N76-16777

THE ISO STANDARD: "GUIDE FOR THE EVALUATION OF HUMAN EXPOSURE TO WHOLE-BODY VIBRATION"*

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INTRODUCTION

After 10 years of intensive work of Subcommittee 4, "Human Exposure to Mechanical Vibration and Shock," of the ISO Technical Committee 108 "Mechanical Vibration and Shock," the first international standard on human exposure to whole-body vibration has been accepted as an ISO standard (ref. 1). The ISO member bodies of 20 countries interested in this subject, including the United States, voted approval of this standard; two countries (USSR and UK) voted disapproval on technical grounds, although one of them (UK) issued basically the same document as a provisional national standard (BSI DD 32). The United States national vote was strongly in favor of adoption of this document as an ISO standard and as a national ANSI standard (29 in favor, 2 against); however, final submission of the document as an ANSI standard was delayed awaiting the outcome of the international deliberations. All U. S. Government Agencies with an interest in the area of human vibration exposure, including the Department of Transportation, were strongly in favor of the standard. As Chairman of the ISO subcommittee which prepared this document, I am gratified to see such unusually broad support for a document which tries to provide standard guidelines in an area where nothing existed and where data points and opinions were very far apart. The ISO standard stimulated, during its draft stages and during the short time of its existence, a large number of clarifying studies directed to fill in gaps in our knowledge or to support or refute positions adopted in the standard, and fostered international collaboration in this area to an unprecedented degree (ref. 2). This newly accumulated body of information must clearly be taken into account to understand fully the background of the present standard and future standardization plans. I am the first to admit that the present ISO standard is not completely satisfactory in all respects; every standardization, particularly on an international scale, involves technical compromises and compromises between judgements, and some of these will not satisfy everybody. On the other hand, the standard constitutes a tremendous step forward, giving for the first time positive guidance for most vibration exposure conditions incorporating the all-important exposure time as a factor. I can assure you that all decisions and compromises underlying the standard were made after prolonged deliberations taking into consideration the data, or the official comments by the various nations and the expert opinions of the subcommittee members. These

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experts were not only from different geographic locations, but they covered the spectrum of expertise interested in this area from the fields of medicine, physiology, and psychology; the various fields of engineering; the automotive, aircraft, shipbuilding, agricultural, and building industries; and, last but not least, the instrumentation field. Researchers and practitioners from industry as well as from government health departments, were represented. The standard which emerged had to be a compromise, not so much because no adequate data were available but because the large body of data available exhibited a considerable spread (refs. 3, 4, and 5). In most cases the reasons for the differences between the results can be explained by the differences between the experimental conditions and by the differences between the questions asked. Vibrations can act very differently on man; small changes in posture and support can change the effects considerably, and the effects themselves are manyfold and, when it comes to their evaluation, to some extent a matter of judgement. Considering all these variables, agreement of the data from various parts of the world is very good.

The purpose of the ISO effort was to obtain a valid, practical, and safe standard. The first two conditions mean that the standard should cover as many experimental data and practical situations as possible and that simplifications are desirable to facilitate the standard's use. The last condition calling for a safe standard means that if there is any doubt where the exposure limits should be, the more conservative (i.e., protective) interpretation be accepted. The introduction to the standard clearly states these basic philosophies and that it is not to be considered a standard setting firm limits but a general guide for the evaluation of vibration exposure with respect to various human responses. It is obvious that humans judge vibration exposures differently depending on the circumstances and the "benefit" derived from the vibration; they are accepted within certain limits in transportation vehicles because the transportation benefit outweighs the discomfort. The same vibration in a private home is intolerable. The standard tried to average over these differences as much as possible to make it as generally applicable as possible. The "discomfort boundaries" and "fatigue-decreased proficiency boundaries" apply generally to the transportation and industrial environment. For ships - or for the population electing to go on ships - they might be somewhat higher; for residential buildings they must be lower. The ISO working group is presently laboring on amendments to the standard providing much more detailed guidance for specific situations. For example, with respect to desirable vibration limits in various types of buildings such as industrial, residential, and hospitals, we are already close to agreement. But for all these special cases the frequency dependence and the time dependence of the human responses stay the same; the recommended boundaries as a whole are shifted up or down on the intensity scale. The measurement methodology, weighting, and reporting of the data, in other words the overall framework of the standard, remain unchanged. With the overall standard agreed upon as the best guideline available, it is very unproductive not to use it or to exercise any parochialism, be it as an individual, as an industrial branch, or as a country. It is important that the vibration environments of all industries and in all countries can be compared with one and the same measuring stick, even if the absolute boundaries selected as goals or specifications are different. As the standard states, one of its principal aims is to encourage, in comparable and reproducible form, the collection of further and better data. The progress achieved through the development and acceptance of this standard is easily demonstrated by the impressive amount of new information which became available in response to the various unofficial draft stages of the standard and now after its acceptance. This information, gathered in many countries, was essential in changing the drafts, in shaping the final form of the standard, and in getting confidence in its validity. (See refs. 6 to 10 and refs. in ref. 1.) Vibrations on tractors, in tanks, in automobiles, in aircraft, on ships, and in buildings were evaluated by means of the standard (ref. 2); frequently the boundaries recommended in the standard, and in some cases their time dependence, were confirmed by these new data. Any criticism of the standard based on arbitrary restriction to a narrow data base and on personal preference (ref. 11), without considering all evidence available and without being familiar with the recent publications in this field, is unjust and unprofessional.

COMMENTS REGARDING SOME OF THE DECISIONS UNDERLYING THE STANDARD

The basic foundations of the standard are the acceleration limits as a function of frequency and of exposure time. Let me make a few comments regarding each of these.

Curves of equal strength of perception as a function of frequency have been measured by many authors. (See refs. 4, 5, and 7 and refs. in ref. 1.) For longitudinal[1] vibrations they show maximum sensitivity, that is, a minimum acceleration required for constant sensation somewhere in the frequency range between 2 and 8 Hz. The width of this minimum changes with posture of the subject, type of sensation, and exposure time - to name just a few of the variables. Its position appears to change slightly with the same variables, the weaker sensations and the relaxed position having the minimum at somewhat lower frequencies. This range of maximum human sensitivity has been explained generally by the physical resonances of body parts and organs occurring in this frequency range (refs. 12 to 15). Although the range is frequently called the range of "principal body resonance", it has been well shown long ago that several "resonances" are involved. For example, for the erect sitting subject the strain in the lower abdomen peaks around 4.5 Hz; in the upper abdomen, at 5.5 Hz; and in the chest, at 6 Hz (refs. 14 and 15). (For the relaxed subject these curves change again.) A subject being asked to report equal strength of sensation or of discomfort does not report sensations in the abdomen, or chest, or head alone but equates the sensations from all receptors and reports one integrated response. This integrated sensation is at some frequencies predominantly determined by abdominal sensations; at other frequencies, by sensations in the chest; and at still higher frequencies, by sensations in the head (refs. 4 and 12). Therefore, measured curves of equal perception usually are not simple physical resonance curves, but at best - assuming that sensations in the different body areas are proportional to the

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[1][The term follows terminology used in ISO 2631, where longitudinal is defined as foot (or buttocks)-to-head (vertical).]

physical strain - envelopes to a whole series of resonance curves (ref. 14). Once this fact was established, it made the correlation of subjective tolerance curves with any parameter of a simple oscillator - be it strain or power - unlikely (ref. 13). Therefore, looking at a broad frequency range, curves of equal injury, tolerance curves, or curves of equal sensation are almost always "composite tolerance curves," that is, envelopes of the tolerance curves of several individual subsystems, each by itself having maximum sensitivity in a different frequency range. This knowledge also makes it theoretically very unlikely that curves of equal strength of human perception should be curves of equal mechanical power transmitted to the man and absorbed by him. As soon as more than one reasonating system is responsible for the curve of equal perception, and these systems are in series and not parallel, the absorbed power concept cannot be correct theoretically; for example, a very disturbing head resonance at higher frequencies leading to blurred vision is not appreciably reflected in the mechanical impedance at the seat-buttocks interface, which determines the power absorbed by the subject (ref. 16).

Since sometimes simple concepts work even if they are theoretically not fully correct, the absorbed power concept was tried out very early by Coermann (ref. 13) to explain subjective short-time tolerance curves and was found to be unsatisfactory to explain these curves. When Pradko and Lee (refs. 17 and 18) later revived this idea and made very detailed measurements of the vibratory power absorbed by human subjects, they unfortunately never presented adequate psychophysical or physiological evidence which correlated human response with absorbed power. Without such data the whole approach is a hypothesis not in satisfactory agreement with facts; and all attempts by some individuals to promote this concept have not produced the missing data and agreement and do not change the basic mechanical construction and response of the system man. The limitations and obvious dangers of adopting the concept of constant absorbed power are easily demonstrated by considering the frequency range below 1 Hz: The concept of constant absorbed power predicts increasing human tolerance with decreasing frequency ("constant jerk hypothesis"). Contrary to this prediction, it is well documented that human tolerance has a peak close to 1 Hz and drops off rapidly below 1 Hz (fig. 1) (refs. 19 to 21). Why? Because there is another resonance system in the body which has its maximum response below 1 Hz and results in the complex phenomenon of motion sickness. This system needs much less power to excite it to undesirable responses than the power required to excite the main body system in the frequency range for which the absorbed power concept appeared to be a reasonable approximation. As long as a hypothesis such as the concept of constant absorbed power can lead to such obviously wrong conclusions, it appears unwarranted to make it the basis for a standard.

For all the reasons discussed, the curves of constant perception (or frequency response curves) in the ISO standard are not curves of equal absorbed power or simple resonance curves, but reasonable envelopes to the experimentally observed curves of constant human response. Since these curves change with body posture and support, the final curve was selected as an envelope to most experimental results - arguing that the standard should protect the man against physical harm or undesired psychological responses regardless of whether he sits erect or relaxed on the vibrating seat and free or supported by a backrest.

The final shape of the longitudinal response curve (break points of the curve at 4 and 8 Hz) was then determined by the standardized frequencies for 1/3-octave band and octave band measurements of the vibration spectrum.

The curves of equal vibration perception for transverse vibration were less well defined than the ones for longitudinal vibration at the time the ISO work started. Fortunately, partly in response to the early ISO proposals, excellent and new results by Miwa (ref. 6) became available, supplementing earlier subjective transverse response curves by Dieckmann (ref. 22). Miwa also established the absolute relationship of the longitudinal to the transverse response curve by accurate psychophysical cross-matching of the perceptions in the two directions (ref. 23). (The data by Lee and Pradko (refs. 17 and 18) on transverse curves of constant absorbed power constitute interesting work, but were never considered to contain enough biological evidence upon which to base curves of equal subjective perception.)

The dependence of the acceleration boundaries on the exposure time deserves some comment too. It is true that experimental evidence of the dependence on exposure time of physiological tolerance limits and fatigue and comfort limits for vibration environments was very scarce at the time the standard was first drafted. However, it became obvious that the discrepancies between the absolute levels of recommended exposure criteria in use by different organizations and in different countries had their origin in the fact that exposure time was not taken into consideration (refs. 4 and 24). I compiled available information in 1964 for the ISO group and published it in 1965 (ref. 25): Short-time physiological tolerance decreased with time (observed from 20 sec to 3 min.); subjective judgement of intolerable exposures and working proficiency exhibited a decrease for exposure times from several minutes to 2 hr; subjective "fatigue" of railroad travelers occurred at lower vibration levels with increasing exposure time (reported for 20 min to 8 hr); and similarly, airline passenger comfort required lower levels with increasing exposure time (up to 1 hr). In addition, there was enough evidence that in residential homes the comfort limits are usually exceeded if the vibration levels are above the threshold of perception. This suggested a limit for continuous exposures of 24 hours per day. On the basis of these data, the dependence of the equal perception contours on the exposure time was introduced into the ISO standard. The same time dependence was assumed for physiological limits, fatigue-decreased proficiency, and comfort. The reason for this was that there was not too much latitude for these curves to be drastically different (the comfort boundaries should generally not cross the fatigue-decreased proficiency boundaries, by definition, and similarly the fatigue boundaries are not expected to cross the physiological exposure limits) and the standard had to be not too complex for operational use. One fact which is frequently overlooked has to be kept in mind: The recommended exposure times are for daily routine occupational (habitual) exposures for extended periods, even a lifetime. It is therefore difficult to compare these exposure times recommended for preventive medicine practices or for the prevention of malfunction and accidents due to the vibration environments with experimental laboratory findings. Laboratory tests usually employ a few healthy young subjects not exposed to vibration day in and day out. Therefore in any practical guidance a conservative approach was indicated - boundaries which would not recommend exposures to levels not proven as safe or not presently tolerated in practice. The long-term health effects from chronic exposure to high vibratio levels in some transportation vehicles are still an open question; however, evidence is strong enough to suggest that chronic effects on the musculoskelet system of vibration exposure from presently accepted vehicles cannot be overlooked (refs. 26 and 27). All these arguments spoke in favor of the adopted time dependence of recommended exposure.

Since the publication of the draft standard, several attempts have been made to prove or disprove the time-dependence function (refs. 8, 10, and 28). Data were collected with respect to equal fatigue curves under vibration as a function of exposure time. These data give some additional support to the time dependence selected by the standard (fig. 2). The suggestion to use, instead of the present ISO curve faired through the experimental data, a simila curve represented by a simple analytic expression (refs. 8 and 11), is a good and valid one and might well be adopted in a future revision of the standard without changing the results obtained with it in any appreciable way.

Other experiments concentrated on the one valid question and criticism with respect to the time-dependence concept in which I fully concur and which, by the way, was the main reason for the UK negative vote: It has never been shown by laboratory experiments that task proficiency and performance in general decrease with increasing exposure time. On the contrary, several experiments designed to investigate this question so far obtained a different answer; even 6 hr of vibration exposure did not result in a significant decrease in cognitive or manual performance capability (refs. 5 and 28). In addition, available data clearly show that it is almost impossible to generalize with respect to "performance" under vibration. The nature of the task has been shown to be extremely critical and time dependence must be expected to be related to the nature of the task under consideration. In spite of this it was decided to retain the time dependence not only for the fatigue boundaries, for which it was confirmed, but also for the otherwise identical decreased proficiency boundary. The argument for this decision is based on the experience that laboratory experiments hardly simulate daily, lifelong field exposure with respect to motivation; and if people report increasing fatigue with exposure time, the fatigue can result, at least in some individuals, in decreased motivation and increased error or accident potential. It also appeared unreasonable to recommend boundaries with respect to performance which would be above the fatigue limits and might even cross and be above the exposure limits adopted for health reasons. Such a standard would not fulfill its practical, preventive purpose.

Although stressed in several places in the standard, it might be worth a reminder again here: The disturbance of task performance in the vibration environment depends very much on the task required, and a large body of detaile information exists in the meantime on this subject (refs. 5 and 29). A promising open field in human engineering is the design of controls and display for minimum interference by vibration (ref. 2). Guidelines for this are available. The "decreased proficiency" curves in the standard provide, therefore, some very general guidance only and might have to be moved up or down depending upon the specific task, the man-machine interface, and the reliability required. (On the other hand, these curves should not be above the exposure boundaries except for unusual conditions.)

Finally, it is completely misleading to state, as some self-appointed interpreters of the standard do (ref. 11), that the ISO standard presents the "fatigue-decreased proficiency" boundaries as the "primary limits," or that the ISO group first decided on the "reduced comfort" boundaries and then selected the other boundaries "by arbitrarily multiplying these values" with the recommended factors to obtain the other boundaries. Let me assure you, there was nothing "arbitrary" about it. In the evolvement of the overall framework and the recommendation of specific boundaries as a function of frequency and exposure time, equal consideration was given to the data accumulated for each of the three perception criteria selected for characterizing recommended exposure levels: The "exposure limit" for health reasons, the "fatigue-decreased proficiency" boundary, and the "discomfort" boundary. If there was anything arbitrary about this, it was the desire to arrive at a practical, useful, and safe standard on which the majority of the experts could agree.

FUTURE WORK ON VIBRATION EXPOSURE STANDARDS

The ISO standard has found wide application in the shipbuilding, aircraft, automotive, and building industries (ref. 2). The U. S. Department of Defense and many countries made it the basis for their military specifications (ref. 30). The standard is being used as the basis for the international activities on tractor seat testing (proposals from the O. E. C. D. Committee and from ISO/TC23/SC3) and for national recommended practices (refs. 31 and 32). For practical evaluations and comparative tests the single-number characterization (frequency weighting) methodology by way of frequency weighting networks ("ride meter") is generally preferred (ref. 31), which the standard proposes as an approximation. The fear is justified that if this were the sole methodology for assessing vibration exposure (some countries propose already to standardize such a meter), no spectral information on the various occupational environments would become available and further research data on the correlation of human response with the spectrum of the environment would not be forthcoming. For these reasons it does not appear desirable to standardize too early on a general vibration exposure meter (which would probably require narrower tolerances than presently proposed in the standard, an accuracy perhaps not yet justified), although such a meter definitely has its place for the testing in specific industries. When more experience has accumulated, such a vibration exposure meter should be internationlly standardized.

The ISO Subcommittee on Human Exposure to Mechanical Vibration and Shock is presently working on several projects, some of which are closely related to the standard under discussion (ref. 20):

(a) A document on the evaluation of vibration in buildings (including acceptable acceleration ranges for various uses) is nearing completion and will soon be distributed for vote and comment. This document provides for longitudinal and transverse vibration to be evaluated, if desired, by a combined, averaged weighting function. Justification for this was the argument that in buildings the same environment can act on man in all directions (upright and in the horizontal position) and the expressed desire of the industry to have in addition to the existing standard a simple, single-figure evaluation method.

(b) An amendment or appendix to ISO 2631-1974 (E), which we hope is clc to completion, provides some guidance for the frequency range 0.1 to 1 Hz with respect to motion sickness and equal sensation contours (ref. 19). (It will probably be decided as too controversial to continue the reduced comfort or other boundaries from the higher frequency range below 1 Hz with the same designation, since the definition and causes of discomfort due to motion sickness are too different from the phenomena above 1 Hz.) The guidance might be similar to the information presented in figure 3.

(c) A standard document defining whole-body impedance curves for human subjects will soon be released by the subcommittee for official comments by the ISO countries (ref. 20). The curves are to be used as nominal impedance curves for design and testing and are supplemented by biodynamic models exhibiting the same impedance curves as the human body. Vibration transmission through the body is on the agenda for future working group meetings.

(d) A draft proposal for "Guide for the Evaluation of Human Exposure to Hand-Transmitted Vibration" has seen at least three or four revisions and is being circulated again to the subcommittee for comments and vote (ref. 20). International agreement is difficult to achieve, since several countries alrea have standards or guidance not in agreement with each other or in agreement with present thinking. On the other hand, international guidance and agreement are urgently desired because of the active trade in power tools, such as chain saws, for which the measurement and definition of permissible limits of hand-transmitted vibration, according to an international standard, is highly desirable.

(e) A standard terminology on human shock and vibration exposure is in preparation and is planned for issue as an independent standard and also for incorporation into the general ISO/TC108 "Shock and Vibration Terminology", which is in preparation. This work will be followed by a separate draft document on "Biodynamic Coordinate Systems."

(f) In addition to the efforts listed in the area of human vibration exposure, several documents on human impact testing and evaluation are in preparation.

This list of projects is by no means complete, and I hesitate to predict how soon any of these efforts may result in an approved ISO standard. Comment received through the process of official international circulation can frequently influence or change subcommittee plans and new data might turn up not considered during working group deliberations. All such comments will be carefully evaluated and every effort will be made to obtain as broad support as possible by the international community. This process might not only involve technical changes to the proposed documents but also changes in the overall plans and packaging of the documents. For example, if the planned amendments to ISO 2631, addressing the frequencies below 1 Hz and the vibratio in buildings, should be delayed too long, the subcommittee might consider not issuing such separate documents but incorporating all these amendments into a future revision of the basic guide for the evaluation of human exposure to whole-body vibration. This future revision will also include, in all likelihood, more specific guidance with respect to exposure boundaries for specific situations or industries, such as ships, shops, and tractors. However, more field data on environments and on human responses are desirable to take this step with confidence. In the meantime it is important that these field data be collected and reported uniformly and consistently. The present ISO standard plays an important role in this process. Ongoing investigations will not only result in practical field experience with the standard but will also give new data on problems such as the accuracy of the weighting vs. the rating approach; on single-frequency, multiple-frequency, and random vibrations; on simulataneous multiple-axis vibrations; and on the important problem of impulsive-type vibration, that is, vibrations with a crest factor greater than 3. Data for the establishment of boundaries for rotational vibrations might become consistent enough for inclusion. For all these problems the present standard does not yet give the ultimate answer, but it gives coherent guidance consistent with present knowledge and with sound preventive practices. The ISO subcommittee monitors all these areas and is ready to incorporate any new generally accepted evidence into a future revision of the standard.

Another effort of interest might be mentioned: In its work Subcommittee 4 found it desirable to have standardized environmental inputs available which would be representative of typical field environments imparted by road vehicles, off-the-road vehicles, ships, aircraft, and so forth. At the Subcommittee's request, Technical Committee 108 organized a special working group (ISO/TC108/WG9, "Generalized Road Vibration Inputs to Vehicles"), which has already circulated a draft document for comment proposing standardization of the description and characterization of generalized road, runway, or field inputs into the transportation vehicles. This permits standard description of the quality of these surfaces with respect to vibration generation and will assist in the uniform specification, design, and evaluation, with respect to human response, of such systems and their components.

CONCLUDING REMARKS

In summary, I hope the foregoing remarks provided assurance that

1. The present ISO "Guide for the Evaluation of Human Exposure to Whole-Body vibration" is based on all relevant information presently available and reflects the best judgement of all international experts and all disciplines involved.

2. Advancement in the state-of-the-art is most rapidly achieved by data collection and reporting according to this standard, a proposal which should not stifle parallel research on new approaches and methodologies.

3. Work is continuing to amend and improve this standard as soon as warranted by new data, and everyone is encouraged to submit such data and participate constructively in the standardization process.

4. For the present time the evaluation of vibration environments, occupational as well as recreational, and the testing of equipment and machinery with respect to its effects on man are best accomplished by means of the existing standard to protect man against undesirable effects on his health, safety, performance, and comfort.

REFERENCES

1. "Guide for the Evaluation of Human Exposure to Whole-Body Vibration" International Standard ISO 2631-1974(E).

2. H. E. von Gierke, ed.: "Vibration and Combined Stresses in Advanced Systems". AGARD-CP-145, 1975.

3. Guignard, J. C. and P. F. King. "Aeromedical Aspects of Vibration and Noise," AGARD AG-151, NATO/AGARD (NTIS, Springfield, VA) 1972.

4. Goldman, D. E., and von Gierke, H. E.: "Effects of Shock and Vibration on Man," in Harris, C. M., and Crede, C. E. (eds): Shock and Vibration Handbook, New York: McGraw-Hill Book Co., Inc. 1961.

5. Hornick, R. J. "Vibration" in Bioastronautics Data Book 2nd ed. (Parker, J. F. and V. R. West eds) NASA SP-3006, NASA, Washington D. C., 1973.

6. Miwa, T.: "Evaluation Methods for Vibration Effect. Part 1: Measurements of Threshold and Equal Sensation Contours of Whole Body for Vertical and Horizontal Vibrations." Ind. Health, 5 (1967) pp. 183-205.

7. Miwa, T: "Evaluation Methods for Vibration Effect. Part 6: Measurements of Unpleasant and Tolerance Limit Levels for Sinusoidal Vibrations." Ind. Health, 6 (1968) pp. 18-27.

8. Simic, D. "Contribution to the Optimization of the Oscillatory Properties of a Vehicle: Physiological Foundations of Comfort During Oscillations," Dissertation D.38, Technical University, Berlin, West Germany (1970); Royal Aircraft Establishment Library Translation No. 1707, R.A.E. Library, R.A.E. Farnborough, Hants, U.K.

9. Splittgerber, H.: "Die Einwirkung von Erschuetterungen auf den Menschen in Gebaeuden." Technische Uberwachung Bd. 10, Nr. 9, pp. 325-330 (1969).

10. Miwa, T., Y. Yonekawa and A. Kajima-Sudo: "Measurement and Evaluation of Environmental Vibrations: Part 3, Vibration Exposure Criteria," Ind. Health, 11 (185-196) 1973.

11. Janeway, R. N. "Human Vibration Tolerance Criteria and Application to Ride Evaluation," SAE Paper 750166, SAE Automotive Engineering Congress, Detroit, Mich 24-28 Feb. 1975.

12. Magid, E. B., R. R. Coermann, G. H. Ziegenruecker: "Human Tolerance to Whole Body Vibration: Short-time, One Minute and Three-Minute Studies," Journ. Aviation Med. 31 (915-924) 1960.

13. Coermann, R. R. "The Mechanical Impedance of the Human Body in Sitting and Standing Position at Low Frequencies" in Human Vibration Research (S. Lippert ed.) Pergamon Press, 1963.

14. Von Gierke, H. E. and R. R. Coermann. "The Biodynamics of Human Respons to Vibration and Impact," Indust. Med. Surg., 32(1) (30-32) 1963.

15. Clark, W. S., K. O. Lange and R. R. Coermann. "Deformation of the Human Body Due to Uni-directional Forced Sinusoidal Vibration" in Human Vibration Research (S. Lippert ed.) Pergamon Press, 1963.

16. Payne, P. R. and E. G. U. Band. "A Four-Degree-of-Freedom Lumped Parameter Model of the Seated Human Body," AMRL-TR-70-35, Wright-Patterson, AFB, Ohio, 1971.

17. Pradko, F., and Lee, R. A.: "Vibration Comfort Criteria." SAE-Paper 660139 (1966).

18. Lee, R. A. and F. Pradko: "Analytical Analysis of Human Vibration," SAE Paper 680091, 1968.

19. Allen G., "Proposed Limits for Exposure to Whole-Body Vertical Vibration, 0.1 to 1.0 Hz," in AGARD-CP-145, 1975.

20. Von Gierke, H. E. "Standardizing the Dynamics of Man." In publication, Shock and Vibration Bulletin 1975.

21. Shoenberger, R. W. "Subjective Response to Very Low Frequency Vibration, AGARD-CP-145, 1975.

22. Dieckmann, D.: "Einfluss horizontaler mechanischer Schwingungen auf den Menschen." Int. Z. angew. Physiol. Einschl. Arbeitsphysiol. 17 (195 pp. 83-100.

23. Miwa, T: "Evaluation Methods for Vibration Effect. Part 2: Measurement of Equal Sensation Level for Whole Body Between Vertical and Horizontal Sinusoidal Vibrations." Ind. Health, 5 (1967) pp. 206-212.

24. Von Gierke, H. E. and E. P. Hiatt. "Biodynamics of Space Flight" in Progress in the Astronautical Sciences (S. F. Singer ed.) Vol. 1 North-Holland Publishing Co., Amsterdam 1962.

25. Von Gierke, H. E.: "On Noise and Vibration Criteria." Arch. of Environmental Health 11 (1965) pp. 327-339.

26. Braunohler, W. N. "The Effect of Vibration on the Musculoskeletal System. In AGARD-CP-145, 1975.

27. Dupuis H. "Zur Physiologischen Beanspruchung des Menschen durch Mechanische Schwingungen" Fortschr.-Berichte VDI-Zeitschrift Reihe 11 (7) (1-68) 1969.

28. Wilkinson, R. T. "The Effects of Duration of Vertical Vibration Beyond the ISO "Fatigue-Decreased Proficiency" Time on the Performance of Various Tasks." In AGARD-CP-145, 1975.

29. Shoenberger, R. W. "Human Response to Whole-Body Vibration," Perceptual and Motor Skills, 1972, 34, 127-160 (Monograph Supplement 1-V34).

30. MIL-STD-1472A "Exposure Criteria for Whole Body Vibration" May 15, 1970.

31. "Measurement of Whole Body Vibration of the Seated Operator of Agricultural Equipment" - SAE J1013, SAE Recommended Practice, SAE Handbook, Part 2, 1974.

32. Allen, R. E. "Limits of Ride Quality Through Cab Isolation," SAE Paper 750165, 1975 SAE Annual Automotive Engineering Congress, Feb. 24-28, 1975, Detroit, MI.

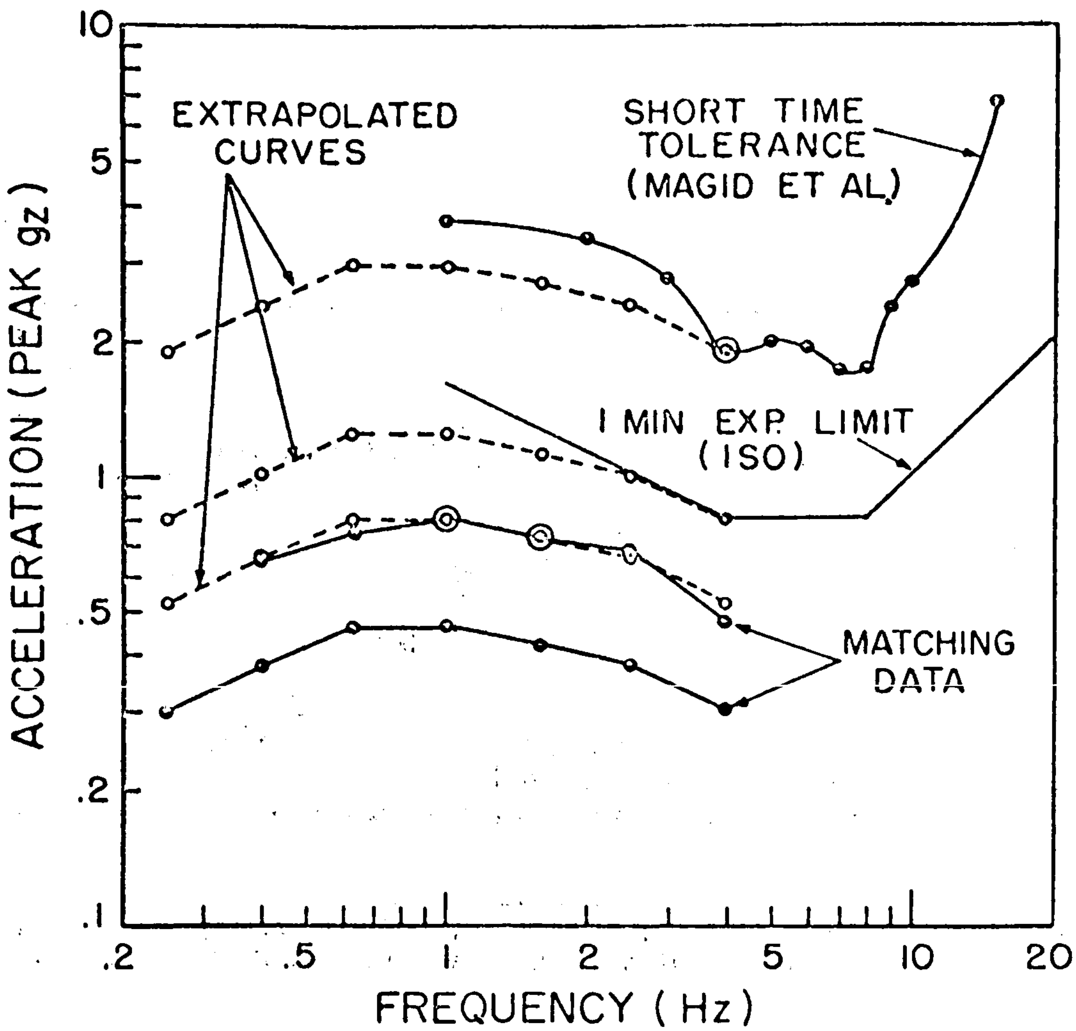

Figure 1.- Curves of equal subjective vibration (g_z) intensity (0.25 to 4.0 Hz). Each match involved a 30-sec exposure at the standard frequency of 1 Hz and at the matching frequency. The extrapolated dashed curves were obtained by magnitude estimation tests at constant frequency. (See ref. 21 for detailed procedures.) The curves are compared with the tolerance data by Magid et al. (ref. 12) and the slope of the ISO Standard curves.

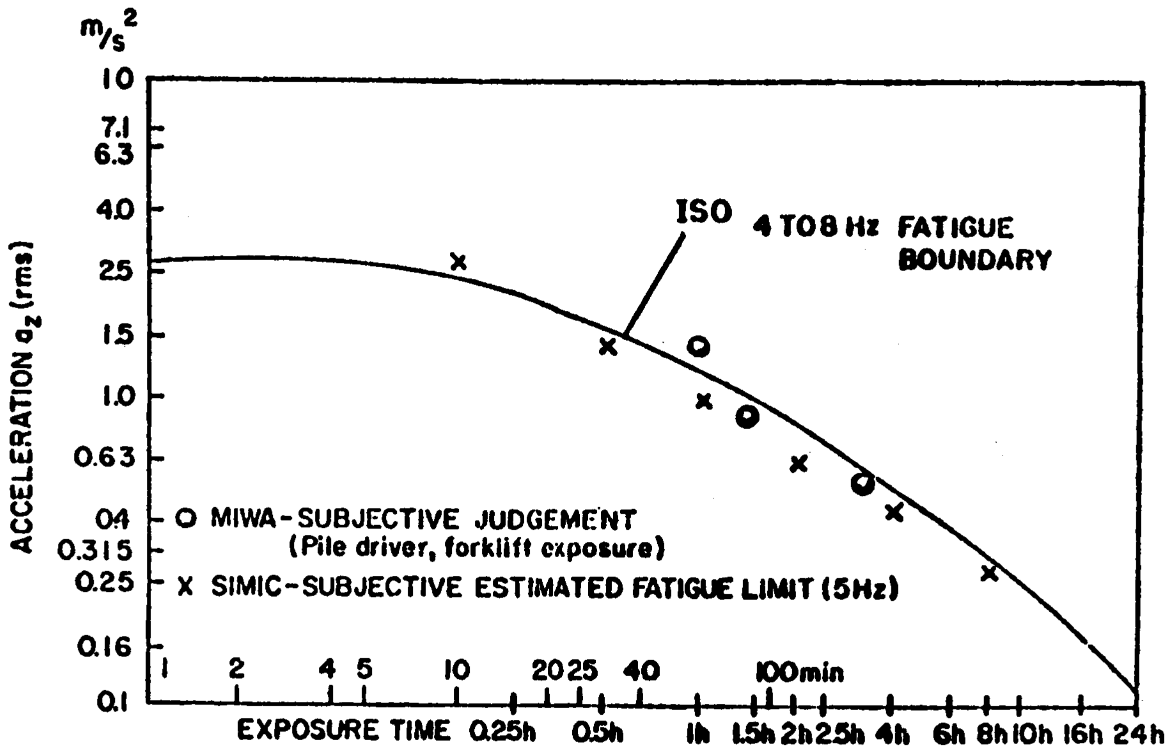

Figure 2.- Subjective judgement of equal fatigue compared with the ISO Standard curves (based on refs. 8 and 10).

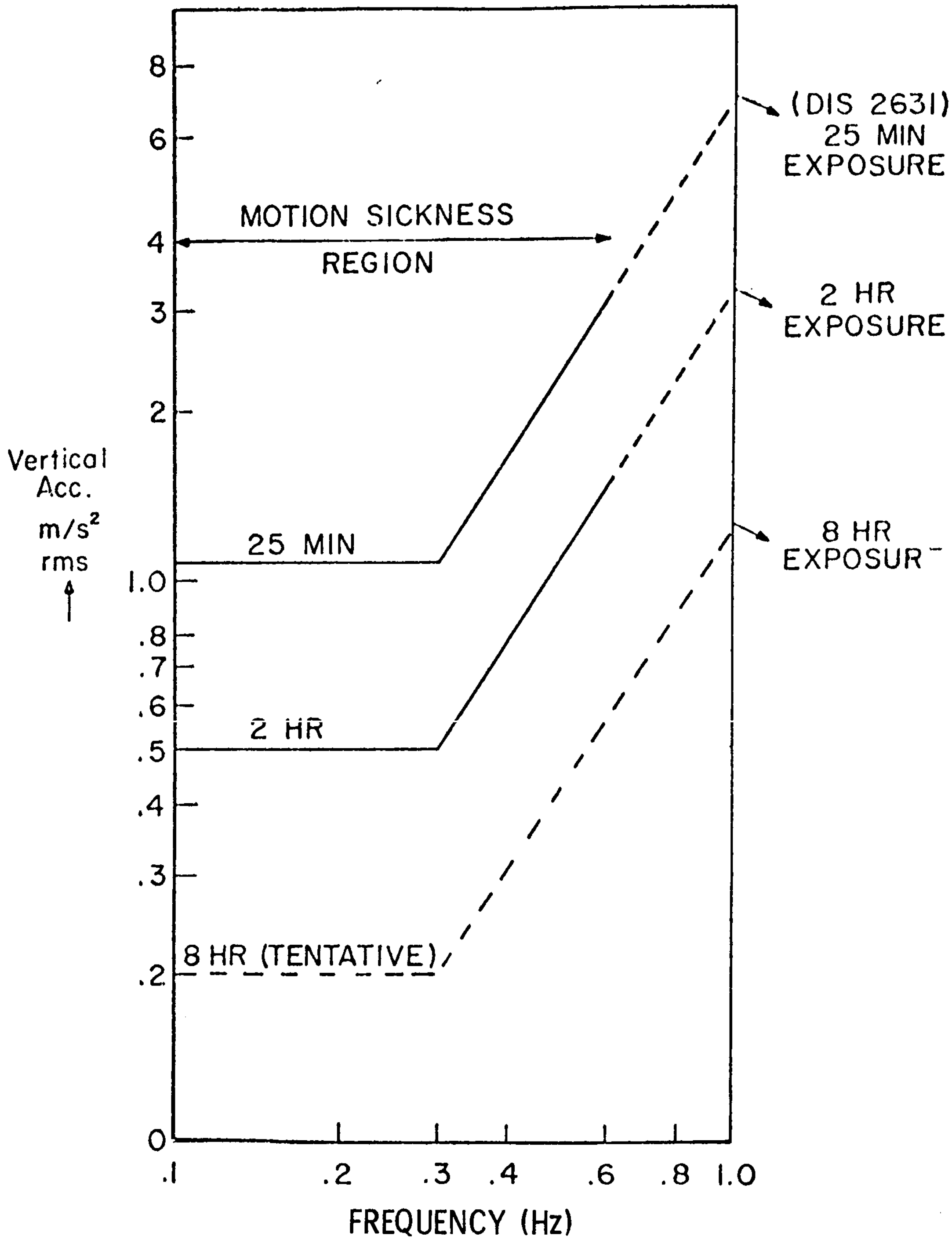

Figure 3.- Proposed "severe discomfort boundaries" for the 0.1 to 1 Hz frequency range (ref. 19). The curves are primarily based upon all available motion-sickness data. (The curves of equal subjective short-time intensity perception (fig. 1) would result in slightly more shallow slopes.)