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ANALYSIS OF PROPOSED CRITERIA FOR HUMAN RESPONSE TO VIBRATION

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SUMMARY

The development of criteria for human vibration response is reviewed, including the evolution of the ISO Standard 2631. The latter document is analyzed to show why its application to vehicle ride evaluation is strongly opposed.

The criticisms are directed not only at the specific limits given for comfort; they extend also to the setting of arbitrary limits for "fatigue-decreased proficiency," together with their decrements as a function of exposure time.

Alternative vertical and horizontal limits for comfort are recommended in the ground vehicle ride frequency range above 1 Hz. These values are derived by correlating the 'absorbed power' findings of Pradko and Lee with other established criteria. Special emphasis is placed on working limits in the frequency range of 1 to 10 Hz since this is the most significant area in ground vehicle ride evaluation, as well as that of greatest diversity from the ISO Standard.

INTRODUCTION

It is most opportune that this Symposium should be called at this particular time. On the one hand, the demand has crystallized for a reliable guide to vehicle ride quality; on the other, there is a pronounced risk that improper criteria, once adopted, may become firmly rooted in practice.

It is this writer's belief that such a risk is presented by the now adopted ISO Document ISO/DIS #2631 (ref. 1) as an International Standard and by the efforts under way to have it adopted as a U.S. Standard. Already, it is evident that the ISO criteria are being applied in a number of important current ride development projects.

One of the objectives of this paper is to discourage the use of the ISO Standard in its present form; the reasons for this opposition are fully documented. The primary objective, however, is to present an alternative set of criteria for application specifically to ground vehicle ride evaluation.

The writer has been actively engaged in the analysis of data on human response to vibration for many years. For the last fourteen years, as SAE

representative on the ANSI S3 Committee and a member of its Working Group on Vibration Levels, he has participated in the consideration of all the material submitted by the ISO and others, and has contributed new data to the Group.

Most recently, in February of this year, the writer presented to the SAE a paper on "Human Vibration Tolerance Criteria and Applications to Ride Evaluation" (ref. 2). Some of the latter material is included in this paper, but other data are presented here for the first time. In all cases, attention will be concentrated on the frequency range of 1 to 20 Hz, since this is the principal area of interest in ground vehicles, as well as the area of greatest diversity among the various criteria proposals.

SYMBOLS

a	vibration displacement amplitude, m
A	vibration acceleration, g
f	frequency, Hz
g	acceleration of gravity
j	jerk (peak rate of change of acceleration), m/sec^3
K	absorbed power constant, $\text{watts}/\text{m}^2/\text{sec}^4$
n	exponent, $y = x^n$
t	time, min
v	vibration velocity
W	watts
P	absorbed power, watts

BACKGROUND OF CRITERIA DEVELOPMENT

Vertical Vibration

Janeway Analysis, 1948.- In 1948, this writer presented a paper to the SAE on "Vibration Limits to Fit the Passenger" (ref. 3; see also ref. 12, pp. 25-26). This was based on an analysis of all the experimental data on human subjective response to vertical vibration that had been published up to that time.

Superficially, these data appeared to be largely contradictory, with no consistent trends. Analysis based on correlation according to the various

derivatives of the imposed sinusoidal vibration revealed definite characteristics depending on the frequency range. The discrepancies among the results of the different investigators were evidently due to wide variations in the precision of their experimental equipment and, especially, in the intensity levels imposed on their subjects.

Figures 1 and 2, reproduced from the 1948 paper, show individual plots against frequency of the peak jerk and acceleration, respectively, obtained for constant response.

In figure 1 it will be seen that, in only one instance, did the jerk increase at all in the range of 1 to 6 Hz, namely, in the Meister extreme discomfort curve. In all other cases, the jerk either remained constant or decreased in this frequency range. The Meister data were judged to be the most reliable (a) because all observations were given, and (b) because he was the only investigator who actually ran his tests down to 1 Hz. The three lines labeled "Meister" were given as the boundaries determined for the most sensitive subjects, rather than for the average responses.

In arriving at a recommended 'jerk' limit, the established practice of the Otis Elevator Company in controlling elevator acceleration and deceleration proved most useful. Figure 3 shows the characteristic patterns developed by Otis to ensure the comfort of elevator passengers, separately for each derivative of the motion. Note that the maximum jerk is limited to 10.9 m/sec^3 over $1/4 \text{ sec}$. (This compares with Meister 'uncomfortable' at $18.3\text{--}21.3 \text{ m/sec}^3$.) The corresponding maximum acceleration limits were $1.8\text{--}2.7 \text{ m/sec}^2$.

Reference to figure 4 for simple harmonic (sinusoidal) motion shows that at 1 Hz a 5.1 cm amplitude produces "jerk" peak of 12.5 m/sec^3 , but a mean jerk of 10.9 m/sec^3 over $1/4 \text{ sec}$, and a peak acceleration of 2.0 m/sec^2 , both values being close to the Otis criteria. This jerk value was also well below the Meister "uncomfortable" level. Therefore, this condition (5.1 cm amplitude at 1 Hz) was adopted as a safe limit to recommend for vehicle passenger comfort in the 1 to 6 Hz frequency bracket, with allowable amplitude diminishing as $a = 2/f^3$.

Reference to figure 2, showing the plot of the peak acceleration data, indicates a general trend to a constant acceleration in the 6 to 20 Hz range, for a constant response at the "uncomfortable" or higher level. The acceleration value corresponding to the constant 'jerk' peak of 12.5 m/sec^3 at 6 Hz is $\text{acc} = \frac{12.5}{2\pi \cdot 6} = 0.33 \text{ m/sec}^2$ or $af^2 = \frac{2}{6} = \frac{1}{3}$. This compared with $af^2 = 0.5$ at 6 Hz for Meister uncomfortable response. Thus it appeared to be a safe margin and was adopted as a recommended constant peak acceleration limit from 6 to 20 Hz.

It is of particular interest to note that Meister's "strongly noticeable" line shows a minimum acceleration at 5 Hz and a sharply increasing value as the frequency increases. It will be seen that this characteristic has been demonstrated by later data to be valid at the higher response intensities.

A possible explanation for the observed leveling off of allowable acceleration at the higher intensities is the additional input due to noise generated by mechanically driven vibrating platforms as the amplitude increased at the

higher frequencies. The acoustic input to the subject has been eliminated in the later experiments with sophisticated electromagnetic or hydraulic-driven vibrating platforms.

The effect of the constant acceleration value selected in the original recommendation is shown in figure 2 to have increased the margin of safety below the Meister "uncomfortable" level until at 20 Hz the indicated response was at the "strongly noticeable" level. This was a deliberate judgment factor, in the absence of exposure data, on the basis that vibration at the higher frequencies tends to be longer sustained.

Above 20 Hz all investigators showed a definite tendency for a constant vibration velocity to produce a constant response. This has been borne out by the later work, at least for vertical vibration.

ISO Standard Evolution.- Starting in 1964, the International Standards Association initiated a proposal for a standard on "Thresholds of Mechanical Vibration and Shock Acceptable to Man." Figure 5 shows graphically the several steps in the evolution of the vertical criteria, as now adopted.

The initial criterion was based on Dieckmann and characterized by a constant acceleration line from 1 to 11 Hz at 0.063 g (rms), followed by a constant velocity line for frequencies above 11 Hz. As a result of strenuous objections to this proposal, which was patently erroneous at low ride frequencies, the ISO Group offered a series of compromises, as follows (referring to figure 5):

1. At 1 Hz, the short term comfort level was raised to 0.12 g (rms); from 1 to 2.8 Hz, the tolerance was reduced according to the relation, $acc \propto 1/\sqrt{f}$, giving a value of 0.07 g at 2.8 Hz. This value was then carried as a constant criterion up to 11 Hz; a constant velocity line was then extended from 11 Hz to the higher frequencies (von Gierke, proposal 166).
2. The final step raised the allowable comfort acceleration to 0.14 g at 1 Hz but retained the previous relationship with frequency, which was extended to 4 Hz where it intersected the previous constant acceleration line. The latter was then cut off at 8 Hz, at which point the acceleration again rose with increasing frequency along a constant line ($acc \propto v_c f$).

The latter modification obviously increased substantially the indicated tolerance above 8 Hz. What is more important, however, the ISO vertical criterion, by rejecting the constant jerk response at 1 to 5 Hz, is believed to be much too permissive at precisely the frequencies to which the human body is most sensitive. In this connection, it may be noted that the vertical vibration frequency range of 4 to 6 Hz has been established experimentally as the area of resonance with the human viscera (ref. 4).

For purposes of comparison, the vertical criterion recommended by the writer has been superimposed in figure 5. The so-called "comfort" limit of the

ISO Standard is shown to be at least twice the "recommended" value, in the range of 4 to 6 Hz. This will be discussed more fully in a later section.

Absorbed Power Concept.- In the 1960's, Fred Pradko and Richard Lee, of the U.S. Army Tank-Automotive Command, Mobility Systems Laboratory, carried out a unique series of vibration experiments on human subjects, using the most sophisticated equipment and experimental techniques. It is this writer's belief that this investigation and, especially, the brilliant analysis of their results, constitute the greatest contribution to date to our knowledge of human responses to vibration.

The equipment consisted of a hard, flat chair which could be vibrated in five separate degrees of freedom, namely vertical, horizontal (lateral and longitudinal) and angular pitch and roll, about axes through the seat base. The vibratory motion was imposed by servo-mechanisms controlled by an oscillator which could generate any desired wave form and intensity either periodic or aperiodic. The instrumentation measured not only the subject's acceleration, but also the phase relation between the input and output motions, and the "absorbed power" or rate of energy absorption internally by the subject's body in resisting the induced vibratory motion.

By correlation with the subjective responses, Pradko and Lee arrived at the conclusion that the subjective response is a function of the "absorbed power" and consequently, that a constant absorbed power corresponds to a uniform degree of subjective response. To the extent that absorbed power is a valid indicator of human response, its discovery means that the objective measurement of response now becomes possible for the first time. It follows that the quantitative findings are bound to be much more precise than any subjective determination.

Moreover, since energy and power are scalar quantities, as opposed to vector quantities, they proposed that the resultant response to a complex vibration can be measured by directly summing the power absorbed by each directional component of the imposed vibration. This is another of the great practical advantages of the absorbed power concept.

Their findings were reported in a series of papers presented to the SAE and ASME from 1964 to 1966. In particular, a paper entitled "Analysis of Human Vibration (ref. 5; see also ref. 6) contains the definitive quantitative data for each of the basic degrees of freedom of motion of a seated person, as illustrated in figure 6. In addition, separate data are given for vibration transmitted vertically to the person's feet. These values are given in tables of absorbed power constants, varying with frequency. It should be noted, however, that constants which were extrapolated below 1 Hz should be disregarded. Lee has since disavowed the validity of 'absorbed power' in this very low frequency range because of the dominance of a different human response mechanism, namely, that associated with motion sickness.

The absorbed power in watts for any given acceleration is:

$$P = K (A)^2$$

where K = a constant for a given frequency and direction of motion
 A = acceleration, m/sec^2 (rms).

Note that, by basing the constants on the rms acceleration value, they are applicable either to sine wave or random vibrations.

Figure 7 shows a comparison of the Pradko-Lee vertical characteristic with the original Janeway comfort criteria on a displacement-amplitude basis over the frequency range of 1 to 50 Hz. It is evident that up to 5 Hz the agreement is remarkably close indicating that constant absorbed power is virtually synonymous with a constant jerk level in the range of vehicle ride frequencies.

In a previous paper (ref. 7), this writer derived a mathematical expression for absorbed power in a simple vibrating system with viscous damping. By assuming a natural frequency of 5 Hz and 50% critical damping, the calculated amplitude vs. frequency for a constant absorbed power was found to agree closely with the Pradko-Lee data for constant response to vertical vibration over the entire frequency range of interest. The calculated points are also plotted in figure 7. Incidentally, other investigators, notably Coermann (ref. 4), have found that human body resonance to vertical vibration occurs in the vicinity of 5 Hz and generally exhibits the characteristics of a damped vibrating system.

It will be noted in figure 7 that a minor resonance is indicated in the Pradko-Lee data at 11 Hz that is not in evidence in the calculated values for the simple systems. Thus, the assumed analog to the human body is an evident oversimplification. The fact remains, however, that the basic mechanism involved in the human response to vertical vibration must be that of forced vibration of elastically supported organs having inherent viscous damping.

It will also be seen in figure 7 that the constant absorbed power criterion above 5 Hz corresponds generally to a constant velocity characteristic (linearly increasing acceleration with frequency).

Other Published Data.- Independent experiments on subjective responses to vibration have been conducted by a number of other investigators. The most noteworthy are Miwa in Japan (ref. 8), Coermann with the ISO Working Group 7 in Prague in 1965, and Volkov in the U.S.S.R. (see item 10 of reference list of ref. 8). Their findings on vertical vibration tolerance are summarized in table 1. (See next page.)

The recommended values are included in table 1 for comparison.

Where the response is designated (allowable to unpleasant), the minimum recommended acceleration at 4 to 6 Hz is seen to be no higher than 0.030 g. In the case of Coermann, the values are taken from the constant response curve nearest to the allowable acceleration at 1 Hz.

Also, it will be noted that the predominant slope in the 1 to 5 Hz range is (-1), corresponding to a constant jerk criterion (acceleration $\propto 1/f$).

Table 1

<u>Source</u>	<u>Response</u>	<u>Freq. at Min. Accel., Hz</u>	<u>Min. Accel. g (rms)</u>	<u>Accel. at 1 Hz, g</u>	<u>Slope n at 1 to 5 Hz</u>
Miwa	Unpleasant Boundary	5	0.029	0.056*	-
Coermann**	Uniform	4-5	0.05	0.15	-1
Volkov	Allowable (Comfort)	6	0.018	0.147	-1
Janeway	Allowable (Comfort)	5	0.030	0.145	-1

NOTES: *Maximum acceleration limit of equipment at 1 Hz
(see figure 10)

**Contour rounded at 1 and 5 Hz

No hard evidence has been found to support the ISO assumption that acceleration $\propto 1/\sqrt{f}$ for constant response, or that an acceleration of 0.07 g (rms) is allowable for comfort at 4 to 6 Hz, even for very short time exposures.

The constant jerk criterion of response in the low vertical ride frequency range has also been confirmed by vehicle field tests, as reported by Van Eldik Thieme (ref. 9), M. Haack (ref. 10), and R. Fine (ref. 11).

Horizontal Vibration

'Absorbed Power' Results.- Until Pradko and Lee published their findings in 1966, information on response to vibrations in the horizontal plane were too meager to provide a basis for reasonable judgment. It was generally agreed that human sensitivity to horizontal vibrations is markedly higher than to vertical vibrations at low ride frequencies. However, it was commonly assumed that the horizontal response contour should parallel the vertical but at a lower level and at a constant ratio. For example, the SAE Ride and Vibration Manual (ref. 12) contained a note recommending that the horizontal criteria be taken at a uniform reduction of 30% from the vertical comfort criteria.

The Pradko-Lee results threw entirely new light on the nature of human response to horizontal vibrations (relative to a seated or standing person). They showed that the greatest sensitivity to these vibrations is at the lowest ride frequencies, namely, 1 to 2 Hz. At 1 Hz, the tolerance was found to be only one-seventh of that in the vertical plane, for the same absorbed power. Above 2 Hz, however, the tolerance increases rapidly and continuously. These characteristics are illustrated in figure 8, with relative acceleration as the ordinate scale, and frequency as the abscissa. The lateral and fore-and-aft responses are shown separately and are seen to be closely the same. They become equal to the vertical response at frequencies of 3 and 3.3 Hz,

respectively. Above 3.3 Hz, the horizontal and vertical contours diverge rapidly, with sensitivity becoming much greater in the vertical direction as the horizontal tolerance increases according to: $\text{accel.} \propto f^{1.5}$.

Miwa Results.- In 1967, T. Miwa in Japan published the first of a series of papers on his subjective experiments, which included response to horizontal as well as to vertical vibrations (ref. 7).

In a general way, Miwa's results resemble those of Pradko-Lee to the extent that the tolerance is a minimum at the lowest ride frequencies, 1 to 3 Hz, and then increases abruptly as the frequency rises. As shown in figure 9, the minimum value at the 'unpleasant' boundary is 0.048 g (rms), and the acceleration increases linearly with frequency beyond 3 Hz (slope = 1). In figure which includes Miwa's equivalent vertical response contour, it will be noted that the vertical acceleration averages the same as the horizontal over the 1 to 3 Hz range, with the two intersecting at 2 Hz.

The indicated equal response to vertical and horizontal vibrations at 1 to 2 Hz is contrary to common vehicle ride observations.

This discrepancy can be accounted for by Miwa's admission that his observations were quantitatively questionable below 6 Hz because of

- (a) The difficulty of subjective judgment in matching response to the standard frequency of 20 Hz (his experimental procedure)
- (b) The limitation of his equipment to a maximum vertical amplitude of 2 cm.

It is believed that the latter restriction prevented the acceleration from reaching the level for equal response. (The acceleration value of 0.056 g at 1 Hz corresponds to the full 2 cm amplitude).

In a recent exchange of correspondence with Miwa, he advises that recent findings indicate his horizontal limit curve should be extended at the same slope from 3 Hz to 2 Hz and then maintained constant to 1 Hz, as shown by the dotted line in figure 9. This reduces his minimum limit value by one-third, to a point between the ISO and recommended values.

ISO Standard Criterion.- Following publication of the Pradko and Lee findings, the ISO commendably decided to adapt these new data to horizontal vibration criteria, comparable to those they had already developed for vertical vibrations.

What they arrived at was a composite of the Pradko-Lee and Miwa results. From Miwa they adopted his minimum acceleration value and the constant velocity contour at the higher frequencies. From Pradko-Lee, they took the cut-off of minimum tolerance at 2 Hz. Also, in combination with the previously adopted vertical contour (as seen in figure 9), this made it possible for the vertical and horizontal response lines to intersect at 3.2 Hz, as shown by Pradko-Lee.

As pointed out in connection with the Miwa results, the ISO minimum horizontal acceleration value is open to question. This is not a matter of hair splitting; the ISO allowable acceleration is fully 2.4 times the recommended minimum value derived for the same constant absorbed power as that established for the vertical comfort criterion.

The question may be raised whether the same absorbed power value will necessarily ensure comfort in the horizontal as well as in the vertical plane. An affirmative answer is indicated by comparison of Miwa's horizontal 'unpleasant' boundary with the recommended comfort criterion based on the constant absorbed power of 0.2 watts. Figure 9 shows, in the frequency range of 3 to 10 Hz, the two lines average closely the same. This is the range of presumed greater reliability for Miwa's results, and the same area in which the two vertical criteria so closely agree.

Pitch and Roll Vibrations

Pradko and Lee also investigated the effects of pitch and roll vibrations about axes through the seat-subject interface (see figure 6).

The isolated effects of these angular accelerations were found to be negligible. This can be accounted for by the observed ability of the subject, when not confined in the seat, to remain in a substantially vertical position during such vibrations.

It should be noted that the imposition of a seat belt and shoulder harness may seriously change this isolation from angular motions per se. This does not apply (to the same extent) to the horizontal linear accelerations on the seat produced by angular accelerations about remote axes. However, confinement in the seat would impose more direct linear accelerations on the driver's head than would otherwise be the case, and, therefore, make for greater discomfort.

Summary: Criteria Comparison

The foregoing review is believed to amply justify the conclusion that the Pradko-Lee absorbed power results are the most reliable and have the greatest applicability to the evaluation of vehicle ride. The reasons may be summarized as follows:

1. The excellence of the equipment and instrumentation ensured precise control of input vibration wave form and absence of extraneous noise disturbance.
2. The thorough execution of the subjective experiments provided a solid basis for the analytical conclusions.
3. The brilliant mathematical development of the absorbed power concept which, for the first time, provided a meaningful objective measure of human vibration response.
4. The greater quantitative accuracy inherent in objective measurement compared to exclusive reliance on subjective responses.

5. The excellent correlation with previously established criteria and human body characteristics.
6. The ability to combine all components of a complex vibration input into a resultant measure of response.

RECOMMENDED COMFORT CRITERIA

For the reasons given in the previous section, the Pradko-Lee concept of "absorbed power," as an objective measure of subjective response to vibration has been adopted by the writer as the most reliable guide to valid criteria of human tolerance.

Although Pradko and Lee have defined the characteristic variations in acceleration for a constant response (constant absorbed power), they have not attempted to fix limits for comfort or for any other degree of subjective response. Their position is that tolerance is a relative term, and that the tolerable intensity level will change with the environment in which the vibration exposure takes place.

Consequently, the principal task in applying the Pradko-Lee findings is to arrive at a viable limit of absorbed power for comfort. Fortunately, we have an accumulated body of observations from experiment and field experience on which to base such a correlation. First of all, the one point of agreement between the ISO Standard and my previous recommendations is the vertical acceleration limit for comfort at 1 Hz. This limit of 0.2 g (peak), 0.145 g (rms), first proposed in 1948 for short term sine wave vibrations, has withstood the test of time.

By sheer happenstance, this acceleration is equivalent to an absorbed power of 0.2 watt, as calculated in appendix A from the Pradko-Lee table of vertical vibration constants. This rate of energy dissipation is equivalent to 0.02 kg-m/sec (1.8 in-lb/sec).

Vertical Limits

Figure 10 shows a plot of the vertical acceleration values corresponding to a constant absorbed power of 0.2 watt over the frequency range of 1 to 50 Hz. For frequencies over 5 Hz, the acceleration values are also given if the power limit includes that absorbed by the feet of a seated person exposed to the same input vibration. As a frame of reference, the boundary of the original Janewa recommended comfort criterion is also shown. It is evident that the constant jerk line approximates the Pradko-Lee values from 1 to 5 Hz. Above 5 Hz, a constant velocity (shown broken) is a perfect fairing of the Pradko-Lee values averaging with and without the power absorbed in the feet. The resultant comfort boundary is an unsymmetrical 'V', which is very simply described mathematically as follows:

$$\begin{aligned} \text{For } f = 1 \text{ to } 5 \text{ Hz accel.} &= \frac{0.145}{f} && \text{g (rms)} \\ f = 5 \text{ to } 50 \text{ Hz accel.} &= \frac{0.145 f}{24} = 0.066 f && \text{g (rms)} \end{aligned}$$

It is important to note that a constant absorbed power implies a constant duration of exposure as well as of response. Referring to the original data sources, a constant duration of 16 minutes has been assigned to the boundary values of figure 10. In ground transportation vehicles, this would correspond to traversing a 24.1 km rough stretch of highway at 85.5 km/hr.

It is evident in figure 10 that the original Janeway criteria incorporated an offset at constant acceleration, from 6 to 20 Hz, between the constant jerk and constant velocity phases. This has already been accounted for in the discussion on the development of the earlier criteria.

Horizontal Limits

It is evident in the Pradko-Lee curves of relative horizontal accelerations vs. frequency for constant absorbed power (figure 8) that the lateral and fore-and-aft values are closely the same at most frequencies. Certainly, the differences are not of an order to warrant separate criteria in the two directions.

Figure 11 is a plot on log-log coordinates of the calculated values of the horizontal accelerations in the two directions, for a constant absorbed power of 0.2 watt, over the frequency range of 1 to 20 Hz. The acceleration limits are virtually identical in the critical range of 1 to 2 Hz, and again at 6 Hz and higher frequencies. The divergence in the 2.5 to 5 Hz range, however, is reasonably well reconciled by a straight line connecting the values at 2 Hz and from 6 to 10 Hz. This line has a slope of 1.5, indicating the relationship:

$$\text{accel.} = 0.02 \left(\frac{f}{2}\right)^{1.5} \text{ g (rms).}$$

Above 10 Hz, the slope increases to 2, corresponding to a variation of limiting acceleration with the square of frequency. For practical purposes, however, the range of 1 to 10 Hz comprises the important range of ride disturbance.

The direct comparison of the recommended limits with the ISO Standard comfort boundaries is shown in figure 12. The outstanding differences are obviously at the most sensitive frequencies for human vibration response, both vertically and horizontally. In both cases, the maximum ratio of acceleration between ISO and recommended values is 2.4, corresponding to an absorbed power ratio of nearly 6.

Vibration Exposure Time

In the course of the deliberations of our ANSI Vibration Tolerance Working Group, it became clear that criteria of exposure limits, in addition to specifications of frequency and intensity, needed a third dimension, namely, the time duration of exposure.

In the search for experimental data on this aspect of vibration tolerance, this writer found only two fragments in the literature, and these from widely different fields. One was in a report by Notess (ref. 13) to the Cornell Aeronautical Laboratory in 1963 on reaction to disturbances in aircraft, in the frequency range of 0.6 to 1 Hz; the other source was a publication of Mauzin and Sperling (see data in ref. 10) on observations in railway passenger cars,

at frequencies of 1 to 2 Hz. Referring to figure 13, these data are plotted on semilog coordinates, with relative acceleration tolerance as ordinate, and exposure time as abscissa. The data were submitted in this form to the ANSI Working Group for their consideration.

It must be considered that these observations were not made under controlled conditions but were incidental to typical operating conditions in each case. Also, the levels of vibration intensity were not likely to have been comparable. Consequently, it was impossible to estimate the degree of validity that could be ascribed to the results.

Nevertheless, the ISO Standard's relative acceleration tolerance values vs. exposure time are largely based on these data and are applied indiscriminately to all frequencies, response levels, and to both vertical and horizontal vibrations.

As far as comfortable levels of vibration are concerned, they should theoretically be independent of time duration. Strictly defined, 'comfort' should mean an absence of disturbance; therefore, there should be no cumulative effect with time. The comfort state, in some ways, may be likened to the condition of dynamic stress in a material below its endurance limit. In the latter case, no damage will occur even after a theoretically infinite number of repeated stress cycles.

This is not to say that fatigue cannot occur in a vehicle over a prolonged period, for reasons of confinement, noise, poor ventilation, etc. The same fatigue could conceivably result even though no vibration were present.

Consideration of fatigue as a result of sustained exposure to vibration is a legitimate concern in environments having vibration intensities well above the comfort level, as a pertinent example, in highway trucks and truck tractor. The drawback here is the difficult problem of establishing valid quantitative relationships between the vibration parameters (direction, intensity, and frequency) and exposure time at onset of fatigue.

So far, no one has succeeded in determining the onset of fatigue in human by any objective measurement, or subjective response, and not for lack of trying on the part of many investigators. Consequently, the promulgation by the ISO Standard of elaborate tables of tolerable exposure time for any given vibration condition must be viewed as completely arbitrary.

It should be noted, also, that the primary ISO Standard data are presented as the boundaries of "fatigue-decreased proficiency." From these values, the corresponding 'comfort' levels must be computed by dividing by a constant (3.1) regardless of frequency or direction of vibration. This constant relationship in itself, is an unsupported assumption. That is, of course, how the ISO values cited in this paper were arrived at.

The coupling of so-called 'fatigue' with 'decreased performance' is still another liberty taken by the ISO Standard except it happens that various aspects of human functional performance are subject to quite precise measurement.

Highly pertinent data on this score are revealed by the results of an extensive series of controlled laboratory tests made by Bostrom Research Laboratories for the U.S. Army (ref. 14). Referring to figures 14 and 15, the following findings effectively challenge the ISO's assumed effects of vertical vibration on performance:

1. Performance can be highly sensitive to frequency, without relation to the passive response to vibration. The following values are taken from figure 14:

Type of Performance	Frequency, Hz	Peak Intensity, g	Performance Error, %
Visual Acuity	2.5	0.35	4
	3.5	0.30	23
Compensatory Track.	2.5	0.35	10.2
	3.5	0.30	14.2
Foot Pressure	2.5	0.35	42
	3.5	0.30	80
ISO Boundary (16 min)	2.5	0.38	
	3.5	0.32	

It is evident that the ISO designated "boundary of decreased performance" for an exposure of 16 min would be far higher than an acceptable limit under all conditions at 3.5 Hz and for at least one of the performance types (foot pressure) at 2.5 Hz.

2. The ISO assumption that the decreased proficiency boundary becomes progressively lower with duration of vibration exposure is without foundation. Figure 15 shows that no appreciable change in performance occurred over a period of 90 min exposure, even at the high sustained intensities of the Bostrom tests.

With regard to the relative effect of exposure time on the onset of fatigue, it is of theoretical interest that the 'absorbed power' concept provides a rational basis for deriving such a relationship. If a given level of absorbed power, P_o , produces fatigue in an exposure time, t_o , then it may be reasoned that this is the cumulative effect of the total energy absorbed, or $P_o t_o$. It might be logical then to expect an equal amount of energy absorbed at some other rate (power) to produce the same fatigue effect.

If $P_o t_o = E_o$ is a known reference condition for onset of fatigue:

Then: $E_o = P t = P_o t_o$

Where P = absorbed power at some other given condition of frequency and direction, at which A.P. constant = K and accel. (rms) = A, t = exposure time at (P)

Then, $P = KA^2$, similarly, $P_o = K_o A_o^2$

and, $KA^2t = K_o A_o^2 t_o$

$$\frac{A^2}{A_o^2} = \frac{K_o t_o}{Kt}$$

$$\frac{A}{A_o} = \sqrt{\frac{K_o t_o}{Kt}}$$

If the frequency and direction are the same under both conditions, $K_o = K$ and:

$$\frac{A}{A_o} = \sqrt{\frac{t_o}{t}}$$

Figure 16 is a plot of $\frac{A}{A_o}$ on log-log coordinates, taking $\frac{A}{A_o} = 1$ at $t_o = 16$ min, for a constant value of K. Obviously, this becomes a straight line of slope = $-\frac{1}{2}$. Also plotted are the relative acceleration values vs. exposure time for the fatigue boundaries specified in the ISO Standard, again taking 16 min exposure as the condition for accel. = 1. It is apparent that the ISO relative values agree closely with this theoretical relationship.

All that remains is for the base condition for onset of fatigue to be established.

RIDE EVALUATION

The details of ride evaluation are outside the scope of this paper. Nevertheless, such determination is the ultimate purpose of any system of ride criteria. It follows that the ability of the applied criteria to measure the resultant human response to the complex vibration environment of the real world is the acid test.

Application of Absorbed Power

The outstanding contribution of the 'absorbed power' concept is that, being a scalar quantity rather than a vector, any number of simultaneous vibration components can be summed directly to obtain an effective one-number resultant. In contrast, a system like the ISO Standard can attempt to evaluate the resultant of a number of component frequencies in the same direction but

with difficulty and with questionable accuracy. (See Notes, pp. 8 and 9 of ISO/DIS 2631.) However, for simultaneous vibrations in different directions, the ISO instructions are explicit; the limits must be applied "separately to each component in the three axes."

This advantage of criteria based on 'absorbed power' is enormously important in such real ride environments as rail cars, trucks, and tractors. Here the horizontal vibrational disturbance can produce equal or greater intensity of operator response as compared with the vertical disturbance. Hence, separate evaluation cannot begin to measure the resultant response.

As a case in point, the results summarized in table 3 were obtained in comparative ride measurements on two current model truck-tractors, under identical operating and road conditions. (The details of this evaluation are given in appendix D of ref. 2.)

Table 3

$A_m^2, (m/s^2)^2$	<u>Tractor A</u>	<u>Tractor B</u>
<u>Vertical</u>		
On Cab Floor - Susp. Freq.	0.92	1.24
Tire Freq.	0.45	0.074
On Driver - Susp. Freq.	1.29	2.07
Tire Freq.	0.043	-----
Fore and Aft on Driver	0.51	0.77
<u>Absorbed Power on Driver, W</u>		
<u>Vertical</u>		
Susp. Freq., (K = 0.775)	1.0	1.61
Tire Freq., (K = 1.59)	0.07	-----
<u>Total Vertical</u>		
Fore and Aft, (K = 1.97)	1.07	1.61
	1.01	1.52
<u>Total Abs. Power, W</u>		
	2.08	3.13
Ratio to Comfort Limit (=0.2 W)	10.40	15.65
Ratio of Equiv. Mean Accel. to Comfort Limit	3.23	3.96

It will be seen that the separately integrated vertical and horizontal vibrations, in terms of 'absorbed power,' are close to the same intensity, in each of the vehicles. Each resultant, obtained by direct addition, is thus about twice as great as the separate components.

By comparing the overall resultant 'absorbed power' with the comfort criterion of 0.2 watt, the true magnitude of the disturbance is revealed, at 10 to

15 times the recommended level. The conversion to 'absorbed power' for any observed acceleration value and vibration direction is obtained from the relation:

$$P = 0.2 A^2 / A_0^2$$

Where A = observed acceleration, g (rms)

A₀ = comfort limit acceleration, g (rms), for the same frequency and direction

or
$$P = KA^2 (9.81)^2$$

Where
$$K = \frac{0.2}{(A_0 \cdot 9.81)^2}$$

A cautionary note should be added. If any system of criteria of human response is to be meaningfully applied, the instrumentation must measure the true vibration input to the subject; and the locations of the measurements relative to the subject must accord with those used in establishing the criteria.

The recommended criteria are directed to the vibration input at the interface of the seat and the subject's anatomy. Where a cushioned seat is present the vertical transducer must be interposed between the cushion and the subject. As an alternative, the vertical input can be measured on the subject's shoulder and a correction made for the amplification or attenuation of the anatomy according to experimentally established average factors (ref. 2). The horizontal input can be measured on the seat frame at the level of the interface with subject. (This assumes no confinement with respect to a cushion seat back.)

The ISO Standard has very explicit instructions as to the location of vertical measurements. It is vague, however, on the matter of horizontal measurement location.

Application to Power Spectral Density

This is a method of analysis that has been widely used with tape recorded accelerometer data. By playing the tape back through a series of narrow band filters and squaring the output, the mean squared acceleration in each frequency band is charted.

In order to apply absorbed power criteria to ride evaluation from power spectral density data, it is obviously necessary to apply weighting factors, according to the criteria for equal response over the frequency range. Since the ordinates of the chart already represent the mean square of acceleration, it is only necessary to multiply the ordinates by the absorbed power (K) value, corresponding to each frequency, to obtain an absorbed power graph. The area under this graph is the total absorbed power.

This type of evaluation has a serious deficiency, namely, that it gives no insight into the amplitude distribution. Thus, the same mean acceleration

square ordinate can be integrated from many small accelerations or from a few large ones. A ride that comprises many small accelerations might be comfortable, while the few large accelerations might make the ride unacceptable.

CONCLUSIONS

The ISO Standard criteria should be rejected in view of the following deficiencies:

1. The 'comfort' boundary values are excessive at the most critical ride frequencies, for both vertical and horizontal vibrations.
2. The primary 'fatigue-decreased proficiency' boundary values are generally at too high a level for reasonable fatigue limits and have no validity with respect to 'decreased proficiency.'
3. The relative change in 'comfort' boundary values should be much less sensitive to time of exposure than the 'fatigue' values, although the same relative sensitivity is assumed for both.

The recommended comfort limits based on absorbed power, for frequencies of 1 Hz and higher, should be adopted because

1. The vertical characteristic vs. frequency is confirmed by the best available subjective data, as well as by experience, especially in the ride frequency range.
2. The horizontal criteria were the first to offer a definitive guide to valid comfort limits for vibrations in the horizontal plane.
3. Absorbed power is an objective measure of human response. As such, it is bound to be much more precise than any subjective determination.
4. The ability to integrate the absorbed power under complex real environments, consisting of simultaneous vertical and horizontal vibrations, means a great step forward in vehicle ride evaluation.

The available experimental data are entirely inadequate to support any valid standards for the following criteria, which are incorporated in the ISO document:

1. Limits of vibration intensity vs. frequency, representing:
 - a. Fatigue boundaries;
 - b. Reduced proficiency of performance.
2. Relative tolerance vs. exposure time at specific response levels.

APPENDIX A

CALCULATION OF ABSORBED POWER COMFORT CRITERION

Taking 5.1 cm in amplitude (single) at 1 Hz as an established comfort limit, the corresponding rms acceleration is:

$$\begin{aligned} A &= \frac{(2 \pi f)^2 a}{\sqrt{2} \cdot 100} \\ &= \frac{(4 \pi^2) \cdot 5.1}{\sqrt{2} \cdot 100} \\ &= 1.42 \text{ m/s}^2 \end{aligned}$$

where: A = accel., m/s², rms

f = frequency, Hz

a = amplitude, cm

From Pradko-Lee table of vertical constants, at 1 Hz, $K_v = 0.0985 \text{ W/(m/s}^2)$

$$\begin{aligned} \text{Abs. Power} &= K_v A^2 \\ &= 0.0985 (1.42)^2 \\ &= 0.198 \text{ W} \end{aligned}$$

check at f = 4.75: recommended acceleration comfort limit is 0.0305 g (rms).
Absorbed power constant (Pradko-Lee) is maximum at $K_v = 2.189$

$$\begin{aligned} \text{Abs. Power} &= 2.189 (0.0305 \cdot 9.81)^2 \\ &= 0.196 \text{ W} \end{aligned}$$

∴ Constant absorbed power corresponding to recommended vertical criterion
P = 0.2 W.

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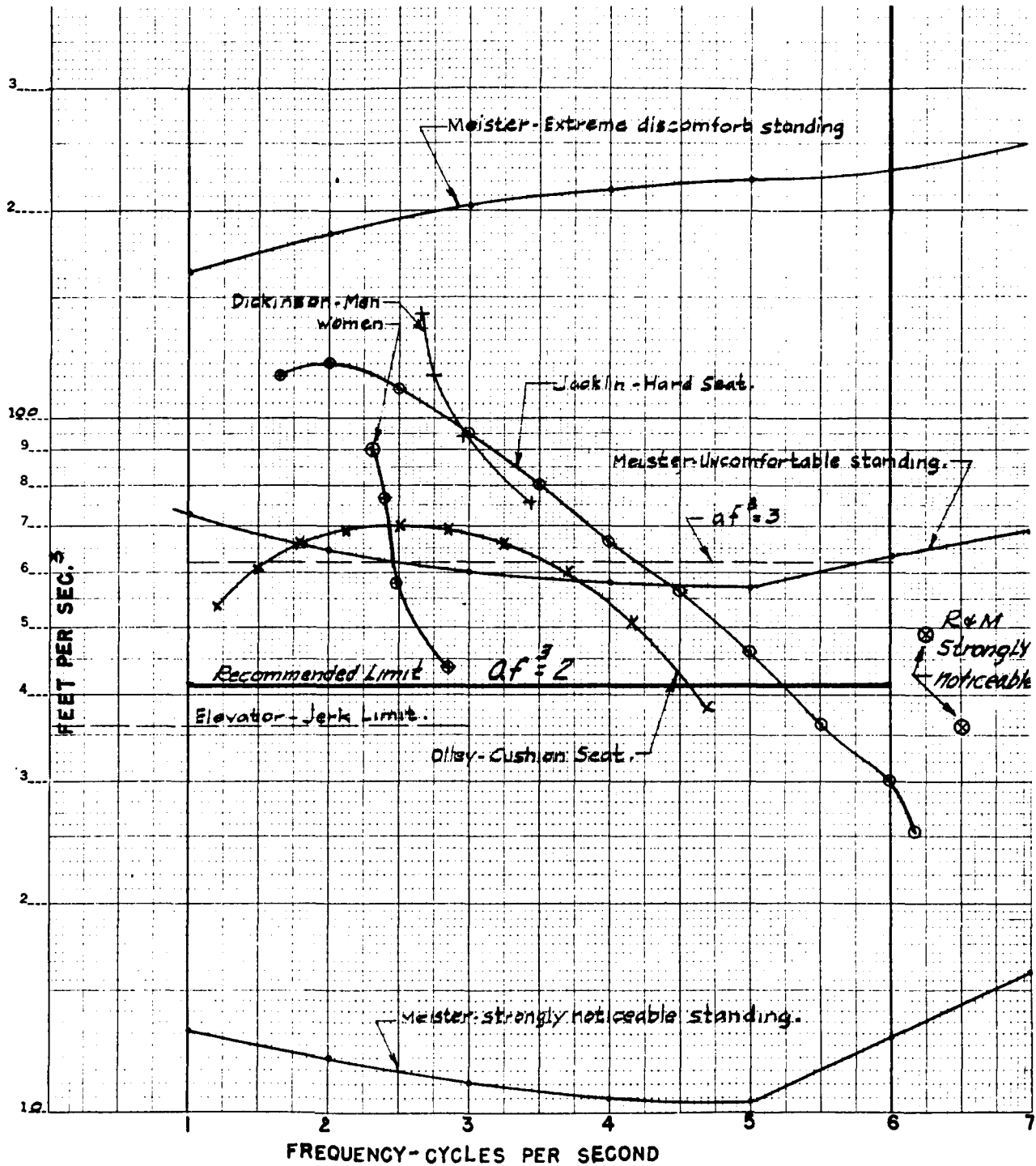


Figure 1.- Correlation of vibration data, jerk as a function of frequency, for constant response. (1 ft = 0.304 m; 1 cps = 1 Hz.)

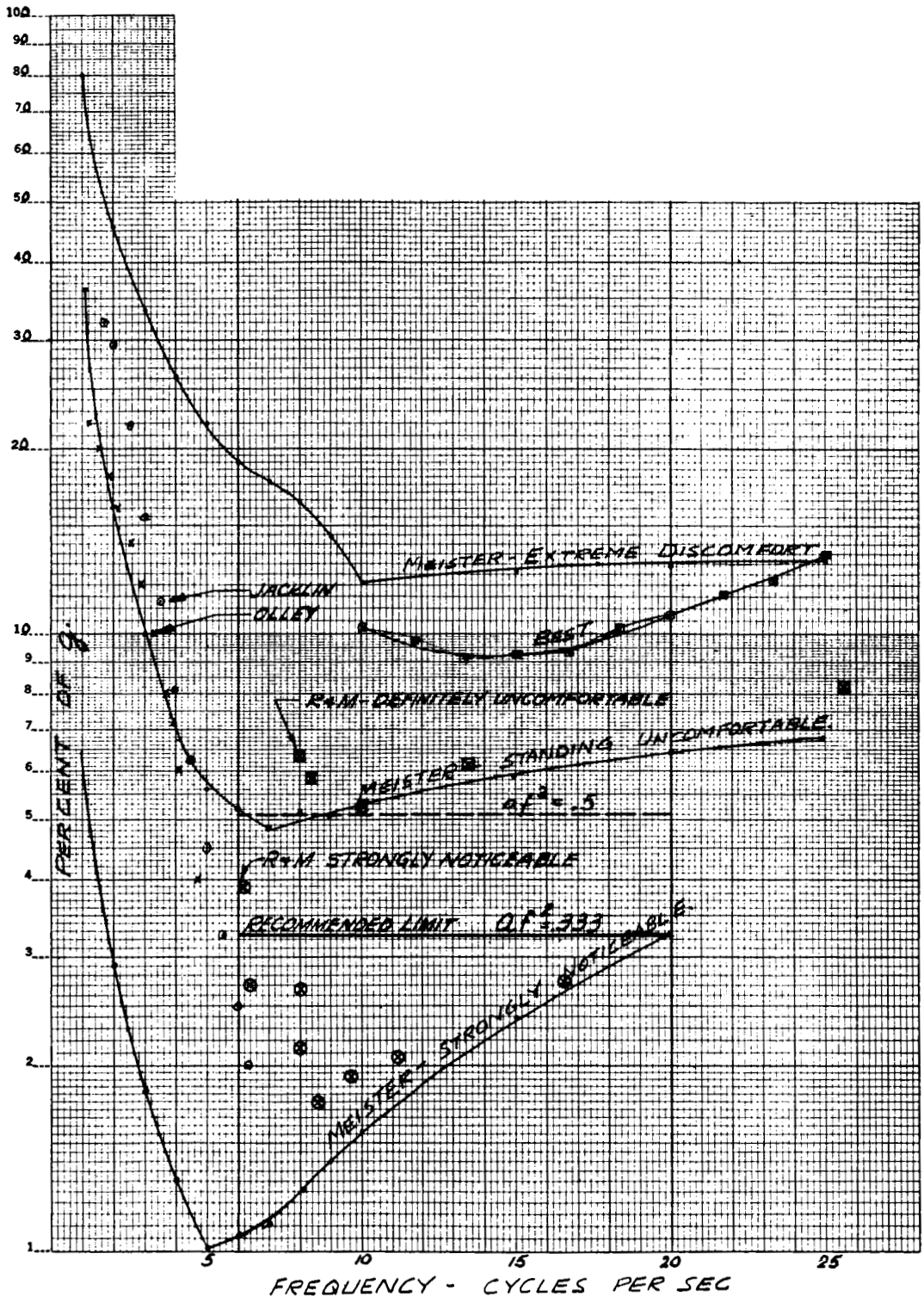


Figure 2.- Correlation of vibration data, acceleration as a function of frequency, for constant response. (1 cps = 1 Hz.)

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DIAGRAM OF AN ELEVATOR RISING 80 FEET
 WITH 20 FT./SEC. MAXIMUM VELOCITY,
 6 FT./SEC.² MAXIMUM ACCELERATION, 9 FT./SEC.² MAXIMUM DECELERATION
 AND PARABOLIC CONNECTING CURVES BETWEEN
 THE LINES OF CONSTANT $\frac{dy}{dt}$ AND $\frac{dy}{dt}$
 IN THE TIME-VELOCITY DIAGRAM

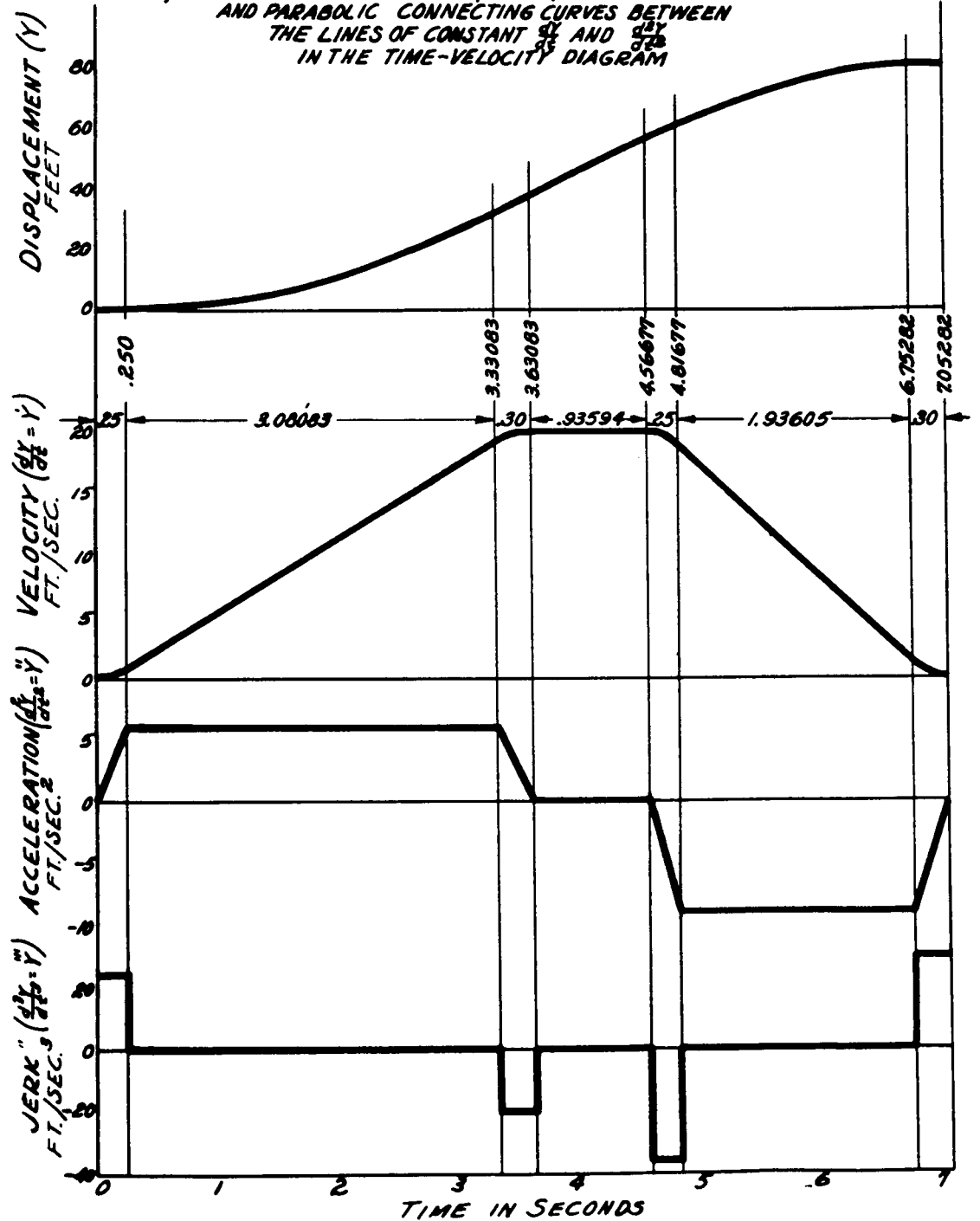


Figure 3.- Desirable limits for comfort in elevator operation.
 (1 ft = 0.3048 m.)

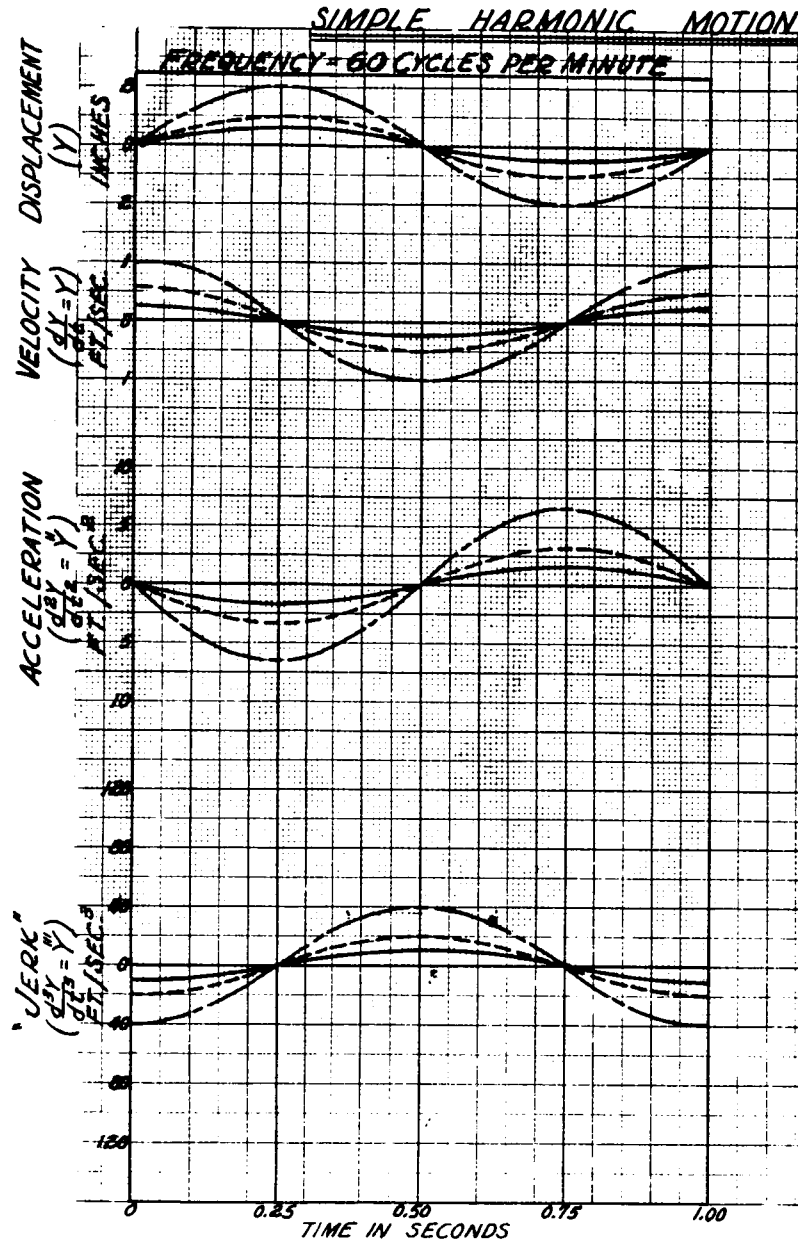


Figure 4.- Simple harmonic motion at 5.1 cm amplitude and 1 Hz.
(1 in. = 2.54 cm; 1 ft = 0.3048 m; 60 cpm = 1 Hz.)

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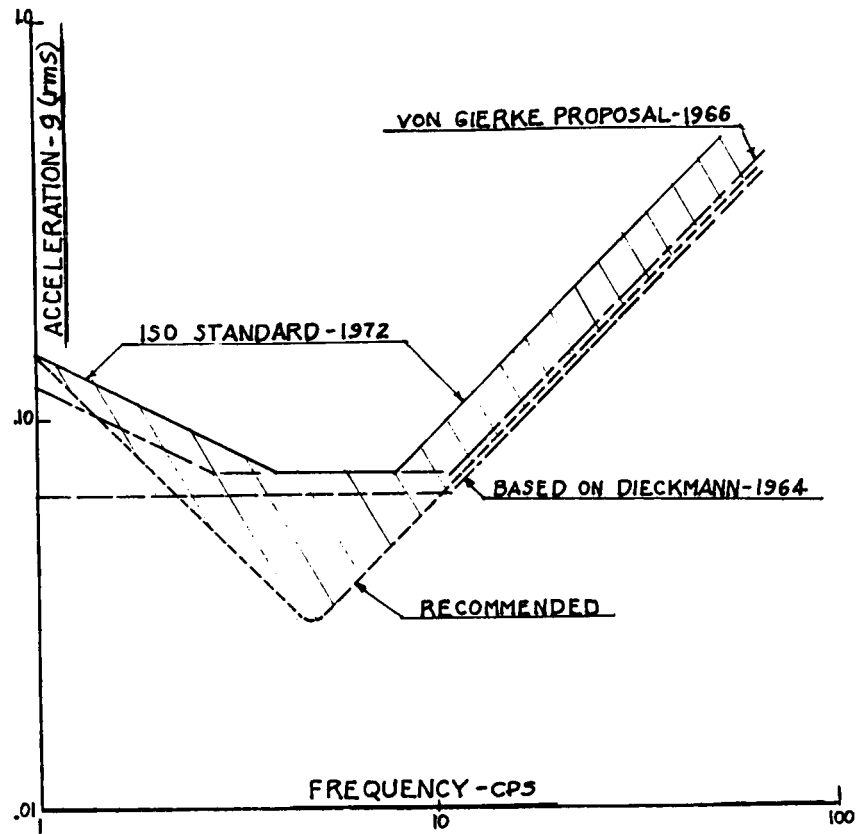


Figure 5.- Evolution of ISO Standard vertical comfort criterion. (1 cps = 1 Hz.)

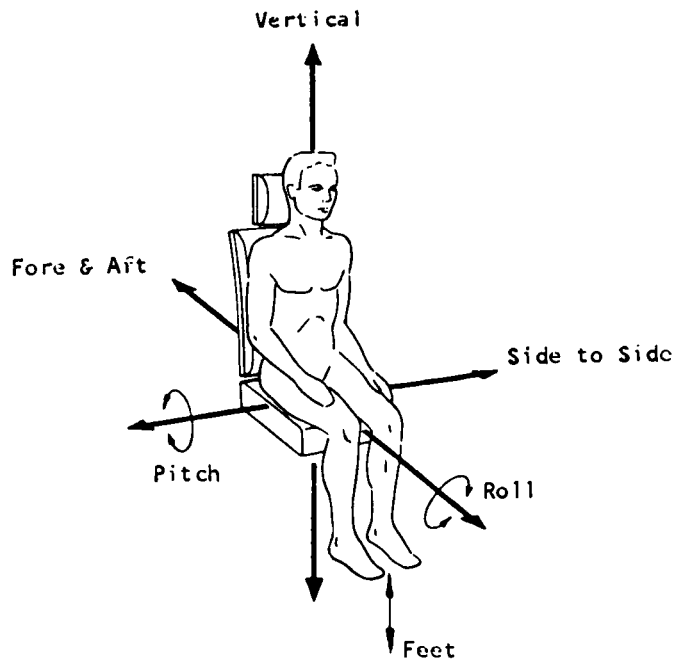


Figure 6.- Vibratory system used in Pradko-Lee tests.

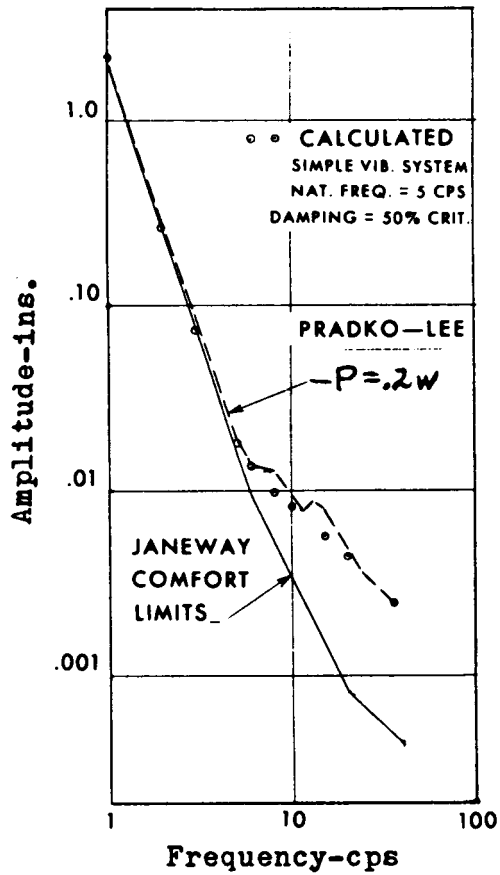


Figure 7.- Comparison of vertical vibration criteria. Calculated points are for constant absorbed power. (1 in. = 2.54 cm; 1 cps = 1 Hz.)

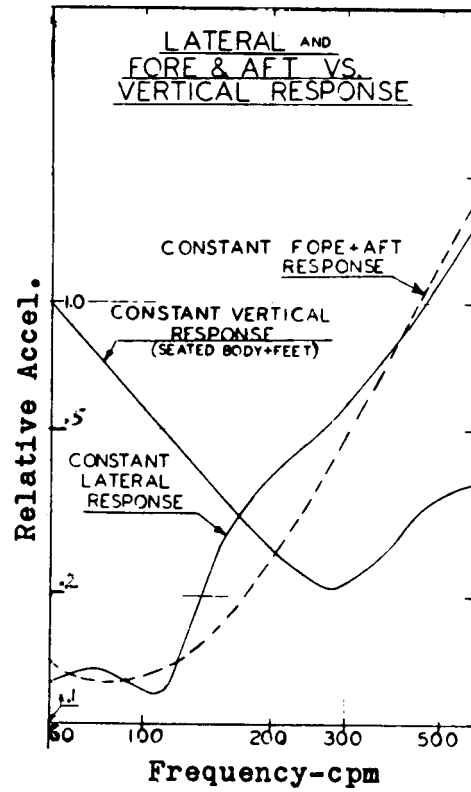


Figure 8.- Relative lateral and fore-and-aft acceleration compared to vertical acceleration for equal response (Pradko-Lee). (60 cpm = 1 Hz.)

'COMFORT' BOUNDARIES

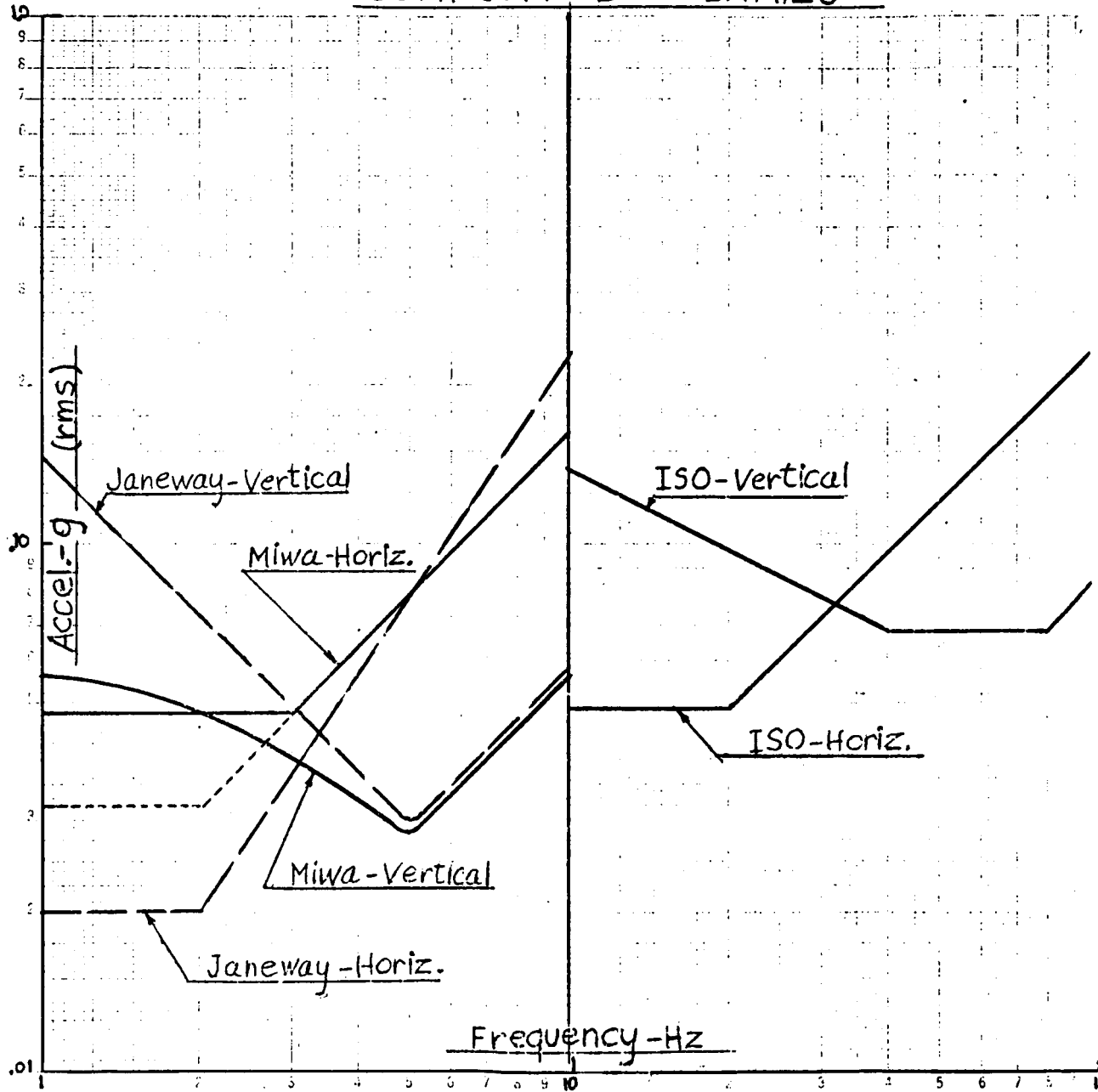


Figure 9.- Miwa criteria compared to Janeway and ISO (16 min exposure).

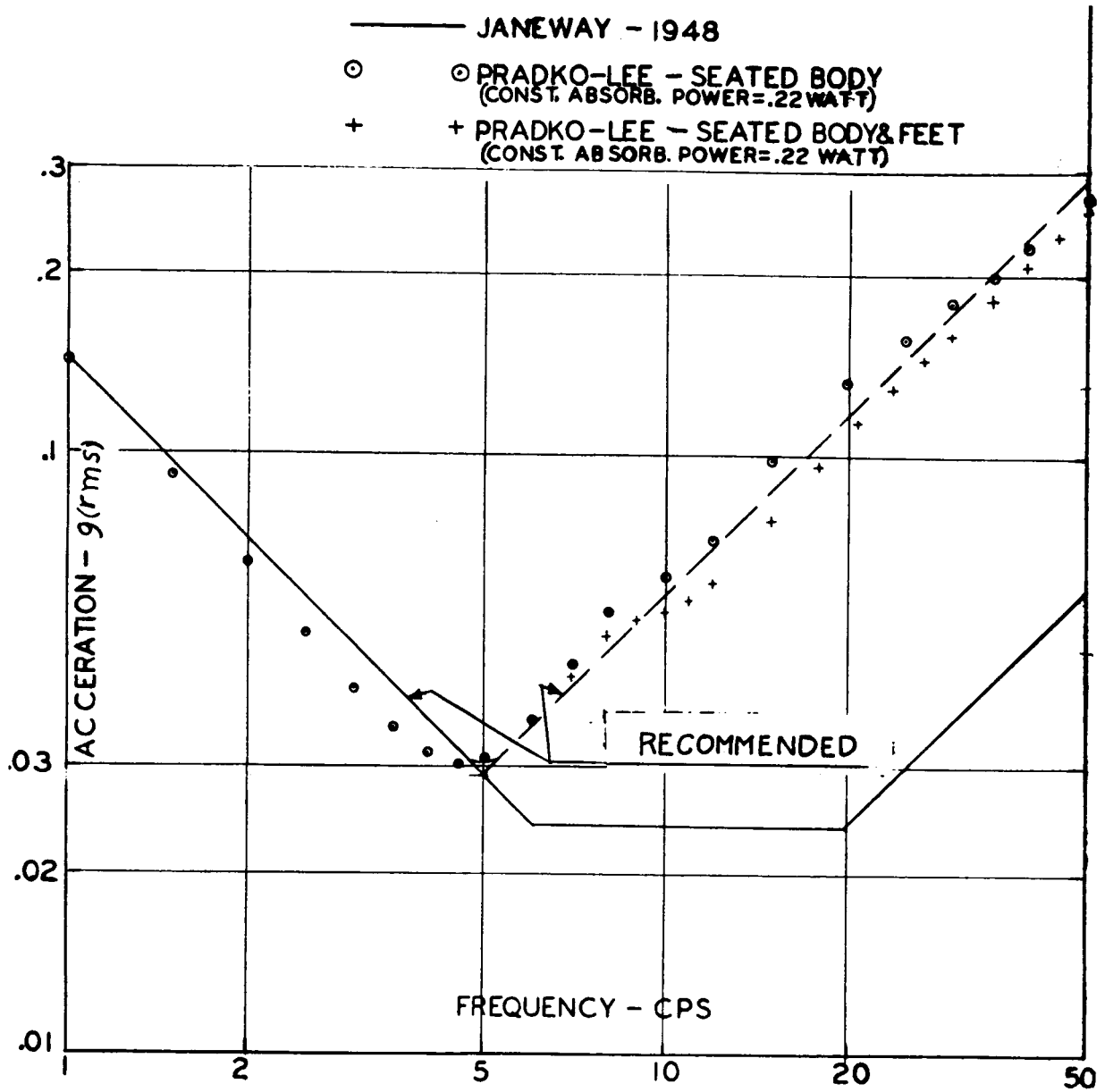


Figure 10.- Correlation of vertical comfort criteria: constant absorbed power and Janeway recommended (1948). (1 cps = 1 Hz.)

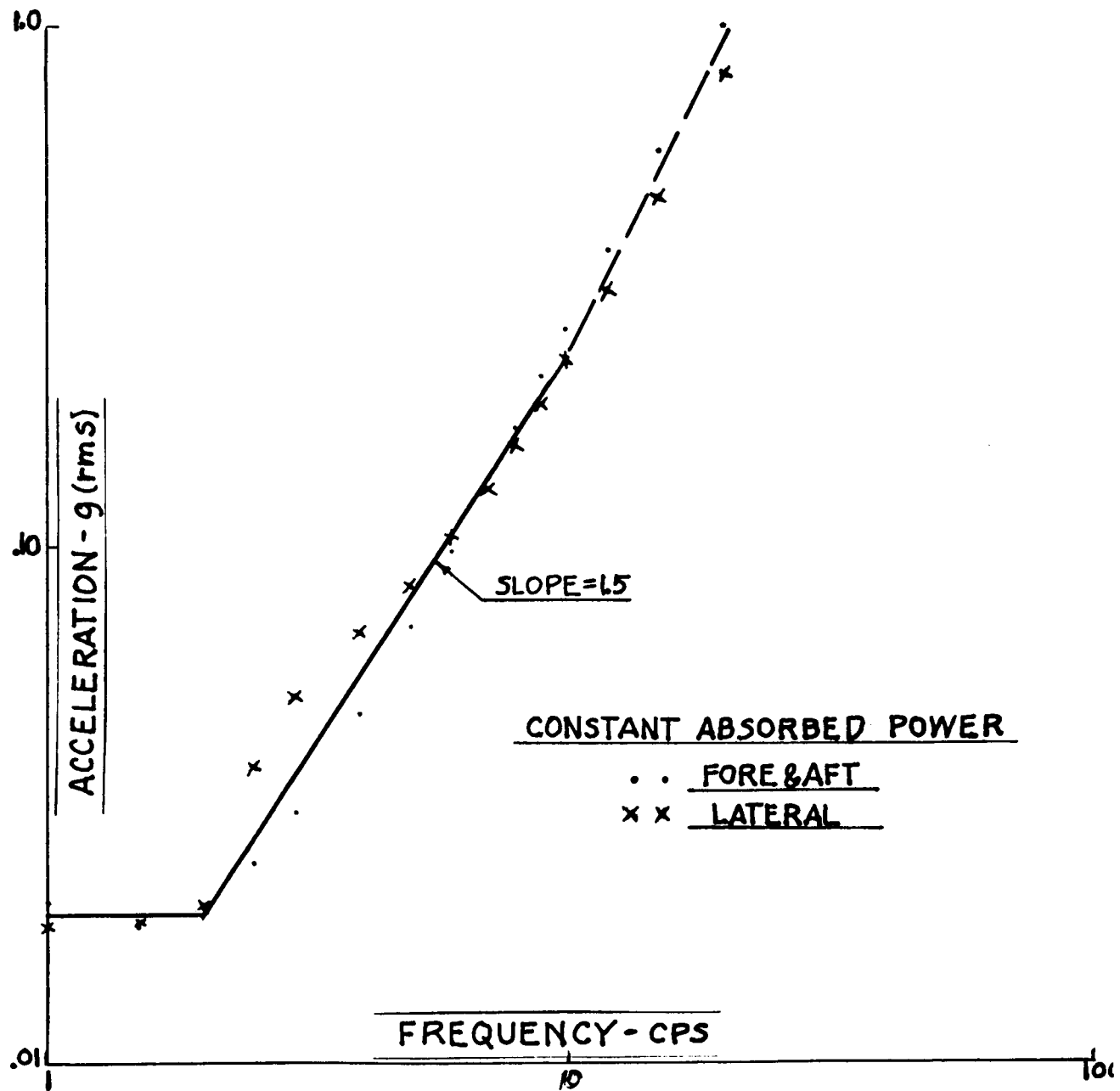


Figure 11.- Recommended horizontal comfort criterion. (1 cps = 1 Hz.)

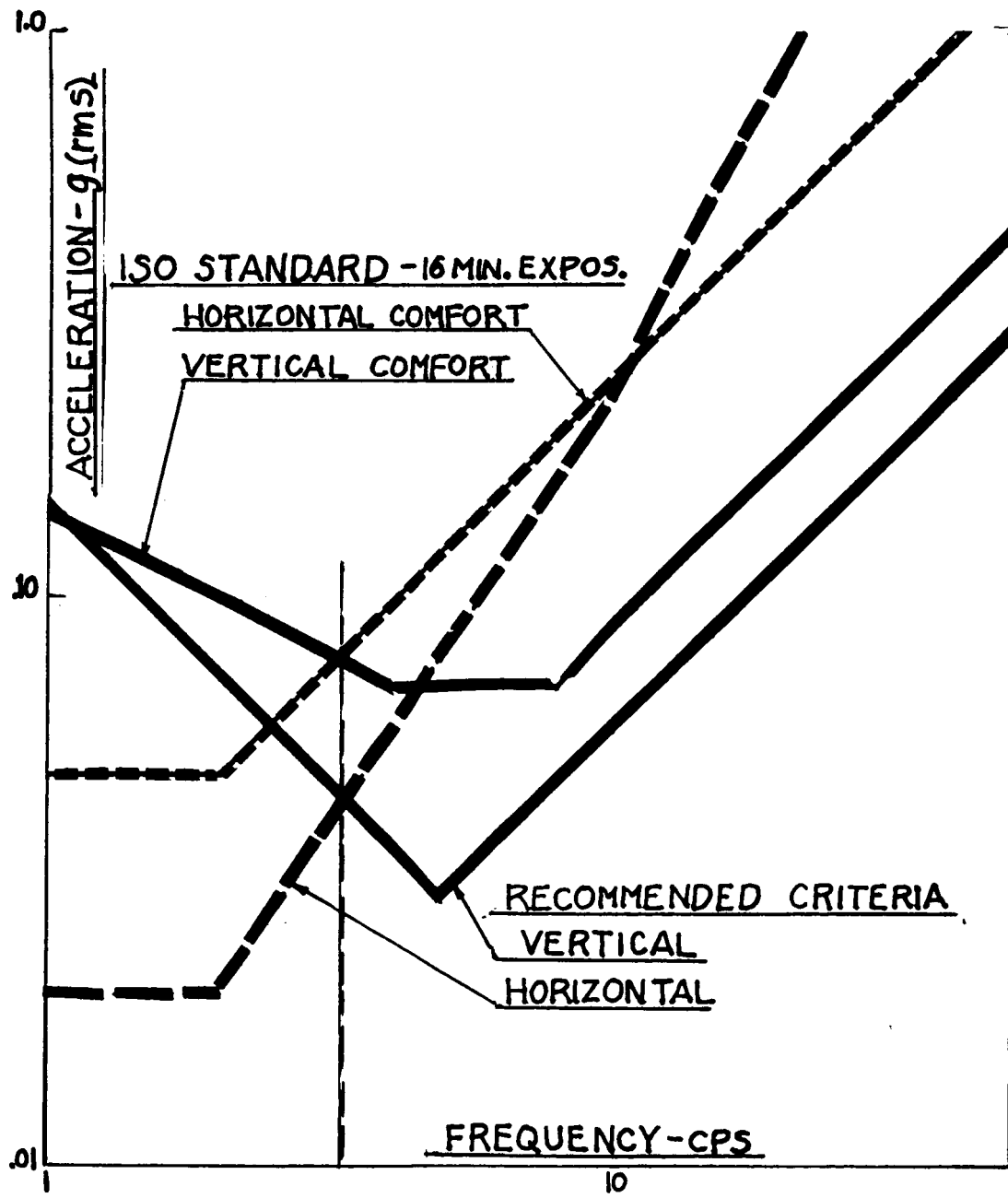


Figure 12.- ISO compared to recommended comfort criteria.
(1 cps = 1 Hz.)

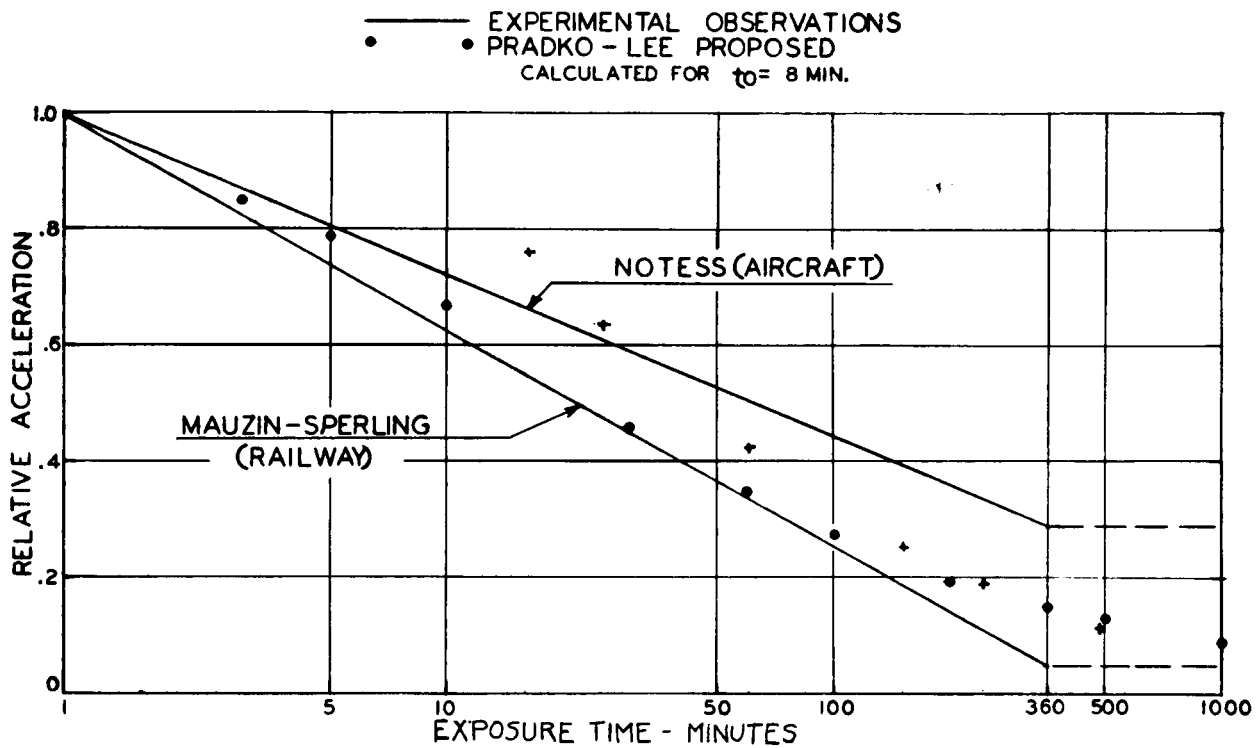


Figure 13.- Vibration exposure time.

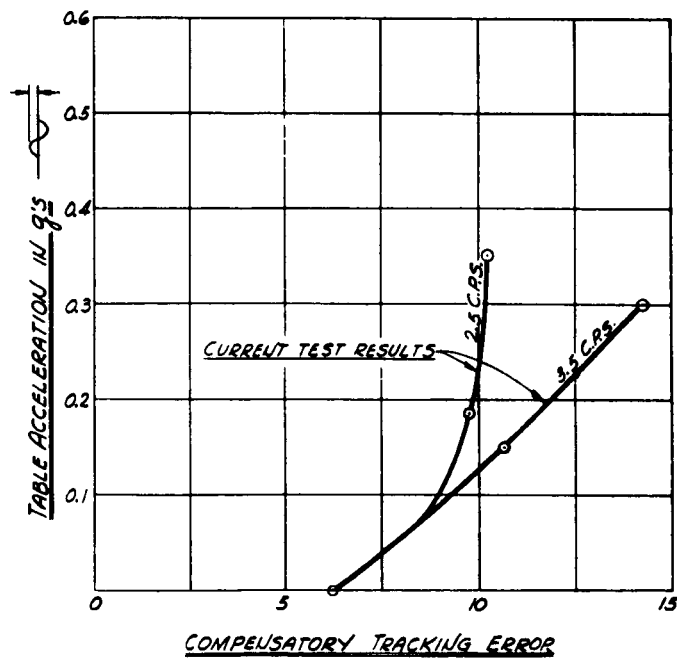
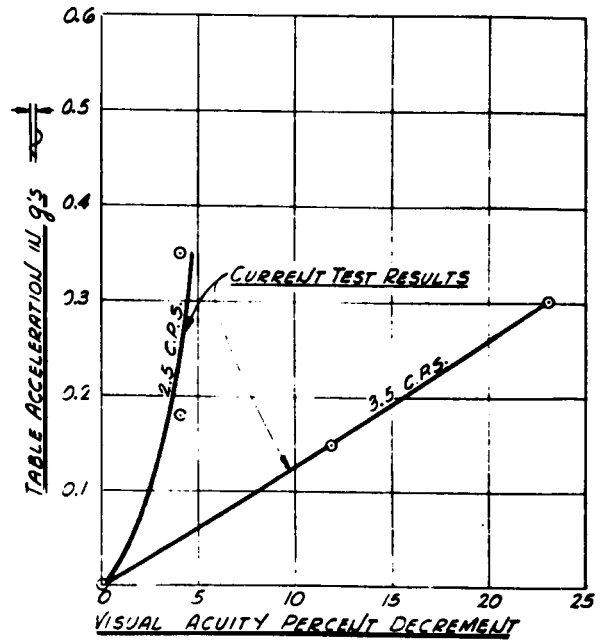
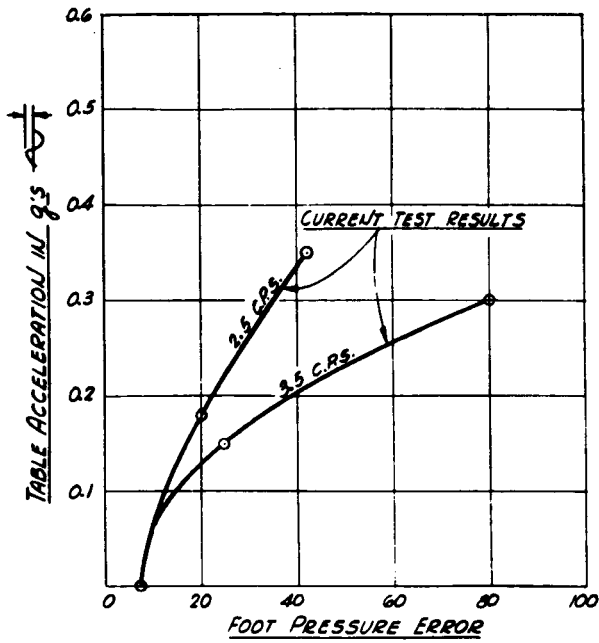


Figure 14.- Performance error as a function of vibration frequency and intensity for foot pressure, visual acuity, and compensatory tracking. (1 cps = 1 Hz.)

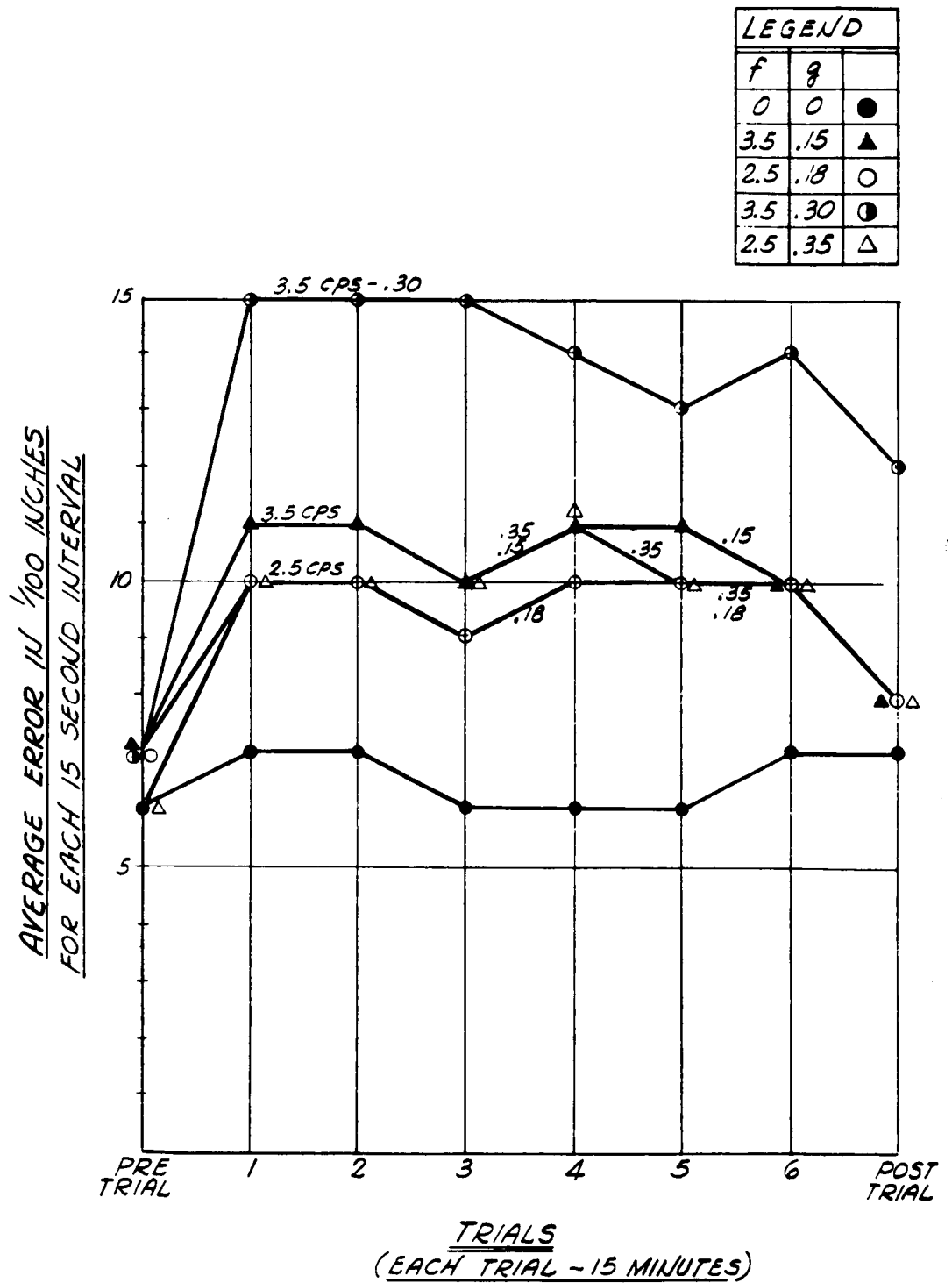


Figure 15.- Performance error as a function of vibration exposure duration. (1 in. = 2.54 cm; 1 cps = 1 Hz.)

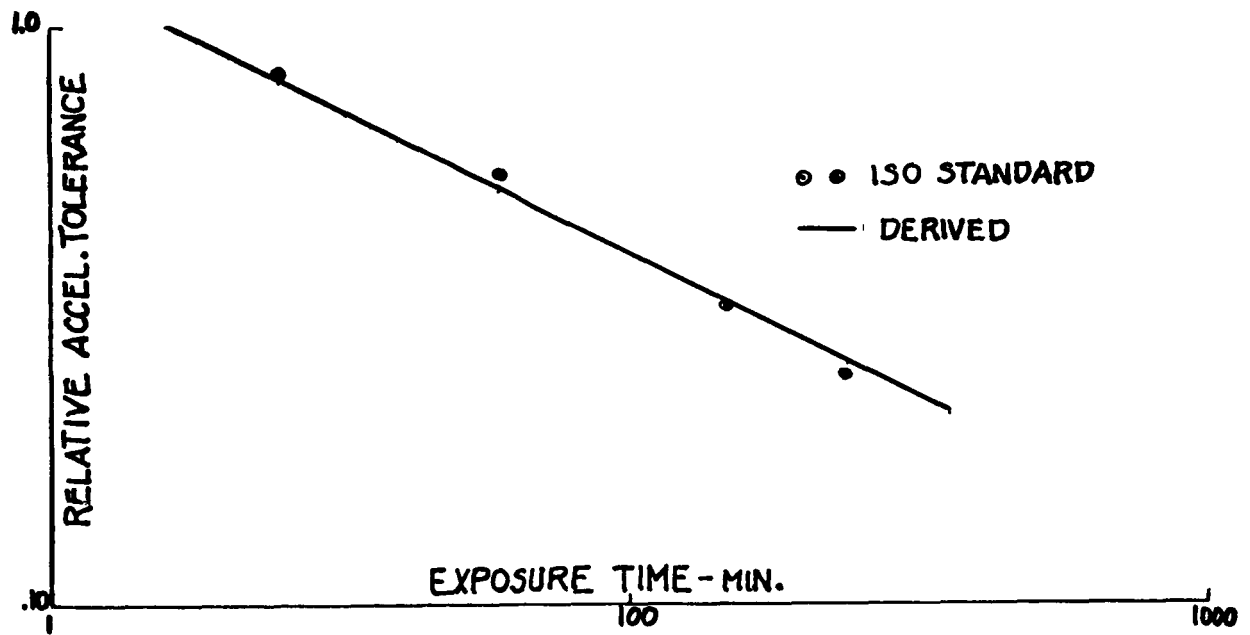


Figure 16.- Relative vibration fatigue tolerance as a function of exposure time, based on constant absorbed energy.