 Hz) – according to ISO 9612:1997,
- G – frequency weighted – according to ISO 7196:1995 and ISO 9612:1997*.

Additionally, equivalent continuous A-weighted and unweighted LIN (in the frequency range 0.4÷22 400 Hz) sound pressure levels were measured. Linear averaging was applied. The results concerning one machine or device were averaged logarithmically.

The measurements were carried out with the following instruments:

- Bruel and Kjaer (B and K) 4147 microphone, B and K 2231 sonometer, B and K 7005 tape recorder and B and K 2133 real-time frequency analyzer type or
- B and K 4193 microphone, B and K 2639S microphone preamplifier and a Hewlett-Packard HP 3569A real-time frequency analyser.

RESULTS

The examined machinery, devices and means of transport were grouped, and the obtained results of noise measurements are summarised in Table 2 and Figs. 3 and 4**.

All objects are the source of broad-band noise including infrasonic and low frequencies under 250 Hz. The highest levels of infrasonic noise were measured inside locomotives, lorries, buses and trams, road rollers, crafts (e.g. ferries, fish cutters) and around piston and centrifugal compressors, Roots blowers, vacuum pumps, open-heart furnaces, arc furnaces, vibrating grates, power moulding machines, ball and beater mills, power boilers, downcast and exhaust fans of power boilers, mine and windmill fans and flour mills devices, especially flour vibrating screens.

It is worth noting that in the cabins of the vehicles, considerably high levels of infrasonic noise are accompanied by low levels of audible noise (Fig. 5). On the other hand, in different machines, e.g. vibrating grates, flour vibrating screens, Roots blowers, ball and beater mills or during routine repair works in diesel locomotives, significant levels of infrasonic noise are concurrent with high levels of audible noise (Figs. 6–8).

The potential effects of exposure to infrasonic noise depend on the sound pressure levels as well as on the actual duration of exposure. In the majority of cases examined there were no well-defined stationary workplaces near the machines (e.g. fans of power boilers, ball or beater mills in the power plants). Thus, the effective time of exposure was less than 8 h. However, at several mobile workplaces, e.g. compressor operators or furnacemen, the workers could spend a large part of the work shift in special, separated rooms (cabins). The cabins are of various construction and serve different purposes: control rooms, maneuver rooms, areas for pauses

*G – weighted sound pressure levels were calculated by results of frequency analysis using 1/3 octave bands (7).

**For detailed results of infrasonic noise measurement see reference (22).

Table 2. Results of infrasonic noise measurements (22)

Sources of noise	Sound pressure level (dB)						
	1/1 octave bands (Hz)				Filter		
	4	8	16	31.5	G	A	LIN
Devices in thermal power stations, electric power stations etc.							
Turbogenerators	61–71	63–67	71–76	76–79	82–86	92–95	96–99
Power boilers	80–91	76–94	74–88	70–87	82–97	75–77	87–99
Fans of power boilers	79–93	84–93	80–94	82–93	92–101	84–102	100–104
Coal pulverizers	91–95	87–92	83–90	82–87	92–98	87–99	99–106
Machinery and devices in chemical plants							
Rotary lime-kilns	68–71	73–80	78–87	82–85	88–95	87–94	94–97
Fans of lime-kiln	68–71	73–80	78–87	82–85	88–95	87–94	94–98
Chemical reactors	62–65	66–71	71–78	70–76	79–86	77–81	84–86
Mixers and centrifuges	65–66	62–68	65–81	76–77	82–90	79–83	84–88
Evaporator and dier	59–64	62–67	71	68–73	78–80	84–85	86
Device for production of coloured dyes	71–74	75–81	72–75	78–86	83–90	86–90	92–100
Calanders and mixing rolls	56–62	66–73	72–74	76–80	80–83	85–88	88–93
Injection moulding machine and presses	64–68	67–69	71–73	73–76	79–81	75–79	82–86
Devices in petrochemical plants							
Windmill fans	95–104	93–102	91–98	86–91	99–106	79–85	101–109
Mixed-flow pumps	73–88	70–86	81–88	78–84	89–96	91–102	95–106
Distillation furnaces	82–89	82–85	80–84	82–83	90–92	84–85	96–100
Rotating machinery							
Piston compressors	65–105	78–111	75–104	74–98	91–113	85–99	100–112
Centrifugal compressors	68–71	74–81	93–98	94–106	102–107	92–101	103–109
Screw compressors	67–88	72–94	73–88	71–88	83–96	79–102	91–110
Other compressors	60–85	54–75	60–85	71–101	73–105	79–107	84–111
Blower and turbo-blower	71–78	72–75	67–94	73–105	78–104	87–102	90–109
Vacuum and gas pumps	67–74	73–81	76–92	79–109	86–106	82–103	89–112
Mine fans	79–89	83–86	81–84	79–84	91–93	86–90	92–96
Steel mill devices							
Open-heart furnace	81–89	80–94	81–97	85–101	90–106	84–91	92–105
Iron blast furnace	74	76	75	75	83	78	85
Arc furnace	79–102	80–105	83–103	85–102	92–110	84–109	93–113
Dedusting funs of arc furnace	78–82	77–80	87–92	93–97	97–101	88–95	100–102

Table 2 (contd)

Sources of noise	Sound pressure level (dB)						
	1/1 octave bands (Hz)				Filter		
	4	8	16	31.5	G	A	LIN
Foundry devices							
Vibrating grates	67– 91	76–103	87– 95	95– 98	102–107	98–100	104–106
Power moulding machines	62– 65	70– 80	79– 80	80– 90	87– 92	86– 95	90– 99
Flour mill devices							
Flour vibrating creens	108–110	83– 94	89– 93	87– 95	100–103	86– 89	108–109
Purifiers and corn scourers	98–101	82– 86	85– 87	93– 97	99–101	90	102–103
Roller mills	93– 97	77– 86	80– 97	84– 91	90–106	78– 85	95–101
Means of transport*							
Electric locomotives	93– 96	89– 96	80– 97	83– 98	92–106	76– 83	98–104
Diesel locomotives	90– 95	92– 97	91– 94	90– 94	100–102	75– 79	99–102
Diesel switching locomotives	74– 96	77–102	89–102	92–105	100–112	75– 88	97–107
Diesel locomotives – routine repair works	74–110	82–109	91–105	95–109	102–114	89–118	101–120
Fish cutters	66– 72	70– 77	81– 86	91– 99	95–103	69– 84	95–100
Engine room	68– 81	75– 81	77– 89	82– 92	88– 98	101–107	103–111
Motorboats	81– 83	74– 84	83– 92	88– 98	92–103	78– 82	97–101
• engine room	79– 84	76– 83	83– 85	94–101	92– 98	112–116	112–118
Ferries							
• captain's bridge	68– 88	79– 89	92– 93	76– 88	100–102	58– 66	92– 97
• inside engine room	83– 89	87– 88	94– 97	97–102	104–105	102–111	107–114
Buses	89– 94	95–100	100–104	93– 97	1082–111	64– 79	104–106
Tram	90	89	92	94	101	77	99
Truck-tractors	97–100	92– 98	88–101	90–100	96–110	68– 73	104–107
Trucks	96– 99	96–102	100–107	98–100	108–115	78– 82	106–110
Road making plant*							
Road rollers	85– 94	84–105	89–104	93–110	103–113	80– 90	101–110
Other machines (compactor and spreader of asphalt)	74– 77	67– 77	64– 78	78– 79	83– 87	86– 91	92– 95

* Results were obtained inside cabins with closed windows.

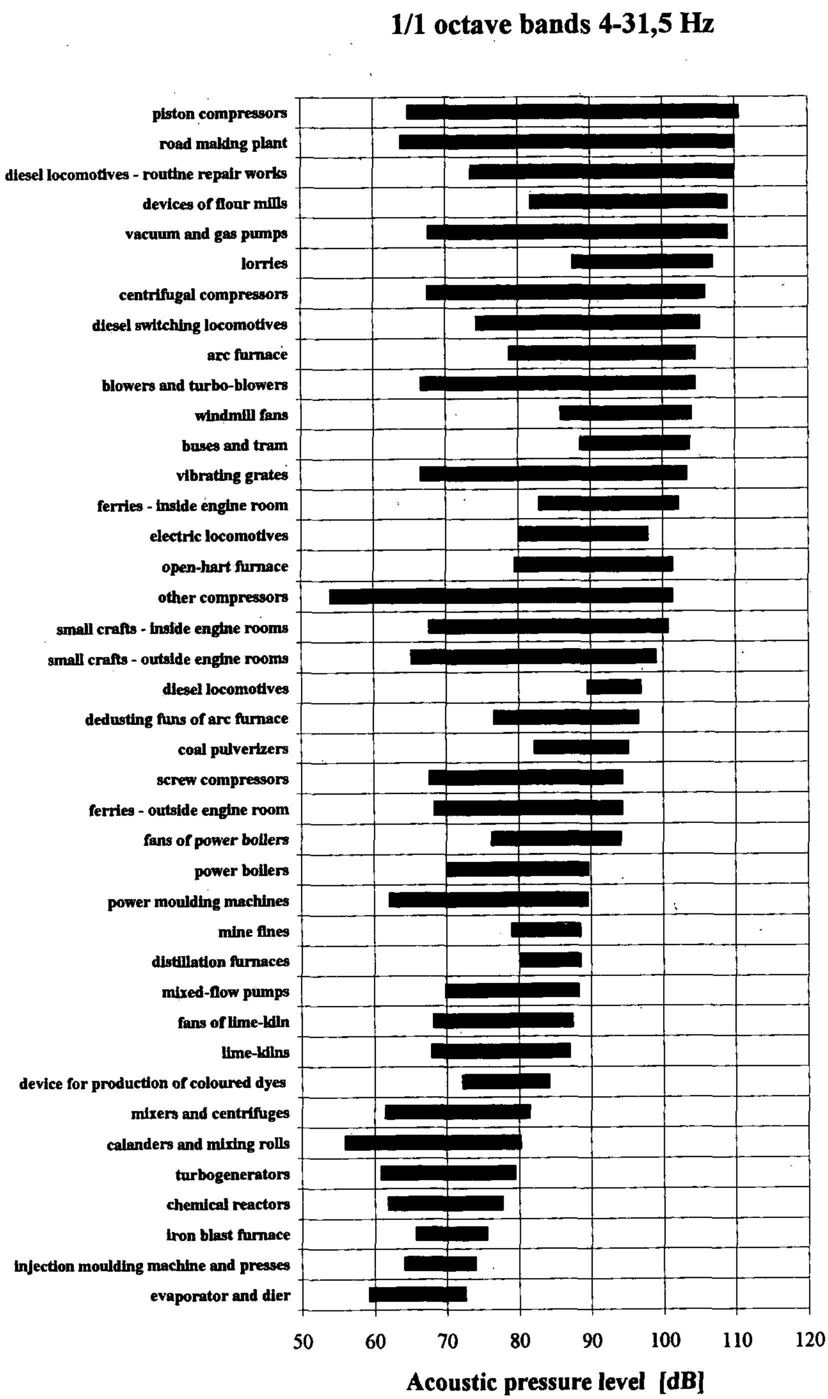


Fig. 3. Measurement results – sound pressure levels in 1/1 octave bands in the 4÷31.5 Hz frequency range (on the chart each bar specifies the range of the measured sound pressure levels).

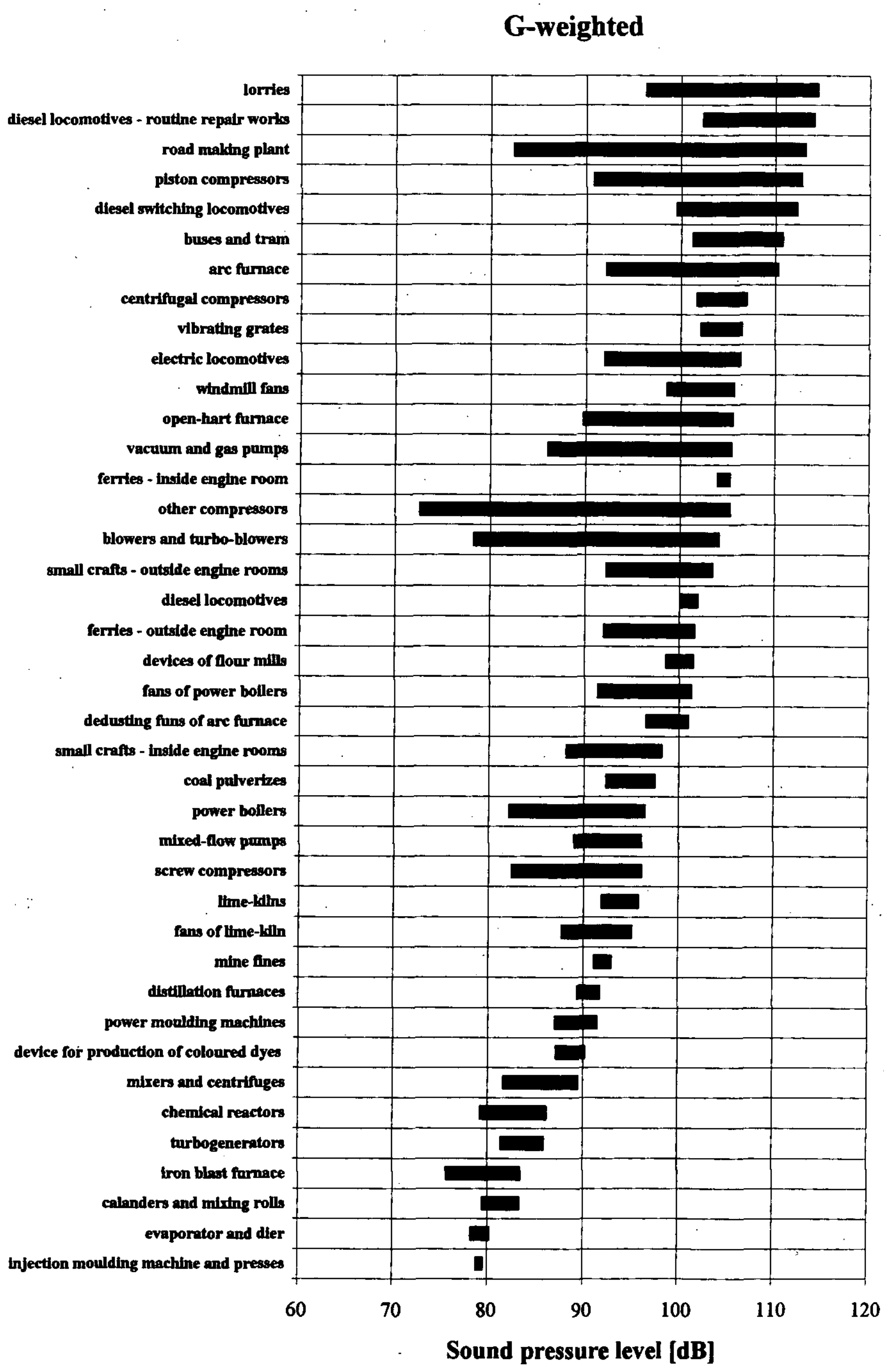
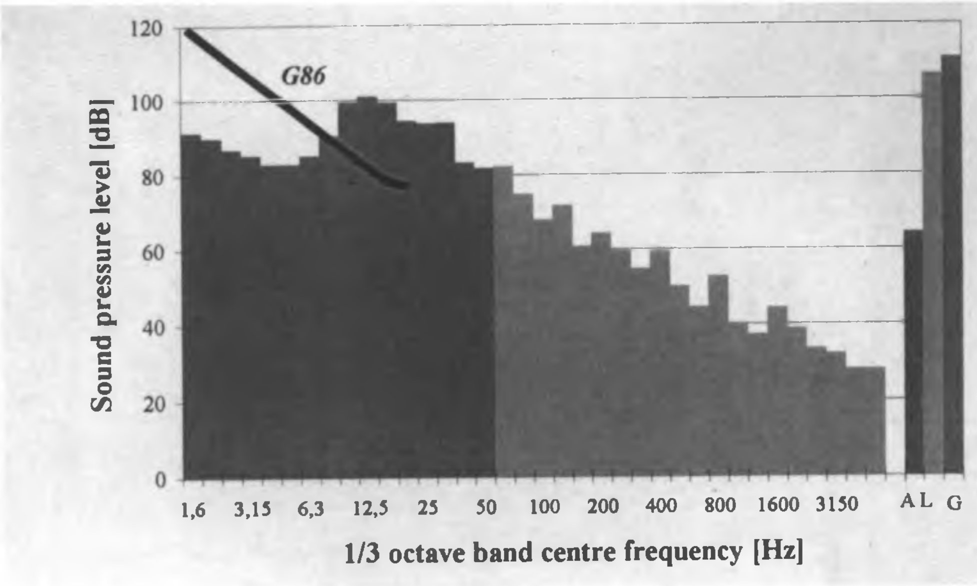


Fig. 4. Measurement results — G-weighted sound pressure levels (on the chart each bar specifies the range of the measured sound pressure levels).



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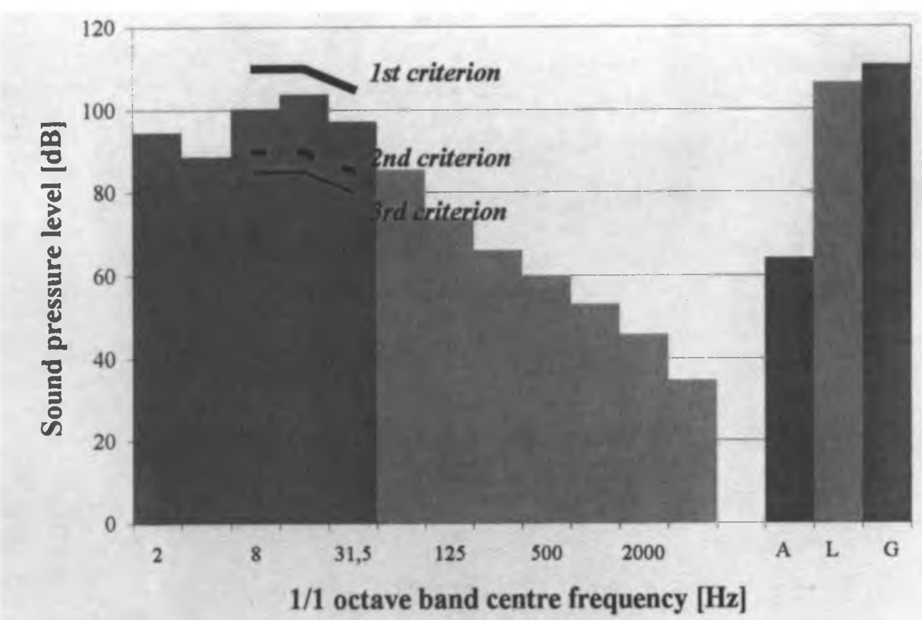
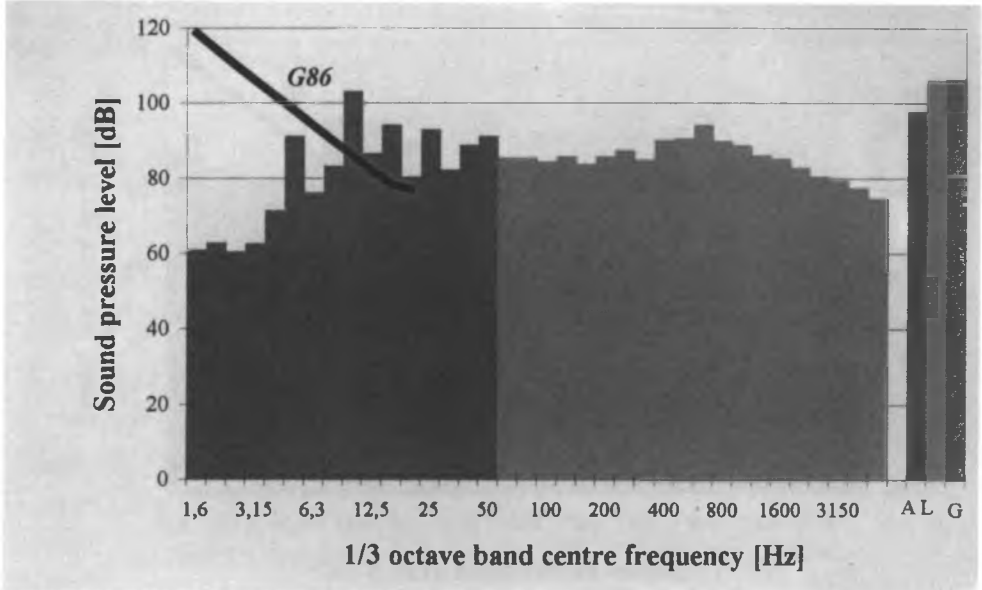


b)

Fig. 5. Broad-band noise measured inside a bus cabin (AG 405N Mercedes Benz) with closed windows; a) 1/3 octave frequency spectrum compared to the hearing threshold of infrasound (G86 curve), b) 1/1 octave frequency spectrum compared to the permissible levels of infrasonic noise established in Poland.



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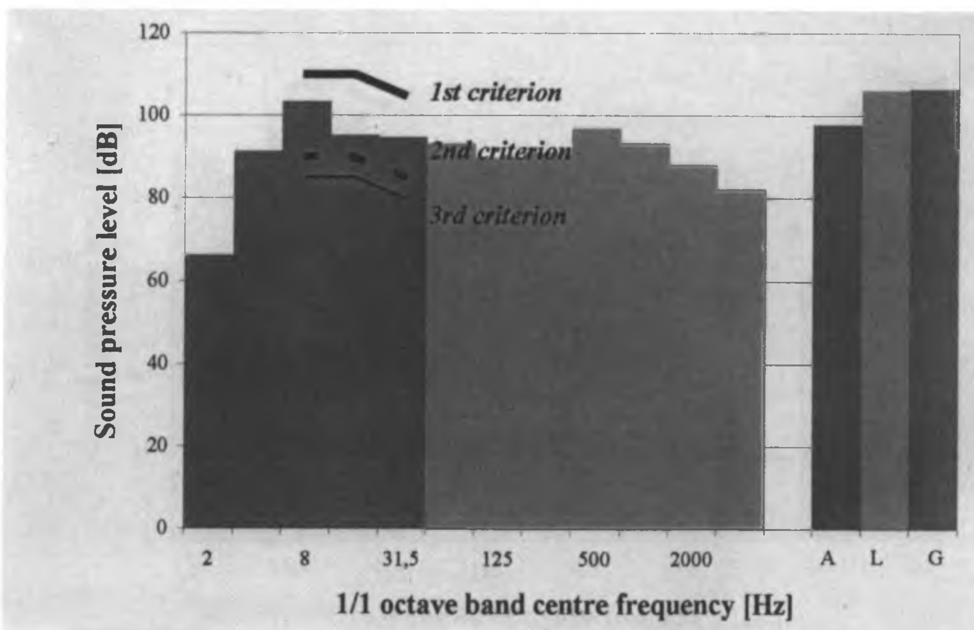
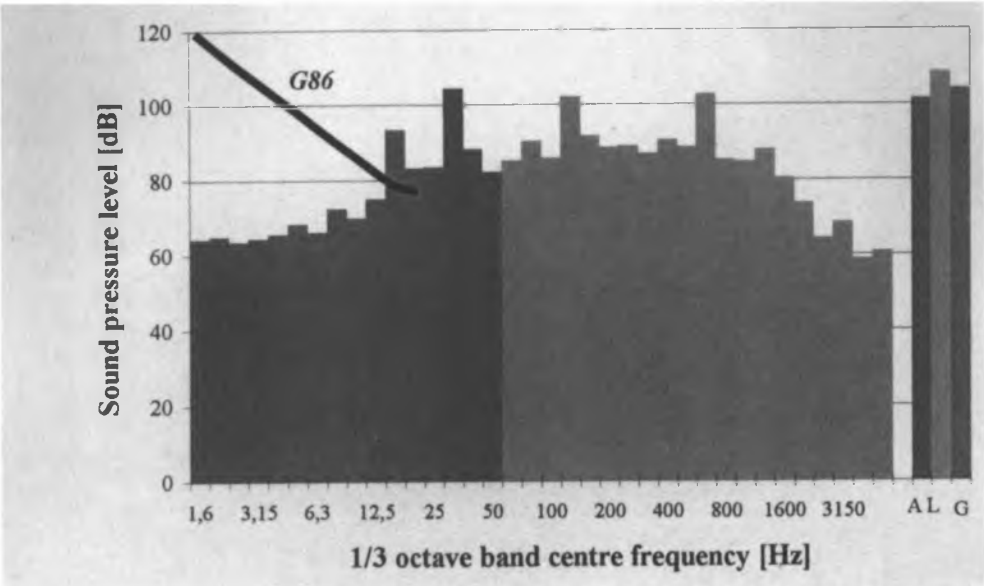


b)

Fig. 6. Broad-band noise measured around the vibrating grate type WKM-4;
a) 1/3 octave frequency spectrum compared to the hearing threshold of infrasound (G86 curve), b) 1/1 octave frequency spectrum compared to the permissible levels of infrasonic noise established in Poland.



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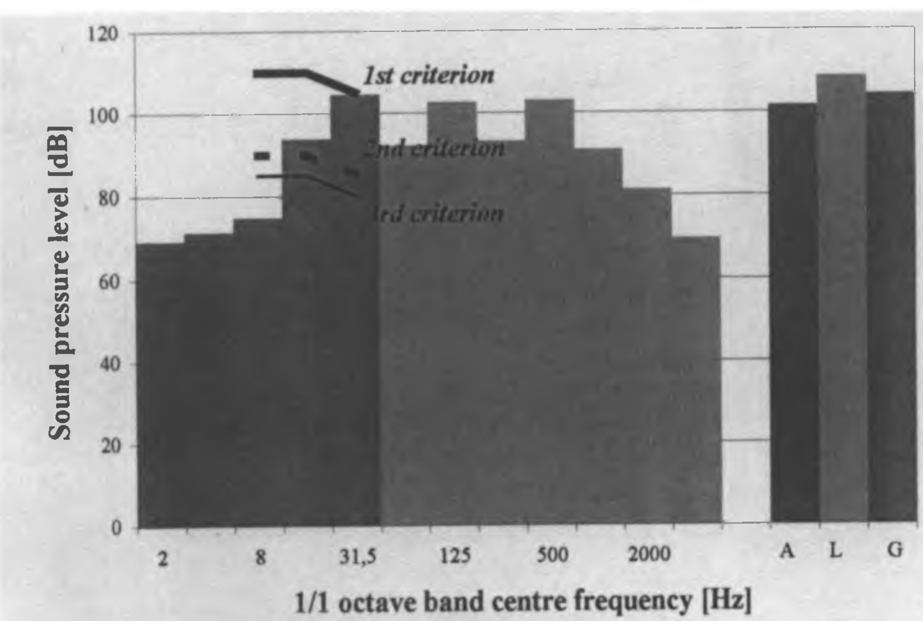
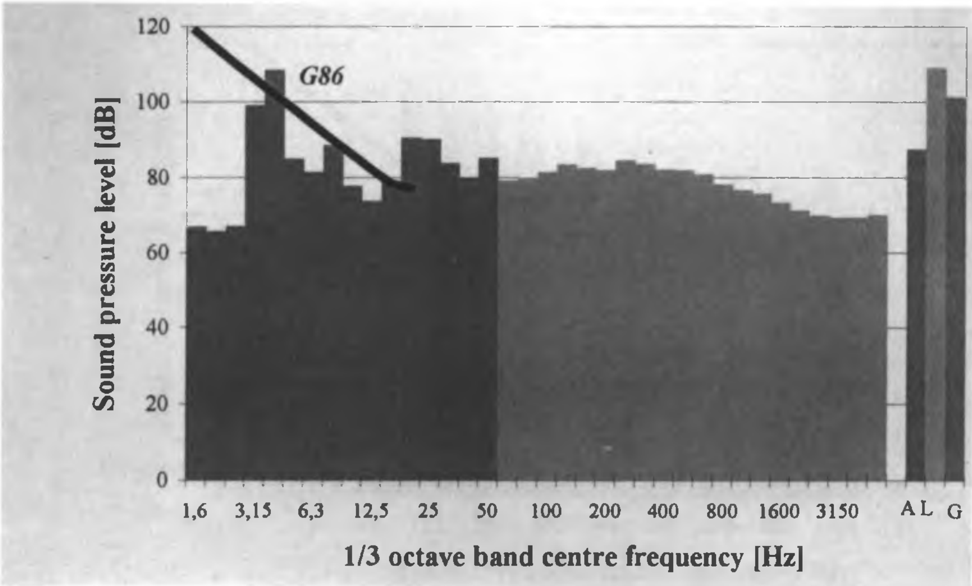


b)

Fig. 7. Broad-band noise measured around the Roots blower, HIBON, type DV 40;
a) 1/3 octave frequency spectrum compared to the hearing threshold of infrasound (G86 curve), b) 1/1 octave frequency spectrum compared to the permissible levels of infrasonic noise established in Poland.



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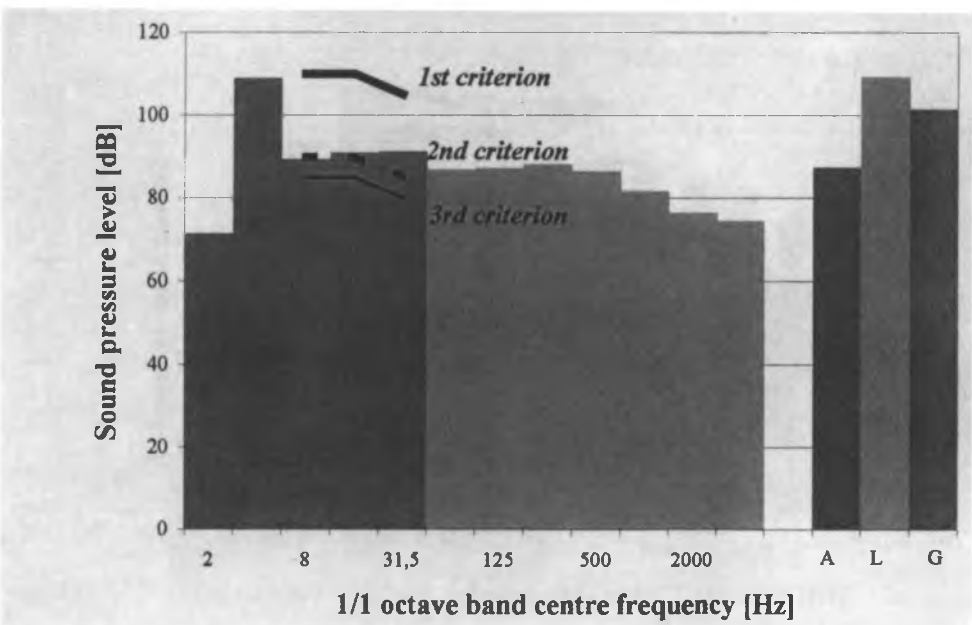

b)

Fig. 8. Broad-band noise measured around the flour vibrating screen;
a) 1/3 octave frequency spectrum compared to the hearing threshold of infrasound (G86 curve), b) 1/1 octave frequency spectrum compared to the permissible levels of infrasonic noise established in Poland.

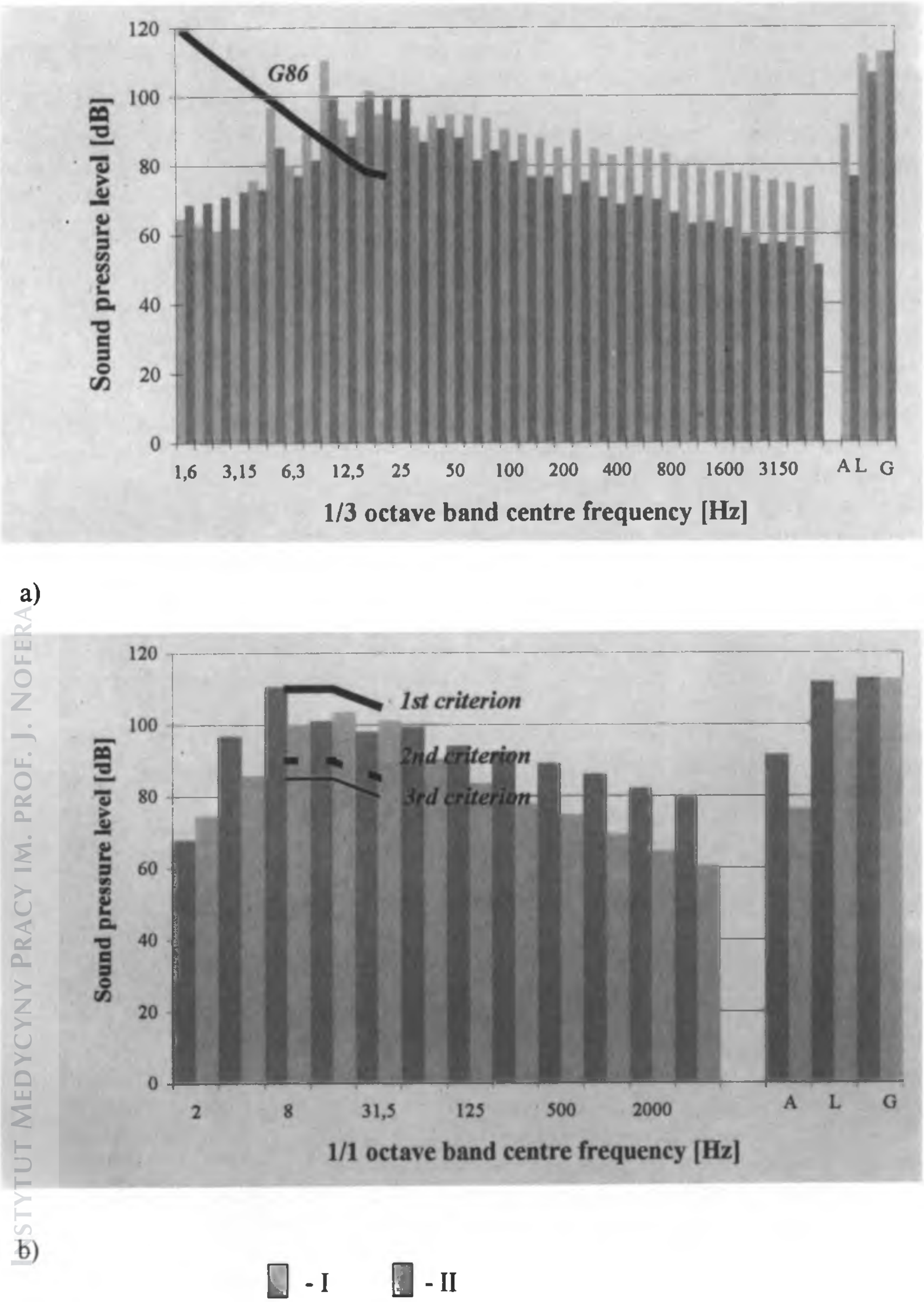

Fig. 9. Broad-band noise measured: (I) around the piston compressor type L-100N; (II) inside the cabin; a) 1/3 octave frequency spectrum compared to the hearing threshold of infrasound (G86 curve), b) 1/1 octave frequency spectrum compared to the permissible levels of infrasonic noise established in Poland.

and rest. The sound pressure levels measured inside the cabins appeared to exceed in 30.0% of cases the admissible levels which ensure proper conditions for performing basic functions in the observational dispatcher cabins.

Most cabins show a satisfactory noise reduction in the frequency range above 500 Hz. Although, in the frequency range 4÷31.5 Hz the difference between the sound pressure levels measured inside and outside the cabin remained within – 29÷9 dB (Fig. 9). The increase in the sound pressure levels (up to 9 dB) in the infrasound range observed in 70.0% of cases was a consequence of the resonant conditions and interference phenomena.

According to PN-86/N-01338 and the Ordinance of the Minister of Labour and Social Policy, except for taking into consideration the effective exposure time, the sound pressure levels in 1/1 octave bands 8÷31.5 Hz exceeding the values admissible for:

- workers' health protection – were found in 5 (4.0%) cases;
- ensuring proper conditions for performing basic functions in the observational dispatcher cabins etc. – in 77 (62.1%) cases; and
- administration premises, design offices etc. – in 92 (74.2%) cases.

The highest levels of the infrasonic noise were detected:

- around a L-100N piston compressor, 3M56 centrifugal compressor (near lubrication system), ELMO 2BEB03 vacuum pump, and HIBON DV40 Roots blower;
- in cabins of a W-110 road-roller and SM-3 diesel locomotive;
- during routine repair works in SU-45 diesel locomotive.

On the other hand, the lowest levels, below the admissible sound pressure levels, in administration premises, design offices etc. were found around frame mixers, basket centrifuges, chemical reactors, evaporator and drier, calanders, mixing rolls, roll press, monolith injection moulding machine and footwear press, turbogenerators and iron blast furnace.

CONCLUSIONS

The admissible sound pressure levels for workers' health protection specified in the Polish Standard PN-86/N-01338 and the Ordinance of the Minister of Labour and Social Policy are in fact the permissible levels for hearing protection, however they do not correspond with the hearing threshold of infrasound the G-weighting characteristic is associated with.

In our study, 66.9% of the industrial machinery and means of transport appeared to generate infrasonic noise at the levels exceeding the hearing threshold of infrasound (G86 curve). The exccess levels occurred mainly in the frequency range of 12.5÷20 Hz. Whereas, exposures exceeding the admissible sound pressure levels for workers' protection were found only in 4.0% of cases.

The Polish occupational hygiene standard concerning infrasonic noise ought to be verified. The recommendations of international standards (ISO 7196:1995 and ISO 9612:1997) concerning the measuring method should be taken into consideration, and permissible values of the sound pressure levels should be based on the threshold of auditory perception.

Of interest here is that the current Swedish occupational exposure limit values for infrasound (sound pressure levels in 1/3 octave bands in the frequency range from 2 to 20 Hz) exceed the hearing threshold by 5–10 dB (24). On the other hand, the application of the G75 curve as the permissible levels for 1/3 octave bands from 4 to 16 Hz was preliminary taken into consideration while preparing proposals for new Polish recommendations concerning low frequency noise in the dwelling* (15,16).

Our studies indicated that locomotives, lorries, buses and trams, road rollers, crafts (e.g. ferries, fish cutters), piston and centrifugal compressors, Roots blowers, vacuum pumps, open-heart furnaces, arc furnaces, vibrating grates, power moulding machines, ball and beater mills, power boilers, downcast and exhaust fans of power boilers, mine and windmill fans, and flour mils devices, especially flour vibrating screens are the most important sources of infrasonic noise. All of them generate infrasonic noise at moderate levels, but above the hearing perception threshold. Moreover, infrasound is very often concurrent with a number of other physical hazards, e.g. audible noise, whole body vibration or/and hand-transmitted vibration. It is also an important fact that in many situations of work performance, e.g. transport operations, there is a high degree of prolonged monotonous infrasonic noise exposure. This could be critical in inducing workers' fatigue and thereby constitute a safety hazard.

Owing to its long wavelength, infrasonic noise is less attenuated by walls and other structures, it is able to propagate over long distances and may affect the human organism even though the latter is far from its source. Earmuffs or other types of hearing protection for practical use have not yet been successfully developed. Infrasonic noise emission can be reduced through the insulation of the source, better maintenance of relevant machinery or active sound attenuation. The implementation of the active methods of noise control seems to be particularly promising.

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*Finally, in order to assess the noise spectra measured in dwelling, the A10 characteristics as the rating curve has been accepted. Its levels for 1/3 octave bands are determined by relation: $L_{A10}: 10 - K_A$, where: L_{A10}, sound pressure level (dB), K_A, relative response of A-weighting filter (dB) (15,16).

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