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To the Graduate Council:

I am submitting herewith a thesis written by Howard Thomas Joseph Duffey entitled "X-Y-Z vibration amplitude risk assessment for 3/8" hobby grade hand-held electric drills based upon current occupational safety standards." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.

Jack F. Wasserman, Major Professor

We have read this thesis and recommend its acceptance:

Judy L. Cezeaux, John H. Forrester

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Howard Thomas Joseph Duffey IV entitled "X-Y-Z Vibration Amplitude Risk Assessment for 3/8" Hobby Grade Hand-Held Electric Drills Based Upon Current Occupational Safety Standards." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.

Dr. Jack F. Wasserman, Major Professor

We have read this thesis
and recommend its acceptance:

Dr. Judy L. Cezeaux

Dr. John H. Forrester

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

X-Y-Z VIBRATION AMPLITUDE RISK ASSESSMENT FOR 3/8" HOBBY GRADE HAND-HELD ELECTRIC DRILLS BASED UPON CURRENT OCCUPATIONAL SAFETY STANDARDS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Howard Thomas Joseph Duffey IV

August 1997

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DEDICATION

This thesis is dedicated to my grandmother

Ms. Martha Mason Duffey

Throughout the years she has provided me with encouragement, patience, support, and Love which has helped me through some very difficult times, both personally and academically. She has stood by me through both my undergraduate and graduate careers. It has always been her dream to see me reach this point in my life. Without her I would have never achieved this milestone. Therefore, I would like to thank her from the bottom of my heart.

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My heartfelt thanks is extended to **Dr. Jack Wasserman**, my major professor. His endless patience, technical expertise, inexhaustible energy, and sense of humor have provided me with both personal and academic guidance throughout my graduate career.

I would also like to recognize the contributions of my other committee members, **Dr. Judy Cezeaux** and **Dr. John Forrester** who have given me their guidance and assistance. **Mr. Logan Mullinix** and the employees of the ESM shop, particularly **Mr. Ken Thomas**, also deserve thanks for the help they have given me.

Special thanks also goes to **Mr. Donald Wasserman**, the leading authority in the field of occupational vibration. He has provided me with much insight about the topic of Hand-Arm Vibration, and provided me with invaluable assistance with this thesis.

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Throughout the past few years I have taught Basic Engineering Graphics for the Department of Engineering Science and Mechanics. I would like to say thank you to all the students I have instructed and to the instructors whose classes I have taken. The **Department of Engineering Science and Mechanics** provided financial support during my graduate career, and I would like to thank the department, and particularly **Ms. Eunice Hinkle** for their support.

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Finally, I would like to thank **my Lord and Savior, Jesus Christ** for listening to my prayers and providing me with the courage, strength and wisdom to achieve this goal.

ABSTRACT

Hand Arm Vibration Syndrome (HAVS) is a pathological condition, associated with the use of a hand-held vibrating tool, that affects over one million United States workers. This condition was first discovered in the early twentieth century. Stages of the disease, with its associated neurological and peripheral vascular components, have been clearly defined. Currently, there are three hand-arm vibration safety standards in use: ISO 5349, ACGIH-TLV, and ANSI S3.34. Since the 1960's, numerous studies have been conducted for various commercial grade hand-held tools known to be associated with the disease. The majority of all reported tool testing has involved tools used by workers who have developed HAVS symptoms. The standards have been used as guidelines for maximum recommended vibration exposure times for these tools.

Standard inexpensive hobby grade hand-held vibratory tools, usually used on a short-term non-continuous basis, are not associated with HAVS. Until now, there has been no data to estimate the risk factors associated with these tools. Therefore, there is a question as to whether this is due to low vibration levels, limited daily exposure, or possibly a combination of factors. Vibration acceleration amplitude testing for this thesis was conducted using 3/8" hand-held electric drills; a standard hobby grade tool commonly used both by commercial contractors and laymen.

This study was conducted to: 1) compare measured vibration amplitudes to the current safety standards, 2) compare measured vibration amplitudes for four different common bit/material combinations, 3) determine any effects that tool age and usage might

have on measured vibration amplitudes, 4) verify repeatability of experiments, 5) determine any statistical correlations that might be present from examination of the experimental data, 6) examine the most appropriate method for testing such tools as those used in the study, and 7) make any necessary recommendations regarding usage and exposure to vibration from these tools.

Ten 3/8" electric drills, representing a wide variety of tool ages and manufacturers were obtained from various local sources. Using conditions designed to simulate the workplace where they might commonly be used, vibration testing was conducted for these tools using four different material/drill bit combinations. Triaxial accelerometer assemblies mounted to the tools in accordance with the current ANSI safety standard were used to obtain accelerations which were recorded on digital audio tape (DAT). The raw unweighted data was then digitized and computer analyzed to obtain Fourier vibration spectra, which were then converted to the third-octave frequency bands and root mean square (rms) acceleration values required by the ANSI S3.34 and ACGIH current safety standards. The results, weighted in accordance with the standards, were then compared to the standards to determine recommended maximum acceptable vibration exposure times.

It was hypothesized that: 1) the vibration amplitudes measured for this class of hobby grade tools would be well within current safety standards, 2) concrete would show the largest vibration amplitudes, followed by steel, wood, and finally plastic, in order of decreasing amplitude, 3) older drills obtained from local rental agencies would show much higher vibration levels than newer/refurbished ones, 4) repeatability would be verified by performing several vertical trials for each material/bit combination and taking an average, 5) certain

statistical patterns would be clearly evident from the experimental data obtained, 6) the reason for lack of HAVS prevalence would be determined, and 7) recommendations regarding usage, exposure, limitations, and testing procedures could be made, based on the results obtained from this study.

All plotted third-octave vibration spectra and rms acceleration values were examined from the perspectives of basicentric axis comparisons and material comparisons. Unfortunately, the experimental testing results did not show clearly definable patterns. Therefore, generalizations could not be made. According to the data obtained, none of the tools drilling in any of the materials tested here could be thoroughly evaluated, based on the limited amount of experimentation conducted for this thesis. Although, in most cases, the results did not exactly support the proposed hypotheses, they did provide some valuable information about this class of hobby grade tools.

In most cases acceleration amplitudes measured for the tool barrel were much higher than those at the tool handle. Student t-tests were performed for four randomly chosen accelerometer mounting location comparisons trials. These results did show statistically significant differences in acceleration magnitudes measured at the handle and barrel mounting locations during two-handed drilling. This seems to suggest that the standard contains some ambiguities concerning accelerometer placement and grip position during two handed drilling, when one hand is used for stabilization. The drills themselves appear to matter more than the specific materials with the appropriate bits, which are optimized for them. The condition of each tool also appears to be critical to measured acceleration levels.

Based on the results obtained herein it is recommended that vibration testing for hobby grade tools, such as those used for this study, should be conducted at the specific workplace under the exact conditions that they will be used. These tests should also be conducted with the specific worker(s) using the tool upon the specific materials for which it will be used. Both handle and barrel mounted acceleration amplitude measurements should be taken simultaneously. The focus of future research should be narrowed to help reduce the number of outstanding variables. Multi-factorial statistical analysis, which takes into account several variables that might affect measured vibration acceleration values should also be performed.

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CHAPTER I

INTRODUCTION

A. Rationale

Vibration is present in most work settings where mechanical equipment is used. Eight million workers in the United States alone are exposed to health effects associated with industrial/occupational vibration; over one million of these are exposed to a pathological condition known as Hand-Arm Vibration Syndrome (HAVS), usually transmitted to the hand and arm by a vibrating hand-held tool (Wasserman, 1988). Assuming that someone works at the same vibration-susceptible job for 30 years, 50 weeks per year, 30 hours per week, that person is exposed to approximately 45,000 hours of vibration (Wasserman, 1987). Examples of tools known to be associated with HAVS include chippers, grinders, jack-hammers, chain saws, trimmers, drills, impact hammers, rivet guns, impact wrenches, and many other hand-held electric, pneumatic, or battery powered machines.

B. Problem Statement

Numerous hand-held vibration-inducing tools, which have been the subject of research studies, are known to be associated with the development of HAVS. They are commercial grade tools that are used continuously for long periods of time in industrial settings. A

comparison of reported data and current safety standards has been used to determine maximum recommended safe vibration exposure times for such tools. However, for standard inexpensive hobby grade tools, which are designed for short-term non-continuous usage, data to support such guidelines does not currently exist. Until now, there has been no way to estimate the risk factors associated with them. There has also been no documented evidence to indicate the reason for the low rate of HAVS associated with such standard hobby grade tools. There is a question as to whether this is due to low vibration levels, limited daily exposure, or maybe a combination of factors.

C. Research Objectives

This thesis reports on a study of vibration in 3/8" electric drills, a class of inexpensive hobby grade tools, used commonly by both laymen and industrial workers. Because of the variety of ways these tools are used, part of the effort involved defining a general testing protocol. The main objective was to compare the results to American National Standards Institute (ANSI) S3.34 and American Conference of Governmental Industrial Hygienists threshold limit values (ACGIH-TLV) safety standards for vibration, and to identify the potential risks, if any, which might be associated with continuous long-term use of this class of hobby grade tools.

Attempts were made to answer several questions with this research study:

1) Why have there been no reported cases of HAVS associated with the use of this class of hobby grade tools? Is the absence of HAVS due to low vibration amplitudes, limited non-continuous daily use, or maybe a combination of factors? It was expected that it was due to a combination of both of these factors.

2) Does the amount of vibration measured for 3/8" electric drills exceed current hand-arm vibration safety standards? It was expected that the vibration amplitudes measured for this class of tools would be within acceptable guidelines, because the safety standards were designed to apply to commercial grade tools such as chipping hammers, which are much more powerful vibration sources.

3) What variations are observed in measured vibration amplitudes for four different common materials: wood, steel, concrete, and plastic? It was theorized that even with the use of specialized drill bits, the composition of different materials, amount of material binding, and material density would have an effect on the amount of vibration measured. Thus, plastic was expected to produce the lowest vibration amplitudes because of its soft homogeneous composition and the large pitch angle of the plastics drill bit. Wood was expected to have amplitudes that were slightly higher than those in plastic, especially in the X- and Y-directions, which were in the same plane as the surface being drilled. This is due to its non-homogeneous composition, which causes

the drill bit to bind. Steel was expected to have fairly high vibration amplitudes, because of its density, hardness, and tendency to bind due to large amounts of heat released during drilling, particularly in the X- and Y-directions, which were in the same plane as the surface being drilled. Concrete was expected to have the highest amplitudes of vibration, mainly in the Z-direction, normal to the surface being drilled, because of its loosely packed composition and the small pitch angle of the drill bit used for penetration.

4) Since the wide variety of 3/8" electric drills used for these experiments, obtained from local rental and personal sources, were of varying ages, it was questioned whether tool age and use would have any effect on measured vibration amplitudes. The assumption was made that tools which had been subjected to more use, particularly those regularly rented by local contractors, would contain more worn and loose-fitting internal parts. Therefore, the amplitude of measured vibration was expected to be higher for them than for the newer/refurbished ones which had not been used regularly.

5) Can the results obtained be repeated and what is the most appropriate method for testing these tools? In order to verify repeatability several vertical drilling trials were conducted for each material with each drill, and an average value obtained. Also, one horizontal trial was performed for each material and each drill, for purposes of comparison with the vertical trials. The results were then examined statistically in order to ascertain the most appropriate method for testing this class of tools.

6) Based on the amplitudes of the acceleration values obtained, what statistical correlations related to material and tool age appear to be present? What is the probability that one material will prove to be a greater cause of vibration than another? Is any statistical significance shown for tools of varying ages used upon different materials? It was expected that statistical patterns would emerge from the measured vibration data regarding both material and tool age.

7) Based on the results of the experimental evidence obtained for this thesis, what recommendations can be made regarding usage and exposure to vibration from 3/8" hobby grade drills?

CHAPTER II

BACKGROUND

A. Introduction

In 1862 Dr. Maurice Raynaud, a French physician wrote a thesis entitled "Local Asphyxia and Symmetrical Gangrene of the Extremities." In his thesis, he described "a condition, a local syncope, where persons, who are females, see under the least stimulus one or more fingers becoming white and cold all at once. The determining cause is often the impression of cold. The cutaneous sensibility also becomes blunted and then annihilated." He called this condition Raynaud's phenomenon. Today it is known as primary Raynaud's disease (Wasserman, 1987). It has been defined as "intermittent constriction of the peripheral vessels with subsequent color change of the skin of the extremities; pallor, cyanosis or both" (Pelmear et al., 1994). This condition may also occur in association with a number of diseases, or from secondary causes. One of the secondary causes of Raynaud's disease is microtrauma to the digital blood vessels leading to occlusion, or thrombosis, which may cause a reduction of finger systolic pressure. The most common cause of microtrauma in secondary Raynaud's Disease is exposure to vibration in the workplace (Pelmear et al., 1994).

Beginning with the industrial revolution, workers began to be exposed to vibration in occupational environments, usually locally applied to specific body parts by gasoline, pneumatic or electrical tools (Wasserman, 1987). Pneumatic tools were first introduced in

Europe by the French in 1839. By 1890, they were used extensively in mines. In the United States, pneumatic tools were first used in the limestone quarries of Bedford, Indiana, about 1886 (Wald and Stave, 1992). Less than a century ago disorders of the hands and fingers were first reported among men who worked with vibrating hand tools. Since the early twentieth century, occupational vibration has been recognized as a subject that merits serious study (Wasserman, 1990). In 1911 Loriga, in Italy, first described "vascular spasm" or "white finger" in the hands of miners using these tools (Wasserman, 1987). Seven years later, in the winter of 1918, Dr. Alice Hamilton, a well-known United States government physician, was sent to investigate worker complaints at the Indiana limestone quarries. Several of the workers using vibrating pneumatic chipping, carving, and cutting hammers were complaining of severe pain in their fingers and hands, accompanied by "white fingers" after using them. Dr. Hamilton discovered that over 80 percent of the men with complaints were affected by this condition, and that they all had one factor in common: they used vibrating hand tools on the job in a cold environment (Wasserman, 1986). Although she lacked today's modern medical diagnostic tools, she concluded that this white finger condition appeared to be caused by three factors: 1) the manner in which the tools were held and used (ergonomics), 2) vibration of the tool itself, and 3) working in the cold environment. This was virtually the first time vibration had been linked with a disease-like condition and documented in the United States (Wasserman, 1987). In 1946 Dart described the effects of vibrating hand tools on 112 aircraft industry workers. The workers complained of pain, swelling, increased vascular tone in the hands and tenosynovitis, inflammation of the tendon sheath (Wasserman, 1995). With the advent of gasoline powered chain saws in the 1950's, the "white finger" condition was

recognized as arising from the effects of prolonged exposure to vibration (Wasserman, 1987).

Repeated exposure to excessive vibration can lead to a type of secondary Raynaud's phenomenon which begins with blanching of the digits. Cyanosis followed by redness may be seen before or after the blanching (Pelmear et al., 1994). This condition, commonly precipitated by cold, is also variously known as Raynaud's phenomenon of Occupational Origin, Vibration White Finger Syndrome (VWF), "Dead Hand" syndrome, and Hand-Arm Vibration Syndrome (HAVS). It is a well documented fact that circulatory hand disorders can result from the use of vibrating hand-held tools over long periods of time. HAVS is known to affect not only the circulatory system, but also the bones, joints, muscles, and nerves in the hands and fingers (Wasserman, 1995). There is also a psychosomatic factor; it has been shown that the number and severity of attacks increases during periods of emotional stress. HAVS can lead to atrophy of the fingers or even gangrene over a period of years. In the early 1960's Ashe and colleagues reported on HAVS. Their research revealed a conspicuous lack of quantitative information concerning both the affected workers and those using small hand-held vibratory tools (Wasserman, 1990). This was a real impetus in the testing of numerous commercial grade tools known to be associated with HAVS. Since that time a large variety of tools has been tested. Evidence has shown that adverse health effects can result from contact with almost any vibrating source if intense vibration between frequencies of approximately 4-5000 Hz is present for a significantly long period of time (Wald and Stave, 1992).

B. Vibratory Motion

Vibration, a mathematical vector quantity, is the periodic or random motion of a body in alternately opposite directions from a position of rest. Periodic motion refers to oscillatory motion of a body about a reference position, which repeats itself after a specified period of time (Wasserman, 1990). Periodic motion is measured and described using: a) sinusoidal motion and b) its frequency in number of cycles per second (Hz). Vibration is defined at each measurement point using three linear directions and three rotational directions. However, in most human vibration research only the linear directions are measured, reported, and compared to current health and safety standards. In addition, displacement of the moving/vibrating object is described with respect to a reference point (Pelmear et al., 1994). Both biodynamic and basicentric coordinate systems are used to define these directions during testing. The biodynamic coordinate system uses the third metacarpal as a frame of reference. However, since it is impractical to mount a triaxial accelerometer assembly to a human hand, the basicentric coordinate system (Figure 1), using the tool itself as a frame of reference, is the coordinate system of choice in hand-arm vibration testing. This means that the experiments conducted for this thesis attempt to provide a measure of hazard amplitudes produced by vibrations from tool, instead of actual vibration dosage received by the operator's hands (personal communication with D.E. Wasserman, 1997).

The simplest form of periodic motion is simple harmonic motion which, when plotted as a function of time, is represented as a sinusoidal curve that exactly repeats itself after certain period of time. Once the instantaneous displacement function of a moving body from

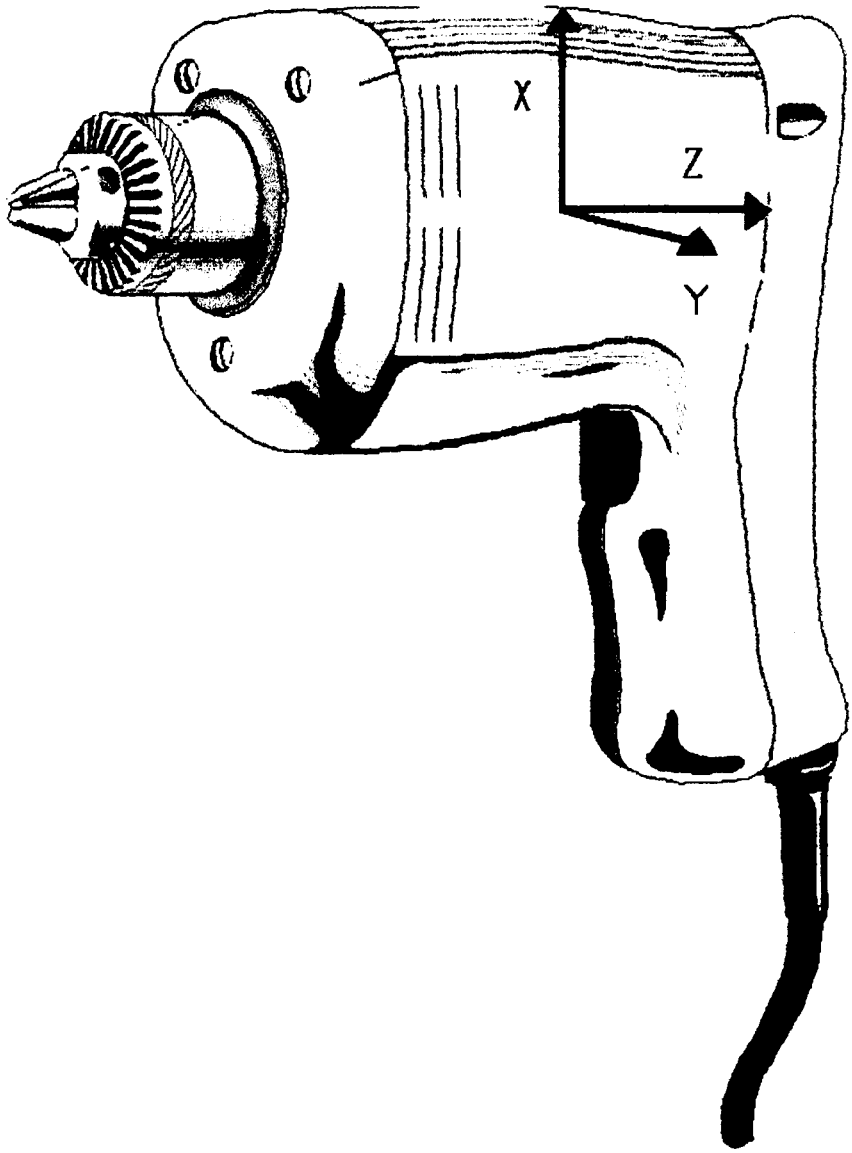


Figure 1. Basicentric vibration measurement coordinate system used for drill testing.

a reference point is known, its time rate of change (velocity) or first derivative, is expressed in units of displacement per unit time, usually ft/s or m/s. Acceleration is the time rate of change for the velocity function. Knowing (or measuring) displacement, velocity, or acceleration means the other two equations of motion may easily be derived and obtained mathematically using calculus (Wasserman, 1995). Units of ft/s^2, m/s^2, or g's (where 1g = 9.81 m/s^2 = 32.17 ft/s^2) are used to describe acceleration.

Merely viewing periodic motion of a moving object tells one little about its acceleration because the waveform includes a variety of different vibration frequencies and does not repeat itself in a cyclic manner. Peak acceleration values are proportional both to peak displacement and to the square of the frequency. Thus, as one visually observes a vibrating hand-held tool in use, even though only very small changes in displacement can be seen, there may actually be many g's of acceleration impinging on the operator's hands because of high frequency vibration components (Wasserman, 1995). This type of vibration may be characterized as complex periodic motion. It is associated with multiple vibration frequencies, all of which contribute various amplitudes. All of this impinges on the worker at once. Because of its non-periodic nature, the result is a broad continuous frequency spectrum (Wasserman, 1995).

When simple harmonic vibration is considered, peak values are useful. However, mechanical vibration found in the workplace is much more complex. The total acceleration waveform does not repeat itself in a cyclic manner and varies irregularly with time. Therefore, the "root-mean-square" (rms) acceleration value, with a sinusoid having a zero mean, is a more useful measurement quantity (Pelmear et al., 1994). Acceleration

measurements are squared, summed over the measurement period, and divided by total measurement time period. Finally, the square root of the quotient yields the resulting answer.

In the 1800s, Fourier, a French mathematician, showed that complex periodic waveforms are composed of a series of sinusoids with differing frequencies and amplitudes (Wasserman, 1987). Complex vibration data contains multiple frequencies all of which contribute various amplitudes to the total measured vibration. Fourier spectrum analysis (Figure 2) may be used to describe this type of vibration (Wasserman, 1995). In order to show the Fourier frequency and amplitude components, a mathematical conversion from the time domain to the frequency domain is performed and the results are plotted graphically (Wasserman, 1995). The horizontal axis of a Fourier spectrum represents frequency and the vertical axis represents magnitude of the quantity being measured (for example: acceleration). The number of vertical peaks indicates the total number of vibratory frequencies, and the horizontal position of each peak defines its vibration frequency in the Fourier spectrum. The height of each peak determines the acceleration amplitude that it contributes to the total vibration spectrum. These relative peaks correspond to their relative contributions to the total measured vibration. The Fourier spectrum can be used as a "fingerprint" to characterize each tool test (Wasserman, 1990). For drilling, vibration spectra are also different depending on the direction (axis) of measurement due to the effects of the composition of different materials, amount of material binding, and material density. Special digital computer algorithms, called Fast Fourier Transforms (FFTs) are used to speed computer processing, and make spectrum analysis in the workplace easier and quicker (Wasserman, 1995).

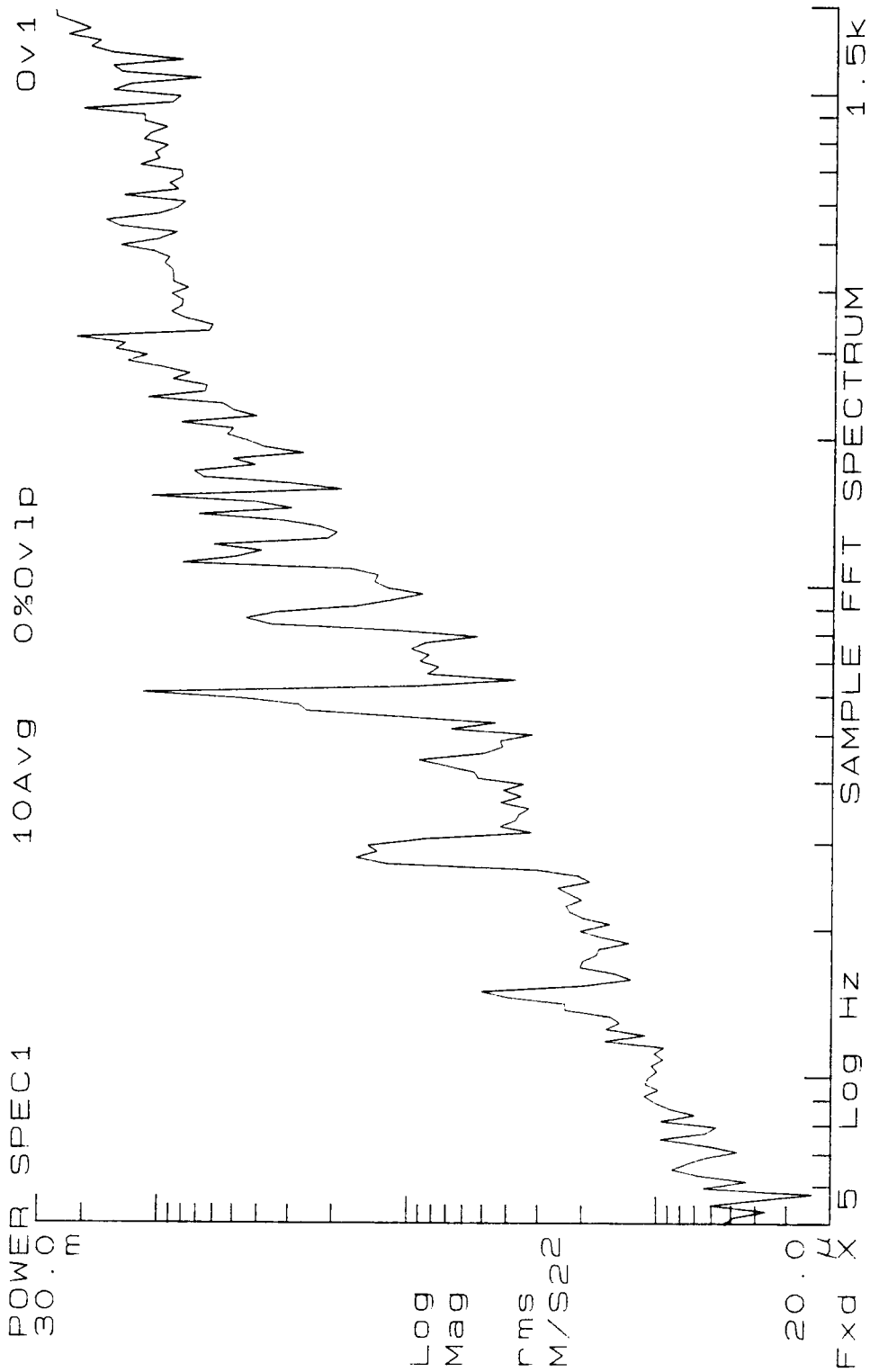


Figure 2. Sample Fourier spectrum of raw unweighted acceleration data on a log scale.

Octave frequency analysis is a standard way in which sound is analyzed. Third-octave analysis is similar to octave analysis, but it uses better resolution to look at the data more carefully. It is a way of looking at the amount of vibration energy for the measured bandwidth defined in section 8.3.2.1 of ANSI standard S3.34. Third-octave analysis is used to convert the Fourier vibration spectra into proper format (Figure 3) for comparison with current hand-arm safety standards.

Vibration, present in most work settings where mechanical equipment is used, is transmitted to the operator of a vibrating hand-held tool in three ways: a) directly by the worker-tool interface, b) indirectly by the tool-material interface, and c) by intrinsic properties of the tool itself, related to the vibratory motion of the electric motor (Pelmear et al., 1994). Acceleration is believed to be the physical source of biological damage for occupational vibration. However, vibration displacement or velocity may contribute to a lesser extent (Wasserman, 1988).

Resonance is the tendency of the human body (or any other mechanical system) to act in concert with externally generated vibration to actually amplify the impinging vibration. This means that the human body acts like a selective filter that rejects certain vibratory frequencies, and readily accepts and amplifies other vibration frequencies. This amplification causes exacerbation of undesired effects (Wasserman, 1995). At these resonance frequencies, the human body is optimally coupled to the vibration source. This allows maximum transfer of mechanical vibration from the source to the worker, with the worker's body amplifying the actual incoming vibration by a factor of 1.5 to 3 times (Wasserman, 1990). In structural dynamics resonance vibration can destroy structures such as bridges. The frequencies from

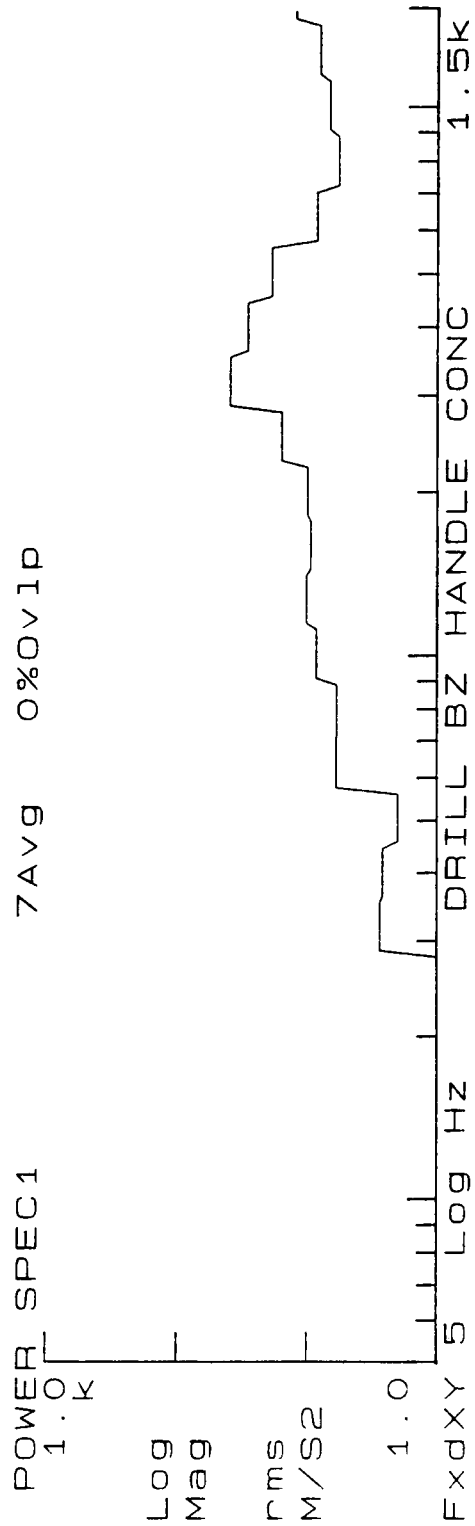


Figure 3. Sample third-octave analyzed spectrum compared to ANSI S3.34 safety standard.

100-300 Hz produce human resonance responses. It is believed that the vibration from hand-held tools producing frequencies within this bandwidth is largely responsible for harm and damage (Wasserman, 1988; Wasserman, 1995).

C. Hand Arm Vibration Syndrome

The predominant health effect related to occupational vibration is the disease entity known as Hand-Arm Vibration Syndrome (HAVS) (Wald and Stave, 1992). It affects one or both upper extremities and is usually transmitted by the continuous long-term use of a vibratory hand-held tool in the workplace. Pathogenic mechanisms for hand-arm vibration-induced disorders are target specific, meaning that occupational vibration must reach an organ in sufficient amounts to cause harmful effects. Finger skin tissue is approximately two millimeters thick (Pelmear et al., 1994). Vibration from hand-held tools is largely absorbed by the skin where it has the potential to cause mechanical damage to the peripheral circulation, vasoregulatory nerve structures, and parts of the musculoskeletal locomotor apparatus of the hand and arm. Circulatory disturbances include cold-induced vasospasm with local finger blanching or white finger. Sensory and motor disturbances include numbness, loss of finger coordination and dexterity, clumsiness and inability to perform intricate tasks. Musculoskeletal disturbances include muscle, bone, and joint disorders such as osteoarthritis and impairment of grip strength due to incomplete muscular contraction (Pelmear et al., 1994).

D. Research and Testing

Adverse health effects from exposure to hand-arm vibration (HAV) were first recognized by Loriga in Rome in 1911 when he reported "dead fingers" among Italian miners using pneumatic tools (Wasserman, 1995). In Dr. Alice Hamilton's comprehensive 1918 study, vibration was first linked to Hand-Arm Vibration Syndrome (HAVS). She examined 28 stonecutters/carvers who had been using vibrating pneumatic tools. One thing they had in common was use of vibrating hand-held tools on job. She found that 89 percent (25/28) of them had similar symptoms (Wasserman, 1987). Since the Hamilton study there have been numerous worldwide reports of health hazards from the use of hand-held vibrating tools (Wald and Stave, 1992). Traditional hand-arm epidemiology and measurement studies have focused on three tool categories; gasoline chain saws, pneumatic hand-held tools, and electrical hand-held tools (Wasserman, 1987). Among those pneumatic tools which have been tested are chipping tools, grinders, jack-hammers, rivet guns, and jack-leg type mining drills. Electric tools tested include impact hammers, grinders, sanders, and pedestal grinders (Wald and Stave, 1992). Table 1 summarizes some of the pioneering research involving hand-arm vibration.

In the 1940's Agate and Druett concluded from a study of portable vibratory tools known to be associated with HAVS, that vibrations of large amplitude were produced between 40-125 Hz. However, their clinical data also showed that vibrations below 600 Hz are not likely to produce HAVS (Pelmear et al., 1989). More recent studies do not support this. In 1945 Hunter and colleagues reported HAVS with a predominant frequency of 30-50

Table 1

Historical Perspective of Some of the Pioneering Research in Hand-Arm Vibration Syndrome

DATE	RESEARCHER	CONTRIBUTION
1839	-	Pneumatic tools introduced in Europe
1862	Raynaud	Thesis entitled "Local Asphyxia and Symmetrical Gangrene of the Extremities"
1886	-	Pneumatic tools first used in Indiana Limestone Quarries
1890	-	Pneumatic tools used extensively in mines
1911	Loriga	First describes "white finger" in Italian miners
1918	Hamilton	80% HAVS prevalence in Indiana workers using vibrating pneumatic tools
1938	ACGIH	ACGIH first organized to develop technical aspects of worker health protection
1945	Hunter and colleagues	HAVS predominant frequency of 30-50 Hz in pneumatic tool users
1946	Dart	Described effects of hand-held vibrating tools on aircraft workers

DATE	RESEARCHER	CONTRIBUTION
1947	Agate and Druett	HAVS not likely below 600 Hz. Large vibration amplitudes 40-125 Hz
1950's	Taylor and Pelmear	Advent of gasoline powered chain saw. Typical studies show 6-89% prevalence. Amplitudes up to 294 m/s^2 for 10-2000 Hz bandwidth
1960's	NIOSH	19-40% HAVS prevalence in foundries and shipyards
1962	Pyykkö and colleagues	Strong vasospasm between 80-125 Hz
1965	Pelmear and colleagues	Ontario rock miners show 43% HAVS prevalence
1966	Nohara and colleagues	Confirmed that vascular and nervous tissues respond to different frequencies. Digital circulation decreased between 60-480 Hz and nerve conduction velocity decreased between 30-120 Hz
1966	Danadell and Engstrom	Observed dominant frequencies between 31 Hz to 6 kHz for various pneumatic tools
1967	Lundborg and colleagues	Most sensitive frequency range for psychophysical vibrotactile perception was 250-300 Hz

DATE	RESEARCHER	CONTRIBUTION
1967	Pyykkö and Gemne	Pacinian corpuscles of skin respond between 60-700 Hz
mid 1970's	-	U.S. research focuses mainly on pneumatic tools
1970's	ISO	First version of ISO 5349 safety standard is published
1971 1977	Abrams plus Reynolds and Angevine	Resonance seen between 150-200 Hz
1978	NIOSH	Repeat of Hamilton Study. 80% prevalence found. Measured amplitudes of 2000-4900 m/s^2
1982	NIOSH	41-47% HAVS prevalence in foundry workers using pneumatic tools
1980's	NIOSH	45% HAVS prevalence in foundry study
1983	Ontario, Canada Ministry of Labour	Pneumatic tools shown to have greatest vibration amplitudes at 5-1000 Hz. Dominant frequency bands seen between 100-125 for tested chainsaws, and 13-16 Hz plus 40-400 Hz for pneumatic tools
1984	ACGIH	Hand-arm ACGIH-TLV is introduced
1984	NIOSH	17.5% HAVS prevalence in shipyard study
1985	Stockholm	Stockholm classification replaces Taylor-Pelmear system. Based on results of clinical testing.

DATE	RESEARCHER	CONTRIBUTION
1986	ISO	latest version of ISO 5349 safety standard published
1986	ANSI	ANSI standard S3.34 for HAV published
1989	NIOSH	NIOSH interim standard published which outlines medical monitoring and engineering controls to help avoid HAVS

Hz in pneumatic tool users (Pelmear et al., 1989).

Considerable vibration is present in gasoline powered chain saws due to the imbalance of the engine. With their increased popularity in the early 1950's, HAVS prevalence began to appear from the effects of prolonged exposure (Wasserman, 1995). Typical studies have shown 6%-89% prevalence of HAVS in chain saw users with a range of latent periods which varies between 1-5 years (Wasserman, 1987). Acceleration amplitudes for conventional gasoline powered chain saws can range as high as 294 m/s^2 for a frequency bandwidth of approximately 10-2000 Hz (Wasserman, 1987). Pneumatically driven vibratory tools which use compressed air have been linked to HAVS in several cases. Vibration amplitude levels for these tools have been shown to exceed 20,000 m/s^2 depending on tool type, condition, and other factors (Fishman et al., 1983). Studies of pneumatic chipping and grinding tools were conducted in foundries and shipyards. A National Institute of Occupational Safety and Health (NIOSH) study of 385 vibration exposed workers showed 19%-40% HAVS prevalence with latent periods ranging from 2-17 years (Fishman et al., 1983). A 1965 study of Ontario rock

miners who used mainly jackleg and stoper drills showed a 43% prevalence of HAVS finger blanching.

The hand-arm resonant frequency is believed to be between 100-300 Hz. Testing by Abrams and by Reynolds and Angevine implied that vibrations are transmitted to the forearms between 150-200 Hz (Pelmear et al., 1989). Limited medical evidence suggests most damaging frequencies for vascular effects are approximately 30-200 Hz plus 480 Hz, and 60-700 Hz for neurological effects (Pelmear et al., 1989). Nohara and colleagues studied the influence of vibration on peripheral circulation and nervous functions, confirming that vascular and nervous tissues respond to different frequencies. They found that digital circulation decreased between 60-480 Hz and peripheral nerve conduction velocity also decreased slightly between 30-120 Hz. (Pelmear et al., 1989). Pyykkö and colleagues found strong vasospasm between 80-125 Hz. After reviewing the pathophysiologic aspects, Pyykkö and Gemne found that the Pacinian corpuscles, rapidly adapting receptors in the skin that signal changes in pressure, respond to vibrations between 60-700 Hz (Sherwood, 1989; Pelmear et al., 1989). Using a vibrometer, Lundborg and colleagues demonstrated that the most sensitive frequency range for psychophysical vibrotactile perception was 250-350 Hz (Pelmear et al., 1989). Observations of HAVS patients which show that vascular and neurologic effects can develop separately support this experimental evidence (Pelmear et al., 1989).

By the mid to late 1970's research in the United States focused mainly on the effects of vibration on pneumatic tool users. In 1978, 60 years after the Hamilton study, a NIOSH team repeated the study at the same location in Bedford, Indiana. Despite the 60-year

difference they found virtually the same statistical prevalence (80%) of HAVS as that found previously, showing that neither the work conditions nor the chipping tools had changed. The measured vibration amplitudes taken from the limestone hammers ranged from 2,000 m/s^2 on the tool barrels where workers gripped the tools, to 4,900 m/s^2 on the chisels (Wasserman, 1987). In a large 1982 study of 386 foundry workers using pneumatic chipping and grinding tools, 41-47% prevalence of HAVS with a latent period of 1.1-2.4 years was seen. Another 1980's foundry study indicated 45% prevalence and a 2.2 year latent period for 49 workers. Approximately a 17.5% HAVS prevalence and a 19.4 year latent period was found in a 1984 shipyard study (Wasserman, 1995).

Since 1983, tool vibration amplitudes for frequencies between 2-1250 Hz have also been measured by the Ontario, Canada Ministry of Labour for three tool categories: 1) rock drills, 2) chainsaws, and 3) sand rammers. Rock drills tested include jacklegs, stopers, pneumatic hammers, chipping chisels, riveting hammers, and impact wrenches. Vibration amplitudes were found to be greatest between 5-1000 Hz. The dominant frequency bands observed between 25-80 Hz related to the drill-rod rotating and hammer stroke frequencies of the tools (Pelmear et al., 1989). For every chainsaw tested, a dominant band was seen between 100-125 Hz, related to the reciprocating forces of the internal combustion engine. Chain saw vibration acceleration amplitudes rose sharply from 5 Hz to the dominant frequency and gradually decreased thereafter. Two main frequency bands were observed for sand rammers; a sharp one between 13-16 Hz and a broader one from 40-400 Hz (Pelmear et al., 1989). In subsequent measurements Danadell and Engstrom tested some pneumatic tools: hammers, chisels, and bucking bars. Dominant frequencies for the hammer were 31.5-

50 Hz, 63-315 Hz, and 3-6 kHz. For the chisel they were observed at 50 Hz, 100-500 Hz, 1-1.5 kHz, and 3-8 kHz. Dominant bucking bar vibration was seen at 40 Hz, 100 Hz, and 2.5-6 kHz (Pelmear et al., 1989).

E. Symptoms and Stages

Some medical conditions may result in symptoms similar to HAVS which makes detection and physician's differential diagnosis very difficult. The Taylor-Pelmear classification for HAVS assessment, which was devised in 1968, describes the stages of HAVS development (Wald and Stave, 1992). The time between first exposure and the onset of fingertip blanching is called the latent interval. It ranges from about 1 month to 30 years, depending on intensity of vibration entering the hand and susceptibility of the worker (Wasserman, 1988). The worker first starts to notice intermittent tingling and numbness in fingers albeit not to the point of interfering with activities. In stage 1, blanching accompanied by numbness starts. Initially it is restricted to the tips of one or more fingers, but as exposure time increases it progresses to the base of the fingers and spreads throughout other areas of hand. The thumbs are usually affected last (Wasserman, 1987).

Attacks are often triggered by cold or dampness, usually lasting 15 to 60 minutes, or as long as two hours in advanced stages. They occur mainly during winter months, especially during early morning, either at home or when driving to work with the hands in contact with cold steering wheels. Recovery from attacks may be painful, starting with red flush, reactive hyperemia, usually seen in the palm and advancing from the wrist towards the fingers. There

is usually tingling and pain as circulation returns to the digits (Pelmear et al., 1994). Eventually, extensive blanching begins to interfere with activities at home and work. Other factors are involved, including central body (core) temperature, metabolic rate, vascular tone of vessels (particularly in early morning) and emotional state (Wasserman, 1987). The amount of tactile, vibrotactile, and thermal threshold impairment may vary from subject to subject; loss of grip strength and/or discomfort and pain in upper extremities are common complaints in workers with greater amounts of exposure (Wald and Stave, 1992).

Studies have shown that as exposure time increases, the number of attacks tends to increase (Wasserman, 1987). During stage 2, workers may report interference with or limitation of activities outside work, especially in a cold environment (Wasserman, 1995). Once the disease progresses to stage 3, attacks occur all year long. There is interference with work, particularly outdoors. There is also difficulty doing detailed indoor work or picking up smaller objects. In addition, there is an inability to distinguish between hot and cold objects, increased stiffness of finger joints, clumsiness, and loss of manipulative skills (Wasserman, 1987). Stage 4 is most severe of all including interference with work, social activities, and hobbies. If the degree of severity becomes great enough, occupational change can become inevitable (Wasserman, 1987).

In the later stages (2-4) HAVS is considered by most to be irreversible (Wasserman, 1987). This appears to arise from cumulative effect of vibration transmitted to hands due to regular and prolonged use of vibrating tools (Wasserman, 1995). In advanced cases, the peripheral circulation becomes very sluggish. There may be a cyanotic tinge to the skin of the digits. In very severe cases changes in the arteries of the fingers may lead to complete arterial

obstruction, and possibly even trophic skin changes (gangrene) (Wald and Stave, 1992). In 1985, the Stockholm classification, which is based on subjective history supported by the results of clinical tests replaced the Taylor-Pelmear system. Using this revised HAVS classification system, vascular and sensorineural symptoms, and signs are evaluated both separately and individually for both hands (Pelmear et al., 1994).

Evidence has shown that the neurological and peripheral vascular components associated with HAVS may develop independently (Wasserman, 1987). Questions remain as to what is actually being affected or destroyed; nerves and/or blood vessels? The most recent thinking is that the syndrome most likely results from cumulative effects of vibration-induced microtrauma to the nerves and blood vessels of the hands due to regular continued use of vibrating hand tools (Wasserman, 1987). It is also possible that there may be direct damage to sensory nerves or that physical vascular impairment results in ischemia or digital blanching. Exposure to vibration, noise and cold have all been shown to induce arterial constriction of the hand (Pelmear at al., 1994). In addition, blanching could be influenced by: a) stimulation of the sympathetic nervous system by vibration, and possibly noise and/or cold, b) increased sympathetic vasomotor tone secondary to (a), c) local effects on the vessel, such as hypertrophy of medial muscular arteriole layers, or hyper-responsiveness of smooth muscle to vasoconstrictive effects of circulating norepinephrine, d) adverse effects on arteriovenous anastomoses, and e) intimal damage to vessels due to shear stress. Increased blood viscosity is known to accompany other conditions associated with vascular damage. Therefore, there is a possibility that vibration-induced vascular endothelial damage, leading to episodic arterial closure induced by sympathetic reflex mechanisms, could result in reduced blood vessel

patency and increased blood viscosity. This could also indirectly decrease digital blood flow during attacks of vasospasm (Pelmear et al., 1994).

There are three major problem areas related to HAVS: 1) very little is known about the etiology and psychological basis, 2) no reliable objective medical screening tests exist for HAVS, and 3) currently used medical modalities are palliative, soothing but not curing, at best (Wasserman, 1995). Very little is known about the effects of such parameters as vibrational acceleration, velocity, resonances, frequency spectrum, or mechanical coupling and how they alter the acquisition and/or course of the disease (Wasserman, 1987).

Along with an increase in the use of hand-held vibrating tools in the 1960's came a consequent increase of HAVS. Therefore, researchers began to propose safety limits for vibration exposure. This eventually led to the creation of safety standards designed to reduce the probability of developing the disease.

F. Safety Standards

There are currently three hand-arm vibration safety standards in use: a) ISO 5349 (International Standards Organization - Geneva, Switzerland), b) ACGIH-TLV Hand-Arm Threshold Limit Values (American Conference of Government Industrial Hygienists - Cincinnati, Ohio), and c) ANSI S3.34-1986 (American National Standards Institute - New York, New York). In addition, the National Institute of Occupational Safety and Health (NIOSH) hand-arm criteria document (Henschel and Behrens, 1989) provides a work practices and medical monitoring approach without a numerical exposure recommendation

(Pelmear et al., 1994).

The International Organization for Standardization (ISO) is a consensus group consisting of the national standards organizations that lists over 5,000 published international standards concerned with noise, vibration, and a variety of other issues. The organization is composed of an estimated 20,000 engineers, scientists and administrators from some 90 ISO member countries who participate in committee meetings (Wasserman, 1987). They represent consolidated views and interests of industry, government, labor, and individual consumers. In the case of vibration, the ISO provides an international forum for individuals working together in the field to formulate consensus standards based on their collective knowledge (Wasserman, 1987).

ISO standards are currently in use in many worldwide countries and under current consideration by others. The most widely known of the hand-arm standards is ISO 5349; "Guidelines for the Measurement and Assessment of Human Exposure to Hand-Transmitted Vibration," which is based on proposals from the Japanese and Czechoslovakian vibration delegations to consider the effects of hand-transmitted vibration on humans (Wasserman, 1995). In accordance with this standard, vibration measurements are obtained using the biodynamic measurement coordinate system. The standard uses a four-hour weighted curve starting at approximately a 0.7 m/s^2 exposure limit for a bandwidth of 6.3-16 Hz and permits higher acceleration amplitudes with increasing frequency up to approximately 1250 Hz at 50 m/s^2 (Wasserman, 1995).

The original data for the standard were based on discomfort and tolerance levels and not derived from medical/epidemiological HAVS data. More intolerance was found at lower

frequencies and the data were weighted accordingly using weighting factors, which attempt to represent actual human hand-arm response to vibration exposure. This is analogous to "A" weighting of the human ear's response to sound (personal communication with D.E. Wasserman, 1997). Throughout the years ISO working groups have modified and reinforced the basic document using new data obtained from medical/epidemiological studies (Wasserman, 1987). Keighley stated that cumulative vibration exposure per day would be a more informative measure (Pelmear et al., 1989). Taylor and coworkers demonstrated a correlation between weighted vibration levels and latent intervals in workers with HAVS (Pelmear et al., 1989). This was further developed by Brammer in the early 1980's (Wasserman, 1995).

In 1982, Brammer performed an important study which provided information necessary for the current version of ISO 5349 issued in 1986. Using the data from many major epidemiological studies for worker populations with up to 25 years of exposure, which included a vibration measurement component and defined stages and latencies based on the Taylor-Pelmear Classification System, he weighted the acceleration values according to the latest revision of the ISO standard. The purpose was to provide a measurement of vibration dosage versus HAVS, which had previously been lacking (Pelmear et al., 1994).

Since the ISO is an international organization, it is the responsibility of the individual member nations to interpret their standards and decide what vibration amplitudes are considered hazardous (Wasserman, 1995). The first standard, introduced in the United States in 1984, was the ACGIH-TLV Threshold Limit Values. The American Conference of Governmental Industrial Hygienists (ACGIH) is not a U.S. government agency. It was

organized in 1938 by several governmental industrial hygienists who desired a medium for the free exchange of ideas and experiences and the promotion of standards and techniques in industrial health. The purpose the organization is the development of the technical aspects of worker health protection (Wald and Stave, 1992). In 1982 ACGIH asked some prominent vibration scientists for proposals of hand-arm Threshold Limit Values (TLV). This TLV was designed to be used in conjunction with a comprehensive package of other protective elements, such as work practices, anti-vibration gloves, and vibration reducing tools, in order to reduce vibration and help eliminate HAVS from the workplace (Wasserman, 1987).

The hand-arm TLV, which was first introduced in 1984, uses the same acceleration amplitude-frequency coordinate system as ISO 5349. However, instead of weighted curves, zones of maximum recommended daily exposure exposure times, from 30 minutes to 8 hours/day, are based on the weighted root mean square (rms) acceleration values obtained by computerized third-octave analysis. The 30 minute exposure amplitude levels starting at 12 m/s^2 are shown, as is the 8 hour/day, 4 m/s^2 maximum exposure in Figure 4 (Wasserman, 1987).

ACGIH criteria uses triaxial acceleration measurements which are obtained over a third-octave band 5.6-1250 Hz vibration frequency range and weighted in accordance with the standard. Total rms acceleration is determined separately for each of three linear orthogonal axes. If measured rms accelerations for any one of the measured three axes exceeds one or more TLV's, then the standard has been exceeded (Wasserman, 1987). As new scientific and technological advances are made, ACGIH bylaws permit periodic revisions of TLVs. Therefore, as more data becomes available this TLV could be modified to provide

FREQUENCY-WEIGHTED rms ACCELERATION (m/s^2)		MAXIMUM RECOMMENDED DAILY VIBRATION EXPOSURE (hours/day)
4.0	---------->	4 hours and less than 8
6.0	---------->	2 hours and less than 4
8.0	---------->	1 hour and less than 2
12.0	---------->	Less than 1 hour

Figure 4. ACGIH-TLV for X, Y, Z exposure of the hand to mechanical vibration. (source: ACGIH-Threshold Limit Values and Exposure Indices., 1989-1990)

increased protection (Wasserman, 1987).

In 1986 the ANSI S3.34 standard, an offshoot and modification of ISO 5349, was published by the American National Standards Institute. Although the ANSI exposure curve is similar to the ACGIH-TLV, its 8-hour limit is more stringent, at low frequencies, and is set to approximately 3 m/s^2 (Wald and Stave, 1992). Graphically, it is described using third-octave vibration frequency bands extending from 5.6-1250 Hz along the horizontal axis, and vibration intensity levels expressed in m/s^2 on the vertical axis. A series of "elbow shaped" weighted curves, (Figure 5) which indicate human frequency sensitivity, represent maximum daily exposure zones (Wald and Stave, 1992). The graph is used separately for the third-octave vibration spectra measured along each of three orthogonal measurement axes. If measured spectral peaks exceed one or more of these exposure zones are exceed along any one of the three axes, then the standard has been exceeded. The maximum recommended daily exposure in hours/day is determined by the highest occurring spectral peak (see p. 15) intersecting the largest number of exposure zone curves.

The elbow shaped weighting curves of the ANSI standards represent a family of frequency-dependent curves for various exposure times in a typical work day. The horizontal portion represents constant acceleration up to 16 Hz. Thereafter, as frequency increases, the amplitudes of the curves increase, representing increasing acceleration at proportional constant velocity for a rotating source. Measured acceleration values which fall below their respective time dependency curves indicate periods of time during which use of the measured tools might be considered safe (Wasserman, 1995). Both standards have the horizontal axis defined over a fairly wide frequency bandwidth in order to encompass multiple tool spectra

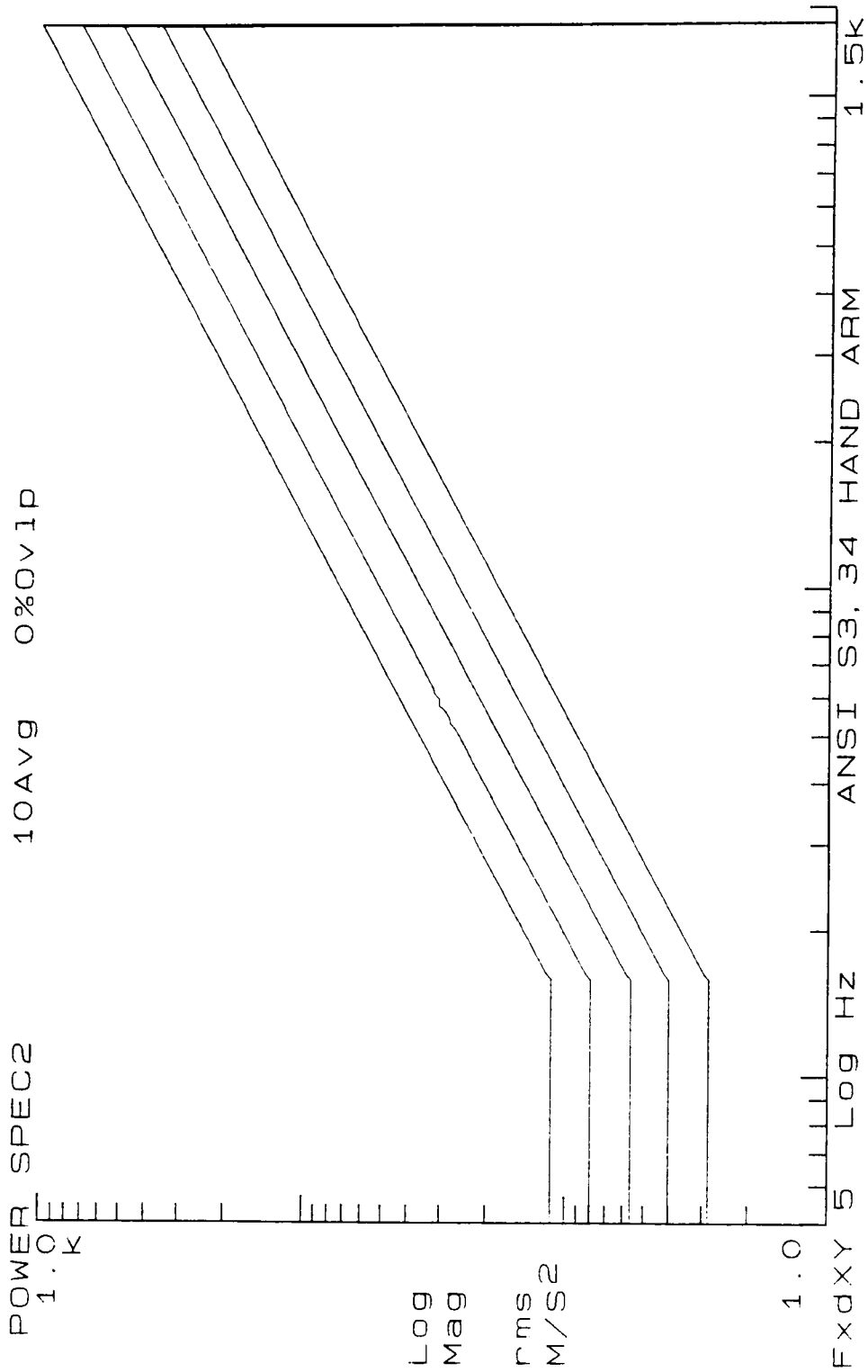


Figure 5. ANSI S3.34 X, Y, Z vibration exposure zone curves for mechanical vibration. (source: ANSI S3.34-Guide for the Measurement and Evaluation of Human Exposure to Vibration Transmitted to the Hand., 1986)

which might be encountered in the workplace. Currently, both the ACGIH-TLV criteria and ANSI S3.34 curves are in use in the United States. Most hand-arm vibration standards are designed to reduce the probability of an HAVS attack occurring (personal consultation with D.E. Wasserman). The engineers and scientists responsible for the development of these standards strove to present the best standards currently known. One of the major problems with such workplace standards is that the user automatically assumes they are the "ultimate in protection," but in many cases they are not. Because there is a possibility for potential unintentional misuse of the standard caveats, footnotes, and appendices are included to emphasize limitations of use (Wasserman, 1987). The National Institute of Occupational Health (NIOSH) has not yet chosen a maximum permissible acceleration value for hand-arm vibration; instead, it relies on medical monitoring and engineering controls plus an extended high-frequency range cutoff of 5000 Hz. This is outlined in the NIOSH interim standard number 89-106 which gives recommendations but does not specify any vibration exposure limits (Wald and Stave, 1992).

Present standards and guidelines all use frequency-weighted acceleration in m/s^2. They presume that health effects are frequency independent between 6.4-16 Hz and frequency dependent between 16-1250 Hz. The standards also assume that low frequency vibration is more hazardous and use unity as the weighting factor, designed to represent actual human response, at the frequencies of 6.4-16 Hz (Pelmear et al., 1989). Griffin suggested that the standards should be used to estimate HAVS response versus vibration dosage but not to specify normal vibration limits (Pelmear et al., 1989). However, recent epidemiological studies have shown both underestimation and overestimation in HAVS incidence from ISO

vibration dose-HAVS response criteria for different tools (Pelmear et al., 1989). In addition, evidence suggests that since the vascular and neurologic effects of HAVS can develop independently, different weighting networks are required to determine appropriate safety levels. Unfortunately, the evidence to date is not conclusive enough to be certain as to what these networks should be (Pelmear et al., 1989). Since higher frequency vibrations are preferentially absorbed by the skin and subcutaneous layers, it is tentatively suggested that vascular tissue is affected mostly by lower frequency components and the neurologic tissue by higher frequency ones (Pelmear et al., 1989).

From the third-octave band analysis of vibratory hand-held tools it is clear that the center frequencies for each third-octave band, defined in Table 1 of section 8.3.6.2 of the ANSI standard S3.34 , not only vary between tools, but are seen well above 6.4-16 Hz. There is now sufficient evidence to question the validity of the current safety standards. In view of the clinical evidence, it is questionable as to whether any frequency should be weighted or excluded in standard determinations (Wasserman, 1987). However, neither frequency-weighted nor unweighted measurements by themselves will necessarily be able to address the different vibration dose-HAVS response relationships for vascular and neurologic effects (Pelmear et al., 1989).

F. Tool Testing Instrumentation

Transducers/Accelerometers

The Piezoelectric effect states that "If a mechanical force is applied to piezoelectric crystal material, a corresponding voltage results across the crystal face which contains an electrical charge that is directly proportional to the applied force" (Wasserman, 1987). Isaac Newton's second law of mechanics states that force is proportional to mass times acceleration. If a very small mass is affixed to a piezoelectric crystal, and applies a varying force, a varying voltage (and charge), results, which is proportional to the acceleration of the small mass moving against the crystal due to the applied force (Wasserman, 1987). This is the basic principle behind the operation of a piezoelectric crystal accelerometer. These devices are available in many sizes and configurations, with their sensitivity expressed in coulombs of charge per acceleration (in units of g's or m/s^2). The choice of which device to use for measurement depends on the work situation and what is being measured (Wasserman, 1995).

In typical tool measurements, high acceleration levels spanning a wide frequency band (approximately 6-2000 Hz) are expected. Piezoelectric accelerometers are typically rugged and to some extent protected from high acceleration levels (Wasserman, 1987). In order to try to characterize the source(s) and transmission path(s) of vibration, accelerometers are attached at the point on the tool where maximum vibration is transmitted to the worker (Wasserman, 1995).

When selecting transducers for vibration measurements, it is either the work situation or that which is being measured which ultimately determines selection. In particular, several parameters must be considered: 1) mass loading, 2) dynamic amplitude range, 3) frequency response, 4) environmental influences, 5) resonance effects, and 6) cross axis sensitivity (Wasserman, 1995).

Small mass accelerometers have less charge sensitivity (expressed in units of charge divided by acceleration) than larger ones which have greater charge sensitivity. However, when testing hand-held vibration inducing tools, a sacrifice of sensitivity must be made. In order to avoid inaccuracies due to devices with large mass (called mass loading), the combined mass of the mounting block plus the three perpendicular accelerometers mounted to it must be as small as possible in relation to the mass of the tool being tested (Wasserman, 1988). The rule of thumb is that "the accelerometer assembly mass should be no more than one tenth of the dynamic mass of the tool to which it is mounted." For hand-held tools such as those tested for this thesis, this equates to approximately 1-2 grams (Wasserman, 1987).

The dynamic amplitude range of the chosen accelerometers must also be able to accomodate maximum anticipated acceleration levels. If the range is exceeded then incorrect measurements are obtained and a different transducer must be selected. Every transducer has a usable frequency bandwidth (or window) where the device response is optimal. The frequency response of the measuring device must be at least as large as the frequency spectrum over which measurements are taken. If measured vibration frequencies are lower than the minimum usable frequency they will not be "seen' or measured by the accelerometer. Conversely, if they are above the maximum usable frequency, the high frequency components

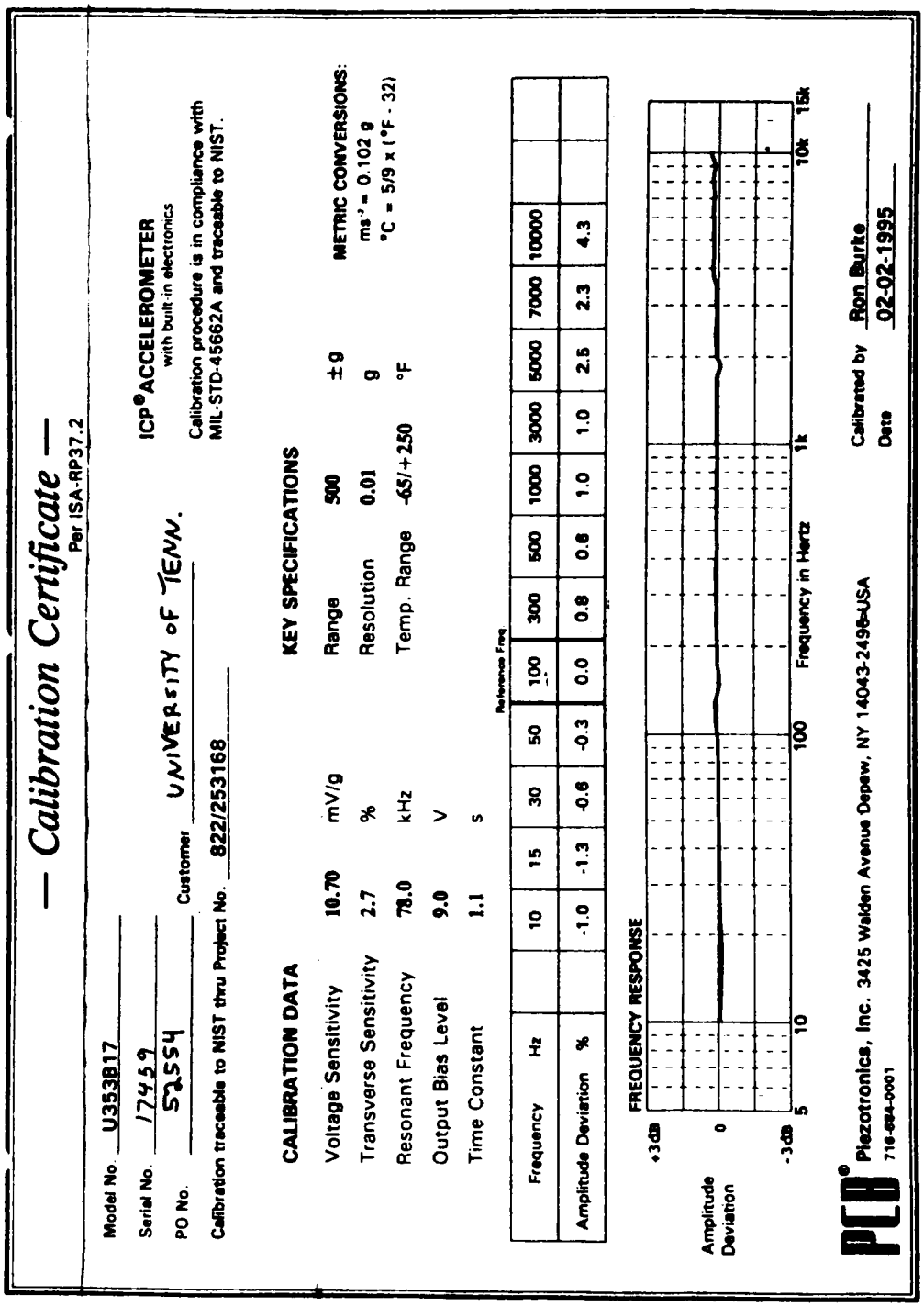
will not be "seen" (Wasserman, 1987).

Cross axis sensitivity of an accelerometer is a measure of how well it measures vibration along the axis on which it is placed, and rejects vibration along other perpendicular axes. Thus, it is a measure of the directionality of a transducer. Optimally, cross axis sensitivity should be 0%. In reality it is desirable to use a device with a sensitivity between 3-4% and no more than 10% (Wasserman, 1987).

Accelerometer Calibration

Piezoelectric crystal accelerometers do not have DC (zero Hz) frequency response. Because of the time constant and decay of the resistive capacitive (RC) circuit, which are characteristics of the crystal inside, this type of accelerometer cannot be calibrated under static conditions. Instead, they are individually calibrated at the factory and shipped with specific calibration sheets (Figure 6). In order to verify calibration the accelerometer is subjected to a known sinusoidal acceleration, and the actual electrical output in mV is compared to the sensitivity calibration data sheets from the manufacturer (Wasserman, 1995).

A small portable battery-powered calibration source with a built-in vibrator can be used to apply a sinusoidal rms acceleration of precisely 1.0 g (9.81 m/s^2) to each individual accelerometer in order to check its calibration against manufacturer specifications. If a transducer is not in line with the vibration motion during this process, part of the measurement will be lost due to misalignment (Wasserman, 1995). The use of the calibrator enables verification of the transducers, and calibration of the entire vibration acceleration



— *Calibration Certificate* —

Per ISA-RP37.2

Model No. U353B17

Serial No. 17459

PO No. 52554

Customer UNIVERSITY OF TENN.

Calibration traceable to NIST thru Project No. 822/253168

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with MIL-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	10.70	mV/g
Transverse Sensitivity	2.7	%
Resonant Frequency	78.0	kHz
Output Bias Level	9.0	V
Time Constant	1.1	s

KEY SPECIFICATIONS

Range	500	±g
Resolution	0.01	g
Temp. Range	-65/+250	°F

METRIC CONVERSIONS:
ms^{-2} = 0.102 g
°C = 5/9 x (°F - 32)

Frequency Hz		10	15	30	50	100 (Reference Freq)	300	500	1000	3000	5000	7000	10000	
Amplitude Deviation %		-1.0	-1.3	-0.6	-0.3	0.0	0.8	0.8	1.0	1.0	2.5	2.3	4.3	

FREQUENCY RESPONSE

+3dB
Amplitude Deviation 0
-3dB
5 10 100 1k 10k 15k
Frequency in Hertz

PCB® Piezotronics, Inc. 3425 Walden Avenue Depew, NY 14043-2498-USA
716-684-0001

Calibrated by Ron Burke
Date 02-02-1995

Figure 6. Sample factory calibration sheet for a piezoelectric crystal accelerometer.

measurement system, including final output, before taking actual experimental measurements. If calibrations are incorrect, the acceleration data against which those calibrations are compared will be incorrect.

Accelerometer Mounting

Hand-held tool vibration testing is conducted using three piezoelectric crystal accelerometers mounted orthogonally in a lightweight steel mounting block. This triaxial assembly, which defines the three perpendicular linear coordinates in the basicentric measurement system (see p. 10), is rigidly affixed to an automotive hose clamp (Wasserman, 1987). It is acceptable to use a hard epoxy, cyranoacrylate glue, or welding to secure the triaxial accelerometer assembly to the automotive hose clamp, but a soft glue should not be used because it tends to act as a mechanical low pass filter. There is therefore a tendency to lower the natural frequency of the system, which reduces the effective band width of the device and results in false spectra (Wasserman, 1987).

Proper mounting of the accelerometer/hose clamp assembly to the body of the tool being tested is very important. It should be done in accordance with section 8.3.3.1 of ANSI standard S3.34 which states that "...the vibration data should be reported for the part with the maximum vibration." If each orthogonal accelerometer is not rigidly affixed to the vibrating source and in line with its respective direction of vibration, rattling can occur which produces a false output signal and part of the measurement will be lost due to misalignment (Wasserman, 1995).

Signal Conditioning

Some previous vibration acceleration measurement studies have used transducers that required charge amplifiers. However, more recent studies have used piezoelectric devices that have a small field effect transistor (FET) incorporated inside the accelerometer itself. Only a multichannel power supply with a very precise voltage and limit on current is needed to supply power to the FET during vibration acceleration measurements. With this type of transistor, no additional amplification is necessary.

Data and Video Recording

When conducting vibration measurements, the acceleration data obtained is recorded on digital audio tape (DAT) or a similar recording media. Three axis (triaxial) acceleration measurements are taken simultaneously at each mounting location on the vibrating tool as it is tested (Wasserman, 1995). During the experiments a portable video recording system can be used to videotape experiments in conjunction with the tape recording system. Extensive written logs of all activities can also be kept. In an industrial setting where vibration measurements are taken, these videotapes and activity logs can then be coordinated with the recorded data for purposes of analysis (Wasserman, 1995).

H. Data Analysis Instrumentation

Frequency Analysis

The recorded vibration data is output from the tape recording system to a dynamic signal analyzer which performs a Fourier transform and displays the resulting Fourier spectra, using a log frequency scale on the horizontal axis and acceleration amplitude on the vertical one (see p. 13). Next, the data are digitized and computer analyzed using third-octave analysis in order to remove random vibration spectra and determine root mean square (rms) acceleration values. Section 8.3.6.2 of ANSI standard S3.34 states that the "measured vibration signal in each of the three axes shall be analyzed and reported as rms acceleration values in third-octave bands with center frequencies as stated in the Table 1 of the standard." Several standardized third-octave programs are readily available from standard suppliers of vibration testing equipment.

Output Devices

The final step in vibration measurement is the comparison of vibration spectra and rms acceleration values with appropriate health and safety standards for hand-arm vibration. To do this, the spectra obtained from third-octave analysis are saved to computer disks and/or output in hardcopy paper form using a plotting device or chart recorder.

CHAPTER III

EXPERIMENTAL PROCEDURES

A. Workplace Simulation

The research conducted for this study was designed to simulate, in a controlled environment, conditions that might be encountered during actual use of this class of hobby grade tools. A testing fixture (Figure 7) was constructed for securing three of the materials tested: wood, concrete, and steel. It consisted of a table with shelving and various clamps. The goal was to simulate an industrial workbench with materials being held in place by vises and C-clamps. The shelves were used to mount the necessary data and recording equipment during drilling and data collection. The two inch thick acrylic plastic slab, however, was too large to be mounted on the bench. Instead, it was laid across two wooden sawhorses much as it might be by a worker using the tool in an industrial setting.

Using the various clamps, each of the four materials tested was held in a position where downward vertical force could be applied during testing. It is acknowledged that by fixing the material in this way, the experiments conducted did not precisely simulate an industrial setting, where drills are commonly used at various angles. This method of fixation was merely used to help narrow down the number of possible variables, such as drill speed and binding which vary at different angles. In order to compensate for the lack of angular

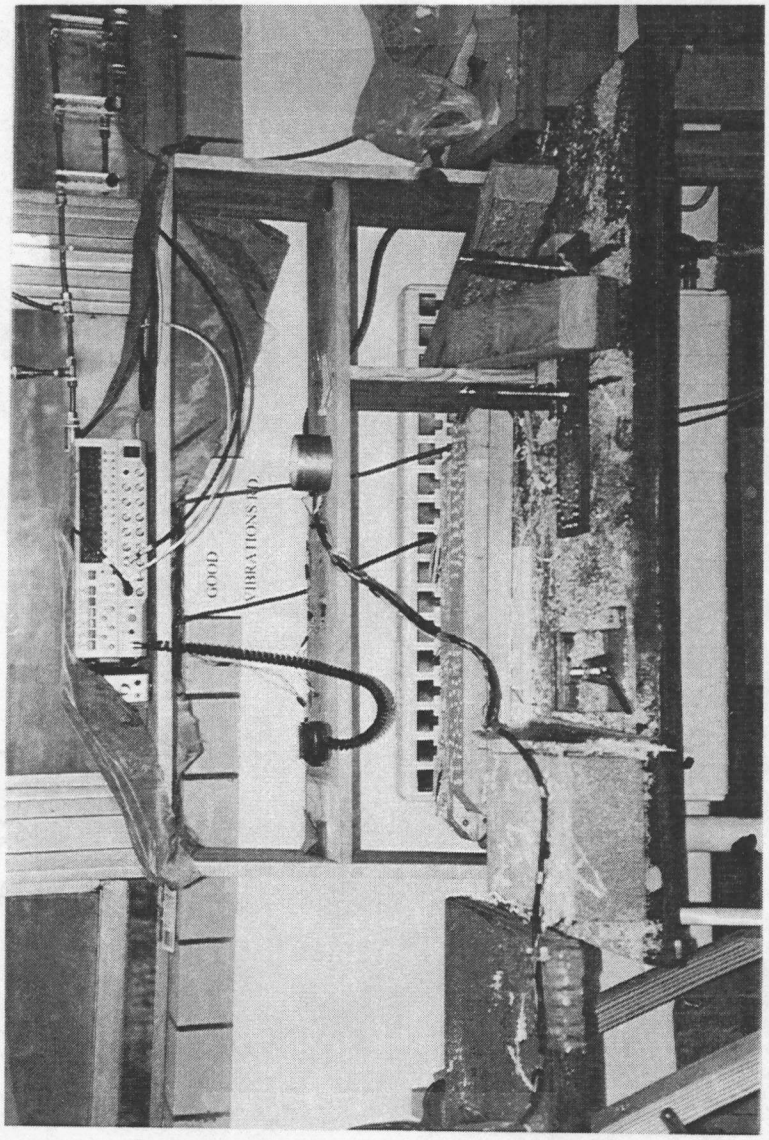


Figure 7. Testing fixture used for conducting mechanical vibration drilling experiments.

variation and to compare the amount of vibration occurring when the tool was used in another direction, in addition to a total of five vertical drilling trials for each material/bit combination, one horizontal drilling trial with the material vertically held was also performed.

B. Tooling

Vibration testing was performed using ten 3/8" hand-held electric drills which represented a variety of possible manufacturers and tool ages. Five of them were obtained from local tool rental agencies and were tools commonly used on a regular basis by local contractors in the Knoxville area. Judging by their appearance, it was obvious that most of these tools were several years old and had been heavily used. Unfortunately, since most of these agencies did not have records indicating the date the rental tools were first put into service, and the identifying labels on the majority of them were fairly illegible, it was impossible to ascertain the exact age of these tools. The other five drills came from personal and on-campus sources. Two of them were refurbished models, one was almost new, and the other two were several years old. A standard 3/8" chuck and bit size was chosen, because, according to research conducted through interviews, this was found to be a size commonly used in both industrial and lay settings.

The drills were tested in random order. In order to avoid bias they were identified only alphabetically as drills A to J. This convention was used throughout the testing, recording, and analysis phases of this study.

C. Testing Materials and Drill Bits

Four different materials were chosen for testing purposes: 1) AISI 1018 hot rolled steel, 2) standard size mortar (concrete) cap blocks, 3) double thickness 2" x 4" scrap lumber, and 4) approximately 2 inch thick acrylic plastic slab. These materials might be seen in an industrial workplace and were obtained through solicitation of donations by local companies in the Knoxville area.

Specialized drill bits (Figure 8) were also paired with and used to test the different materials. Cobalt "split point" drill bits were used to test steel, carbide-tipped masonry bits were used to drill the concrete cap blocks, and standard wood boring bits were used to test lumber. These three drill bit types were obtained from a local home supply retailer. In order to drill the thick acrylic plastic, specialized bits with a larger pitch were obtained from a local wholesaler of commercial plastic materials. All of the drill bits used were specifically chosen upon consultation with and recommendation from an employee of a local home supply store who has expertise and experience in drilling various materials. For reasons of validity and consistency, only new drill bits were used for testing purposes. A new bit was used for each different tool/material combination. This equated to a total of 40 different drill bits; ten of each type.

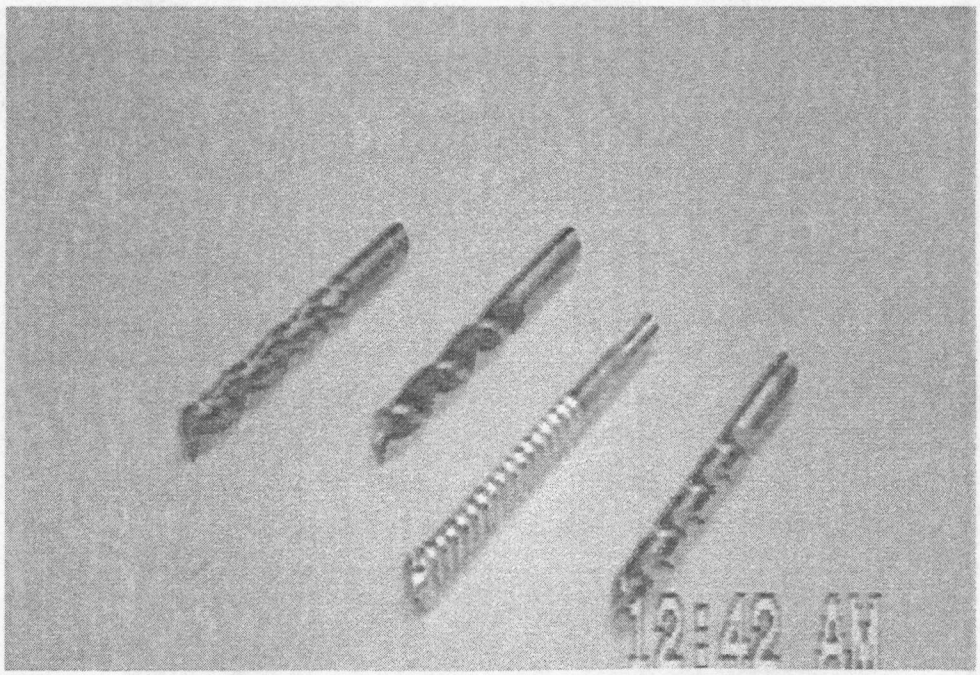


Figure 8. Specialized drill bits used for different materials. (From right to left: steel, wood, concrete, plastic)

D. Hand-Held Tool Testing Instrumentation

For this study six PCB model #353B17 piezoelectric crystal accelerometers (Figure 9) were used. Each device had its own built-in field effect transistor (FET). The calibration sheets showed that the electrical output of each accelerometer was approximately 10 mV/g (1.02 mV / m/s^2).

A small battery-powered PCB model #394M25 hand-held calibrator (Figure 10) with a built-in vibrator was used to apply a sinusoidal vibration of precisely 1.0 g (9.81 m/s^2) to each individual accelerometer. In order to check their sensitivity calibrations against manufacturer specifications, the accelerometers were rigidly affixed to the calibrator (Figure 11) one at a time in line with the direction of vibration. This calibrator was also used to check the entire measurement system before conducting experiments. To do this, a sample measurement was taken with the individual accelerometers attached to the vibrating calibrator one at a time, the signal was conditioned and recorded onto digital audio tape (DAT), and the final output was verified.

After calibration, three of the PCB accelerometers were mounted orthogonally in a lightweight PCB steel block (Figure 12) with tapped holes, that was rigidly affixed with a mounting stud to a modified automotive hose clamp (Figure 13). This triaxial assembly was needed to define the three perpendicular linear coordinates in the basicentric measurement system. The triaxial accelerometer/hose clamp assembly was then mounted to the body of the tool being tested (Figure 14), in accordance with section 8.3.3.1 of ANSI standard S3.34.

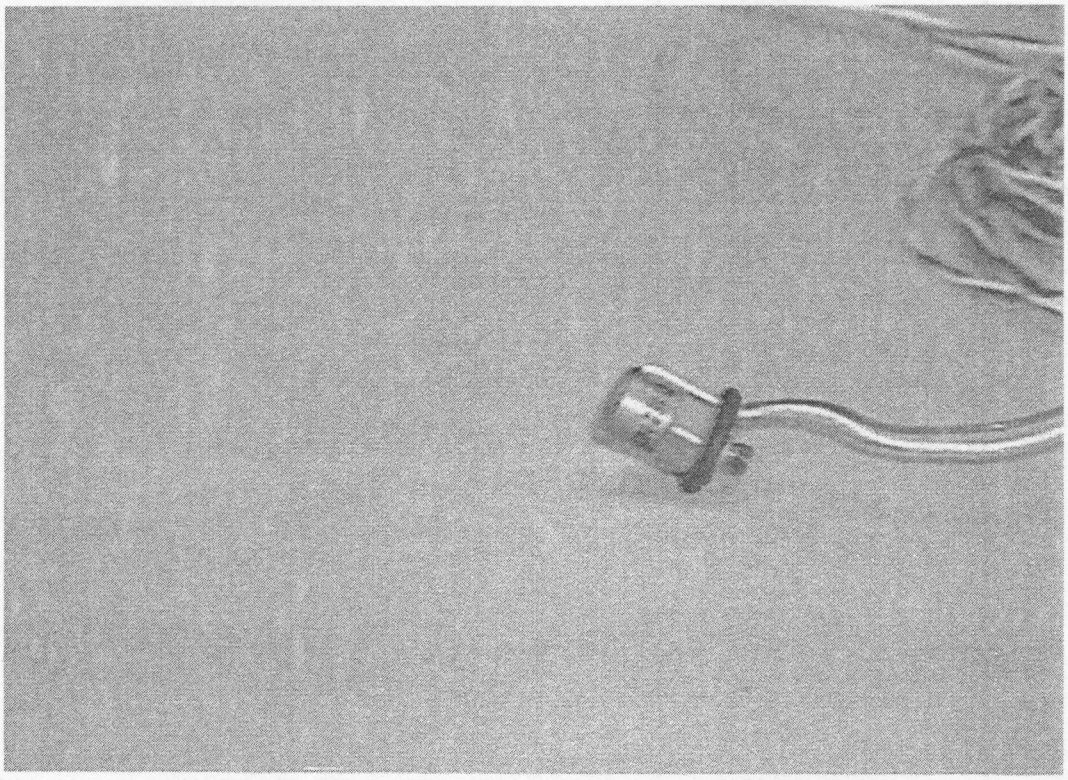


Figure 9. Piezoelectric crystal accelerometer used for mechanical vibration measurements.

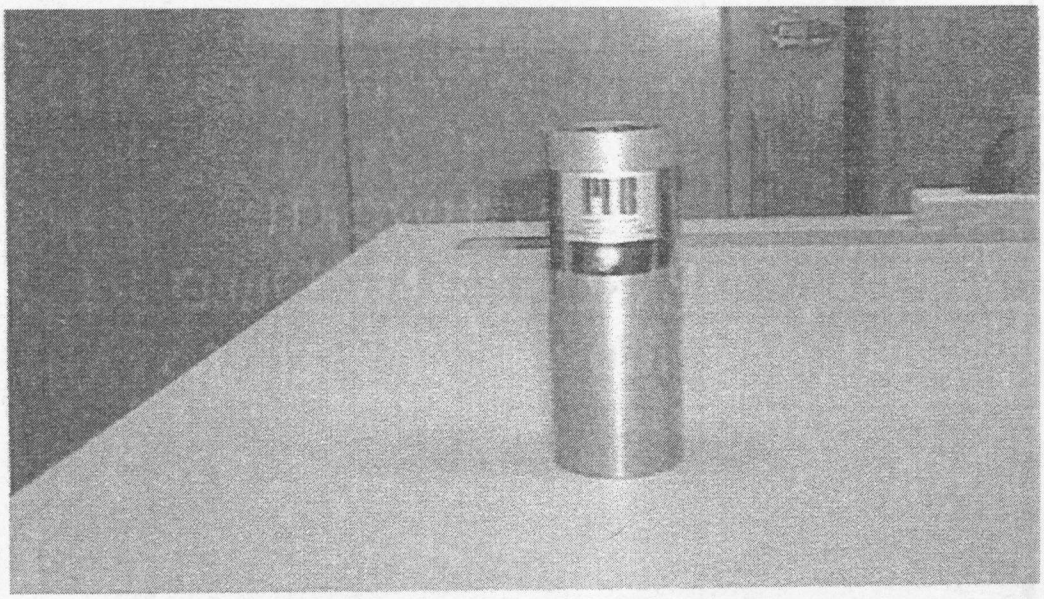


Figure 10. Hand-held portable calibrator for piezoelectric crystal accelerometers.

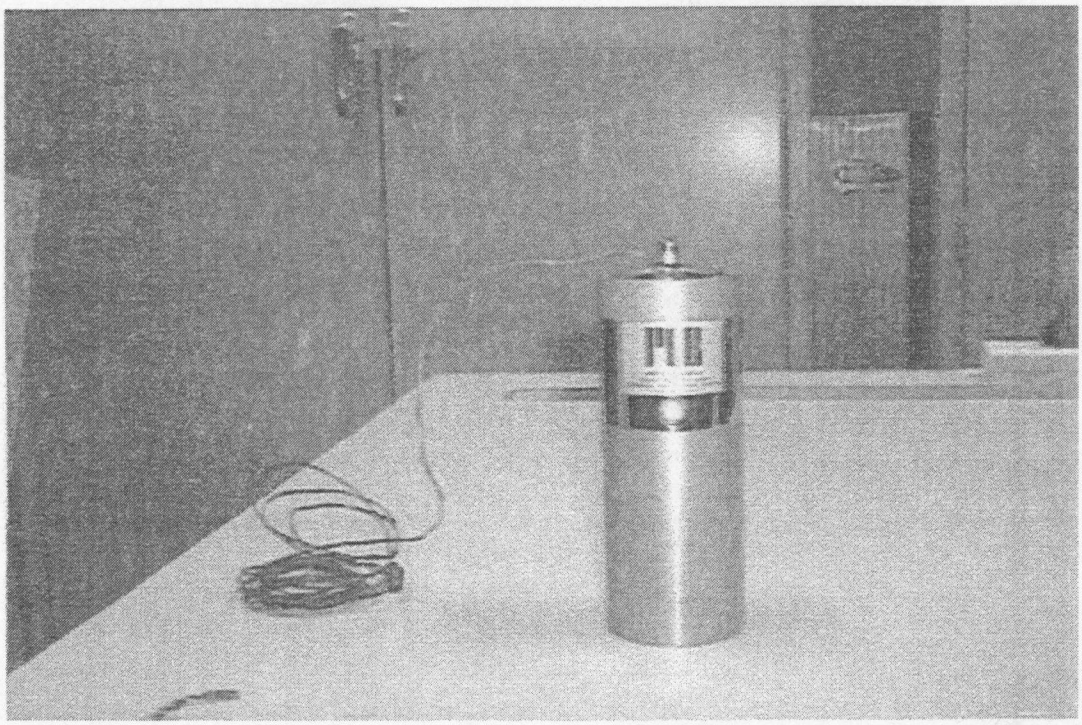


Figure 11. Calibrator with piezoelectric crystal accelerometer rigidly affixed to it.

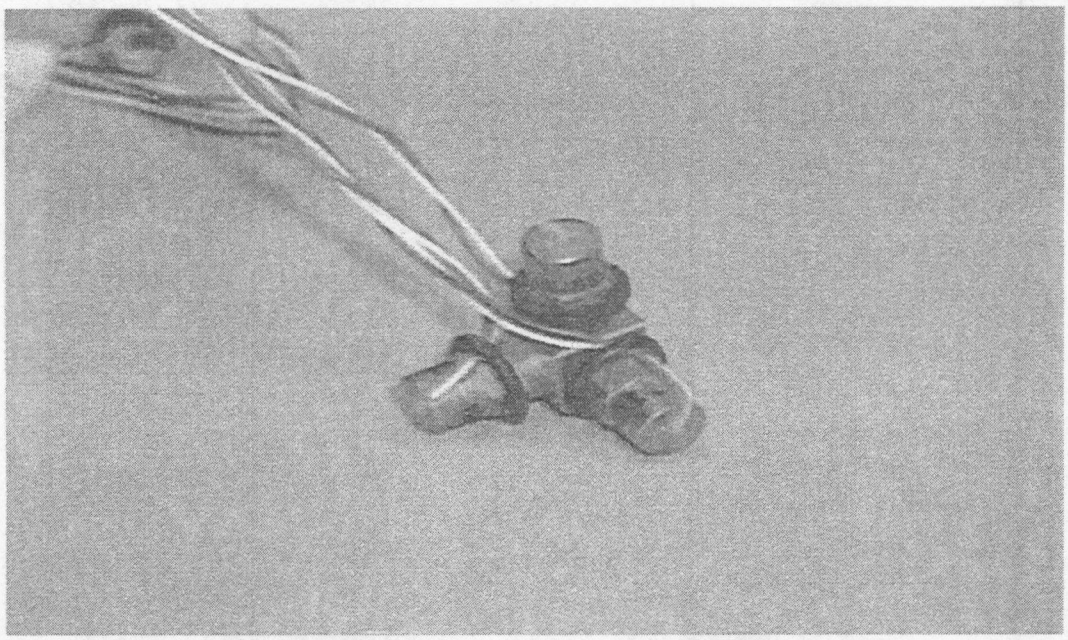


Figure 12. Triaxial accelerometer assembly attached to lightweight steel mounting block.

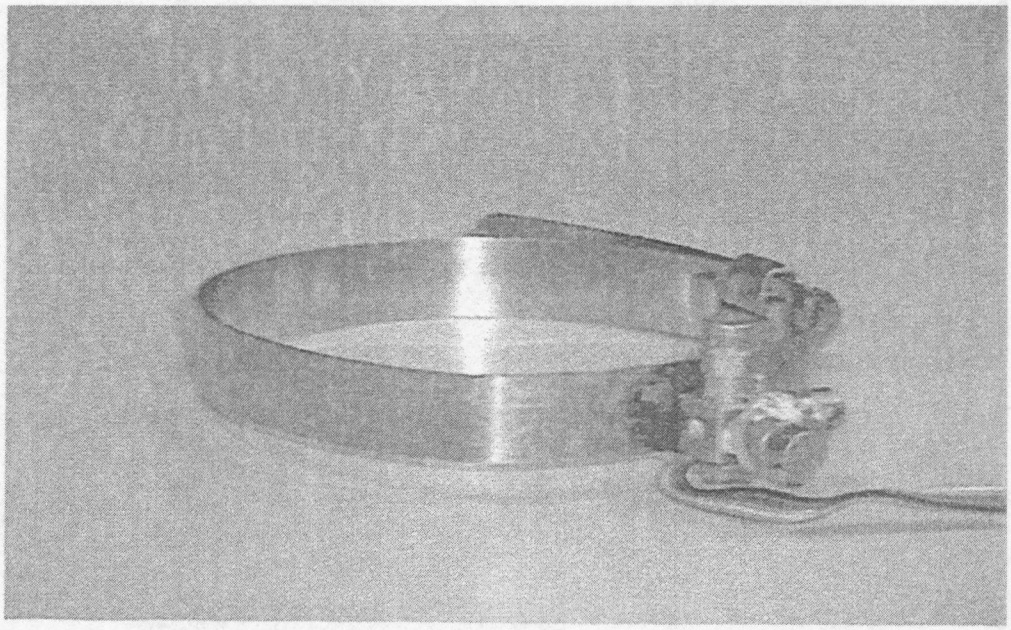


Figure 13. Triaxial accelerometer assembly attached to modified automotive hose clamp.

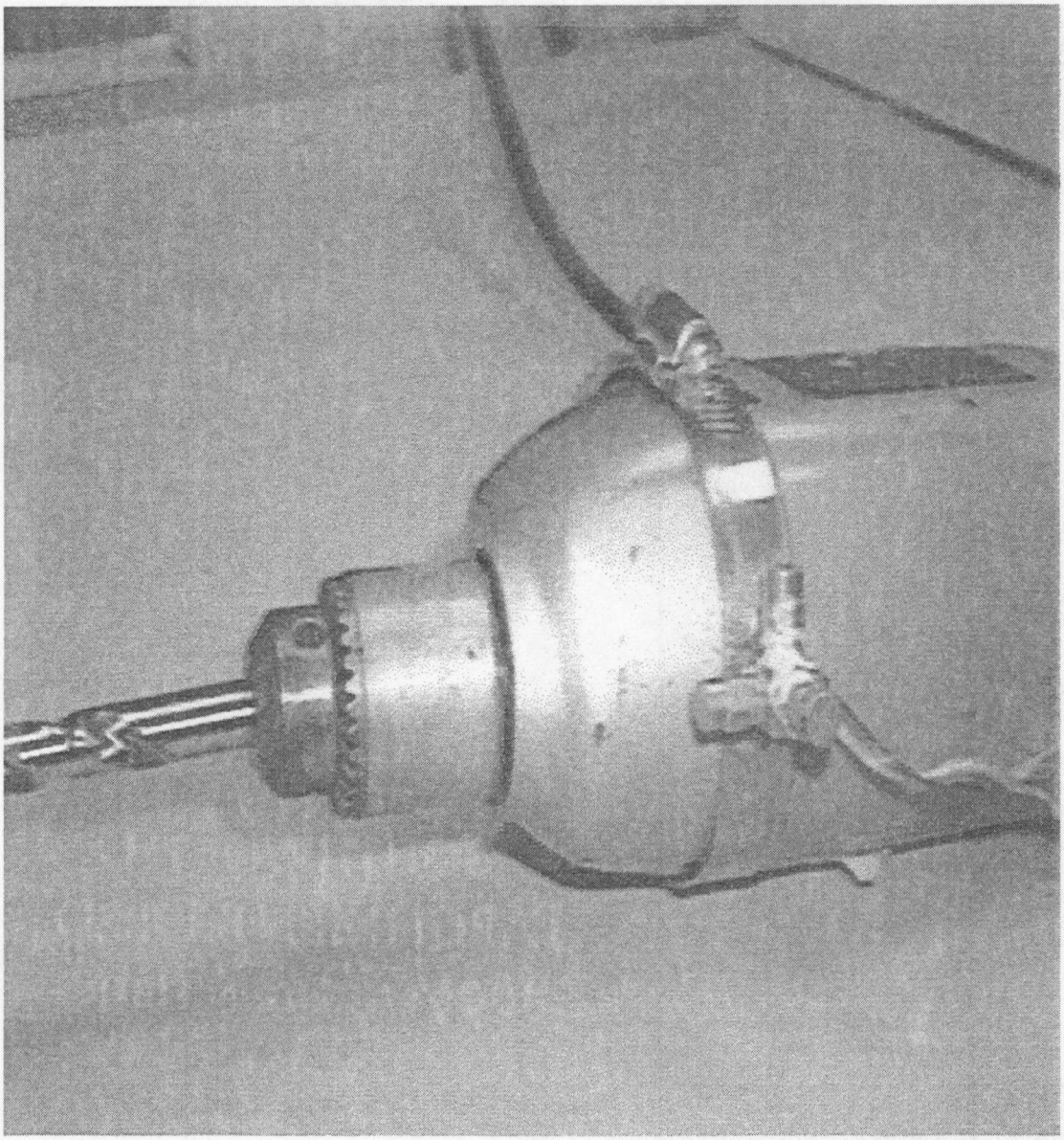


Figure 14. Triaxial accelerometer/hose clamp assembly rigidly affixed to tool body at barrel.

A second triaxial accelerometer/hose clamp assembly was also prepared for accelerometer mounting location comparisons.

During one-handed drilling the worker grasps the tool along the handle. However, when a second cradling hand is used to stabilize a drill, it is placed around the drill casing barrel that surrounds the electric motor inside. For the drills tested here, the assumption was made that this point on the tool body surrounding the motor was where measured vibration would be maximum. Therefore, the triaxial accelerometer/hose clamp assembly was mounted along the tool barrel. Accelerometer mounting location comparison experiments were used to verify that vibration was maximum along the drill barrel.

In order to provide power to the FET inside each of the accelerometers and make the signals adequate for data processing a PCB model #482A04 four channel conditioning power supply (Figure 15) was used to detect the electrical charge from the accelerometers and transform them to corresponding low impedance voltage signals. This was replaced by a PCB model #483A08 six channel charge amplifier (Figure 16) when a second triaxial accelerometer assembly was attached to the tool handle (Figure 17). The 10-32 microdot connectors from the individual accelerometers were connected to the inputs of the charge amplifier. Cables were connected from the BNC connector outputs of the amplifier to the BNC inputs of a TEAC model #RD-135 digital audio tape (DAT) data recorder.

The DAT recorder (Figure 18) was set to record at an input voltage range of +/- 5 volts in order to obtain the best resolution possible. However, if at any time during a particular test the DAT recorder readout was observed to exceed this range and cause signal saturation, the testing was stopped and the input voltage was reset to +/- 20 volts to avoid

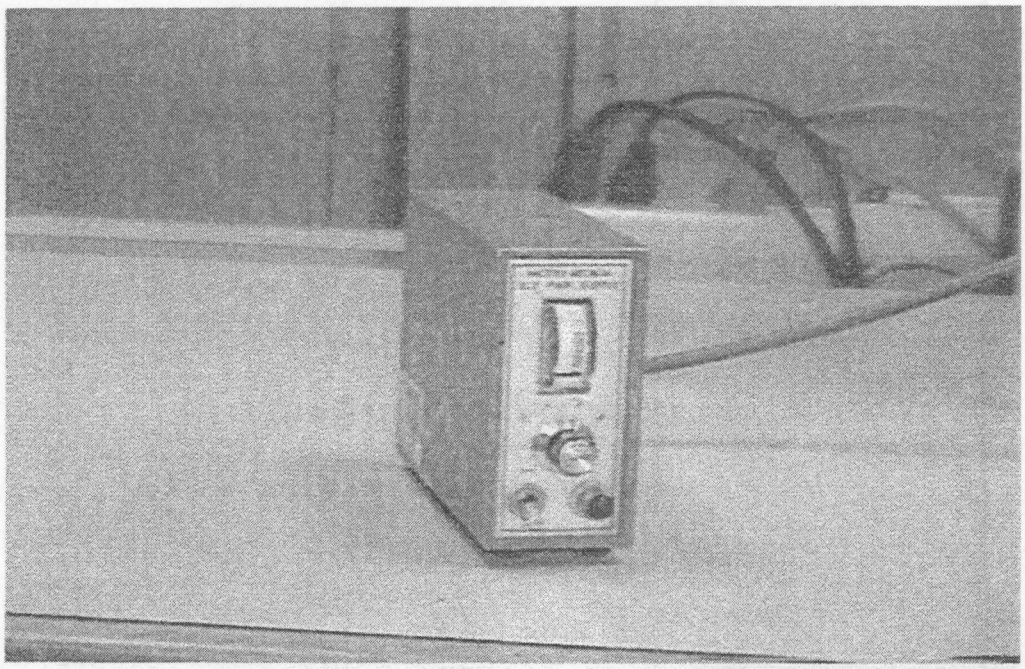


Figure 15. Four channel signal conditioning power supply for piezoelectric accelerometers.

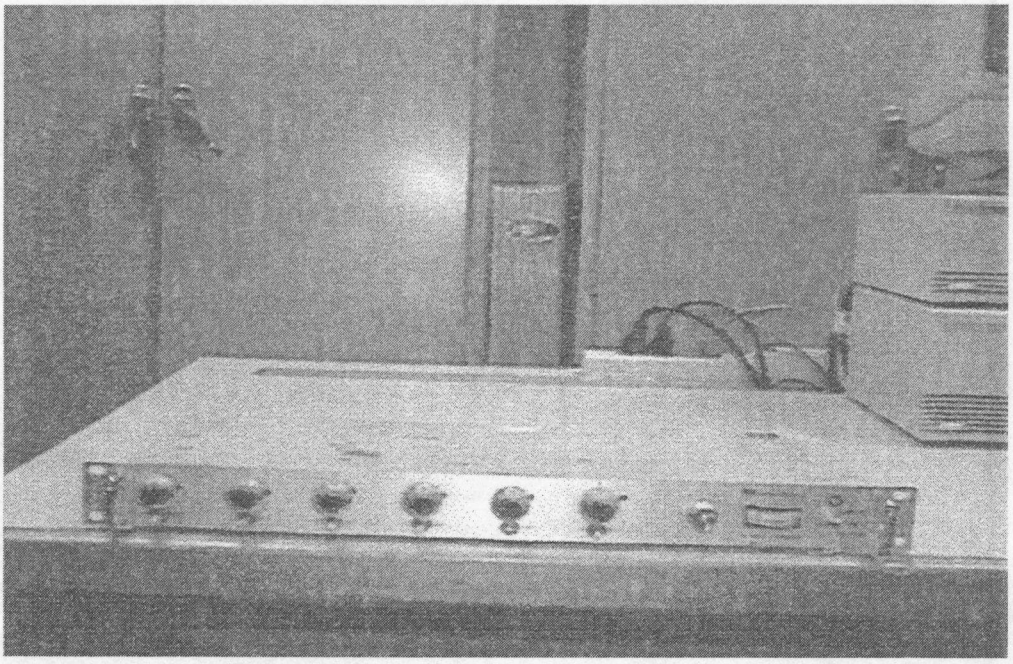


Figure 16. Six channel signal conditioning power supply for piezoelectric accelerometers.

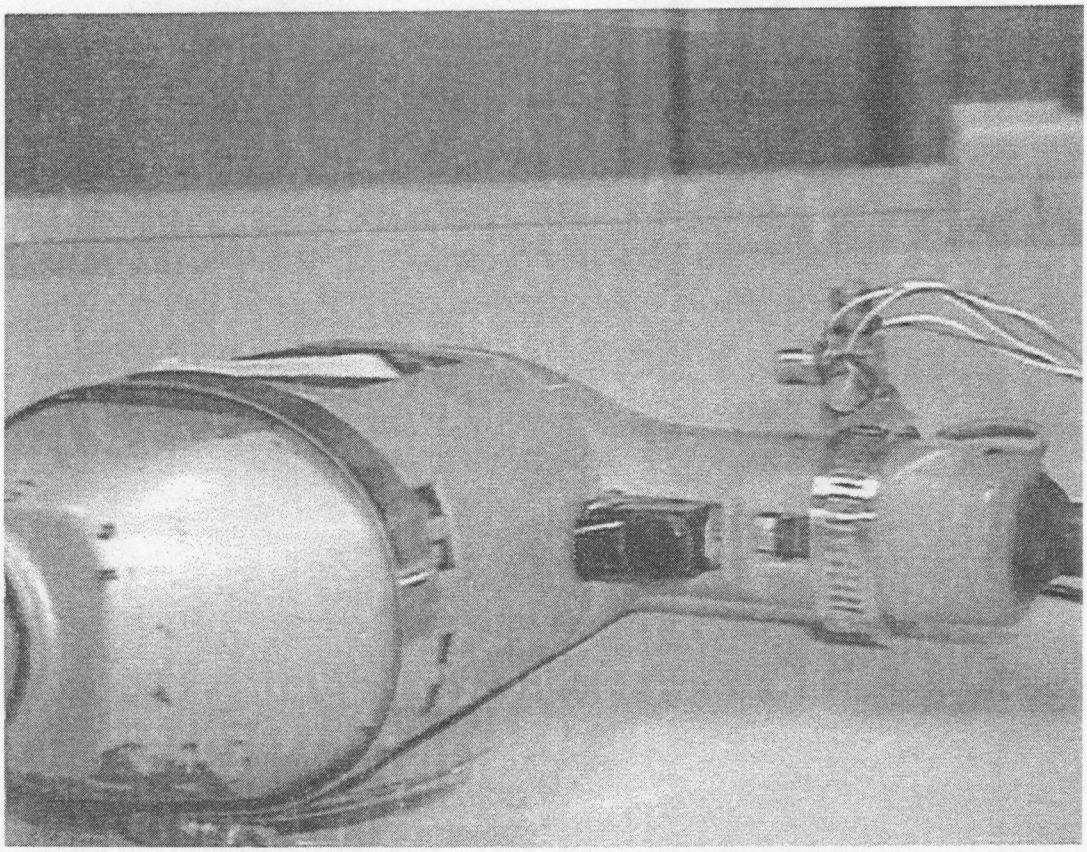


Figure 17. Triaxial accelerometer/hose clamp assembly rigidly affixed to tool body at handle.

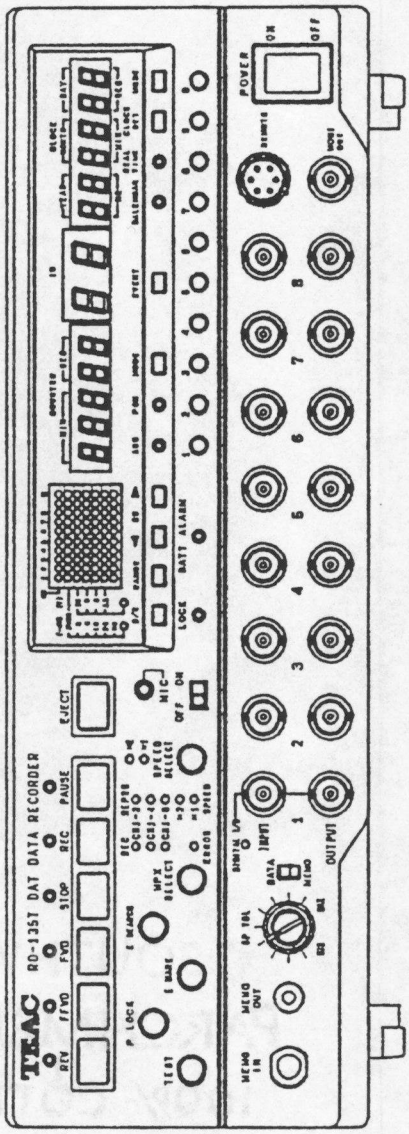


Figure 18. Digital audio tape (DAT) data recorder

inaccuracies and errors which might occur due to these overload conditions. Tape speed was set for standard speed (x1) recording. Recording frequency was set for four channels (DC to 10kHz) for single triaxial accelerometer mountings and eight channels (DC to 5 kHz) for accelerometer mounting location comparisons. A Hewlett Packard (HP) model #3562A dynamic signal analyzer (Figure 19) was used to calibrate the output of the DAT recorder and precisely set it to a range of +/- 5 volts peak. This adjustment was made individually for each tape channel using individual potentiometers mounted on the back of the DAT recorder.

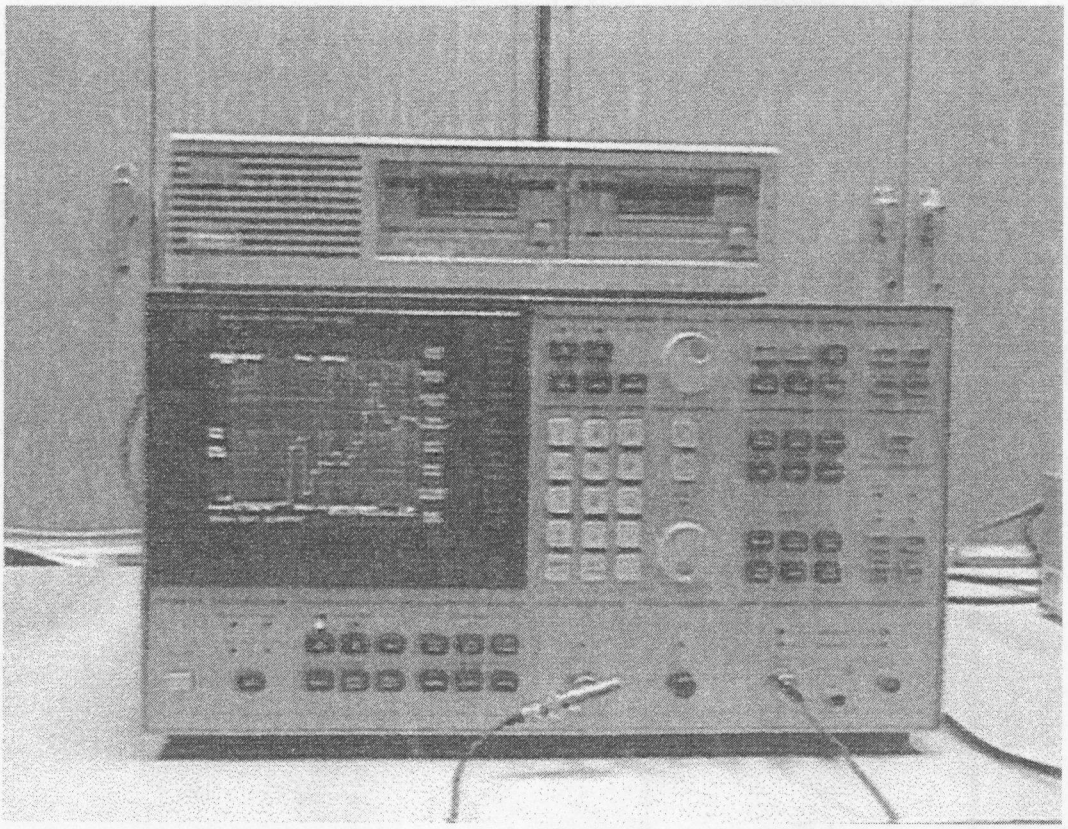


Figure 19. Dynamic signal analyzer used for calibration and vibration data analysis.

E. Measurement and Testing

"Free Run" Drilling with Barrel Mounted Accelerometers

Triaxial measurements were first taken for each drill/bit combination running free (Appendix I) for two minutes with no material. This was done to determine tool periodicity components caused by the electric motor inside and the drill casing, in order to compare them to actual working conditions and to determine a bandwidth of frequencies applicable to a particular tool. However, since the tool does not work against a resistance during free run, free run tests cannot be used to accurately determine acceptable exposure times. Measured acceleration levels in this non-working condition are not accurate reflections of daily tool use. Free run analysis cannot be used to validate or determine the safety of a tool.

Drilling of Materials with Barrel Mounted Accelerometers

Following the free run, one two minute drilling trial was conducted with the tool held in the vertical direction (vertical trial) and one in the horizontal direction (horizontal trial). To verify repeatability four more two-minute vertical trials were then done for each drill/bit combination, making a total of five vertical trials and one horizontal trial for each tool/material/bit combination.

Triaxial measurements were taken simultaneously at each mounting location on the vibrating tool as it was tested. Following amplification and conversion to voltage, the

vibration acceleration data for each basicentric measurement axis was individually recorded on separate DAT tape channels for later analysis. During experiments drilling of the different tool/material/bit combinations was captured on videotape using an 8mm camcorder mounted on an adjustable tripod. Written logs of all drilling experiments were also kept and later used in conjunction with the videotapes during data analysis.

Accelerometer Mounting Location Comparisons

In order to verify that vibration measurements were actually taken at the point on the tool body where they were maximal, handle to barrel accelerometer mounting comparisons were done for drills A and B. To perform such a verification two triaxial accelerometers were mounted on the drills simultaneously; one at the handle and one at the drill barrel. Since the majority of testing was performed along the barrel, and the handle was only used for comparison purposes, the same basicentric coordinate system, defined in section 8.2.2 of the ANSI S3.34 standard, was used at both locations. Six channels of data (three for each triaxial accelerometer assembly) were amplified, converted to voltage and recorded simultaneously with the DAT data recorder. Three vertical trials with the tool held in the vertical direction were conducted for each material/bit combination.

F. Data Analysis

When drilling was completed, cables were connected from the BNC outputs of the TEAC data recorder to the BNC inputs of the HP analyzer. An automatic sequence batch program (Appendix A) was made to enable quick set up of the HP analyzer with the following settings:

MEASUREMENT MODE: log resolution

SELECT MEASUREMENT: frequency response
Channels 1 and 2 active

AVERAGING: number of averages = 10
stable/mean averaging

FREQUENCY: start frequency = 5 Hz
frequency span = 3 decades

SOURCE: source off

RANGE: channel 1 range = 5 volts peak
channel 2 range = 5 volts peak

CALIBRATION: automatic calibration on

INPUT COUPLE: AC channel 1- floating
AC channel 2 - floating

ENGINEERING UNITS: channel 1 EU label = m/s^2
channel 2 EU label = m/s^2

A) For TEAC input range set to +/- 5 volts: channel 1 EU value = 1.02 mV/EU
channel 2 EU value = 1.02 mV/EU

B) For TEAC input range set to +/- 20 volts: channel 1 EU value = 0.255 mV/EU
channel 1 EU value = 0.255 mV/EU

ACTIVE TRACE: A = power spectrum 1
B = power spectrum 2

VIEW INPUT: A = input time
B = input time

COORDINATES: log magnitude

UNITS: Hz

SCALE: X axis fixed scale = 5-1500 Hz
Y axis fixed scale = 1-100 EU

The recorded vibration acceleration data for the basicentric vibration axes (X,Y,Z) were output from their respective DAT channels to the HP analyzer two channels at a time. Ten 16 second time averages of the recorded acceleration data were simultaneously taken for each channel. The Fourier spectra were then displayed, one channel at a time, using a log frequency scale on the horizontal axis and acceleration amplitude on the vertical one. In order to remove random vibration spectra the raw unweighted data were digitized and computer analyzed, using a Hewlett Packard (HP) model #9000 computer with proprietary third-octave analysis software written in HP Basic computer language. The HP computer was connected to the HP analyzer using HP-IB data bus cables. The analyzer was set for address only mode which allowed the software program to read the data from the HP analyzer, and perform the appropriate calculations. The filtered third-octave analyzed spectra (Appendix B) were then returned to the HP analyzer by the program and displayed on the screen. The weighted rms acceleration value was simultaneously calculated by the HP third-octave program and displayed on the computer monitor. This process was performed for one channel of

acceleration data at a time. Each individual filtered spectrum was then titled and saved to floppy disk using a Hewlett Packard (HP) model #9122 disk drive. The rms acceleration values were also recorded in the activity logs for later reference.

G. Comparison with Safety Standards

Following data analysis, the spectra saved on floppy disk were plotted using a Hewlett Packard (HP) model #7550A graphics plotter. The elbow shaped ANSI S.3.34 1, 2, 4, and 8-hour exposure curves were then superimposed on the plot (Appendices B, C, G) to determine whether and by how much the standard may have been exceeded. If one or more vibration axes had exceeded the standard, then the entire standard had been exceeded. Examination of these plots also helped in the determination of the principal axis of vibration plus amplitude and frequency components for different material/bit combinations. The plots (Figure 20) and rms acceleration values for handle and barrel mounted triaxial accelerometer assemblies were also compared with each other, as well as with the ANSI and ACGIH standards. This was done in order to verify the assumption that the barrel was indeed the point on the tool body where measured vibration was maximum. Comparisons for handle versus barrel accelerometer mounting locations were made using Student t-tests. A level of $p<0.05$ was considered significant.

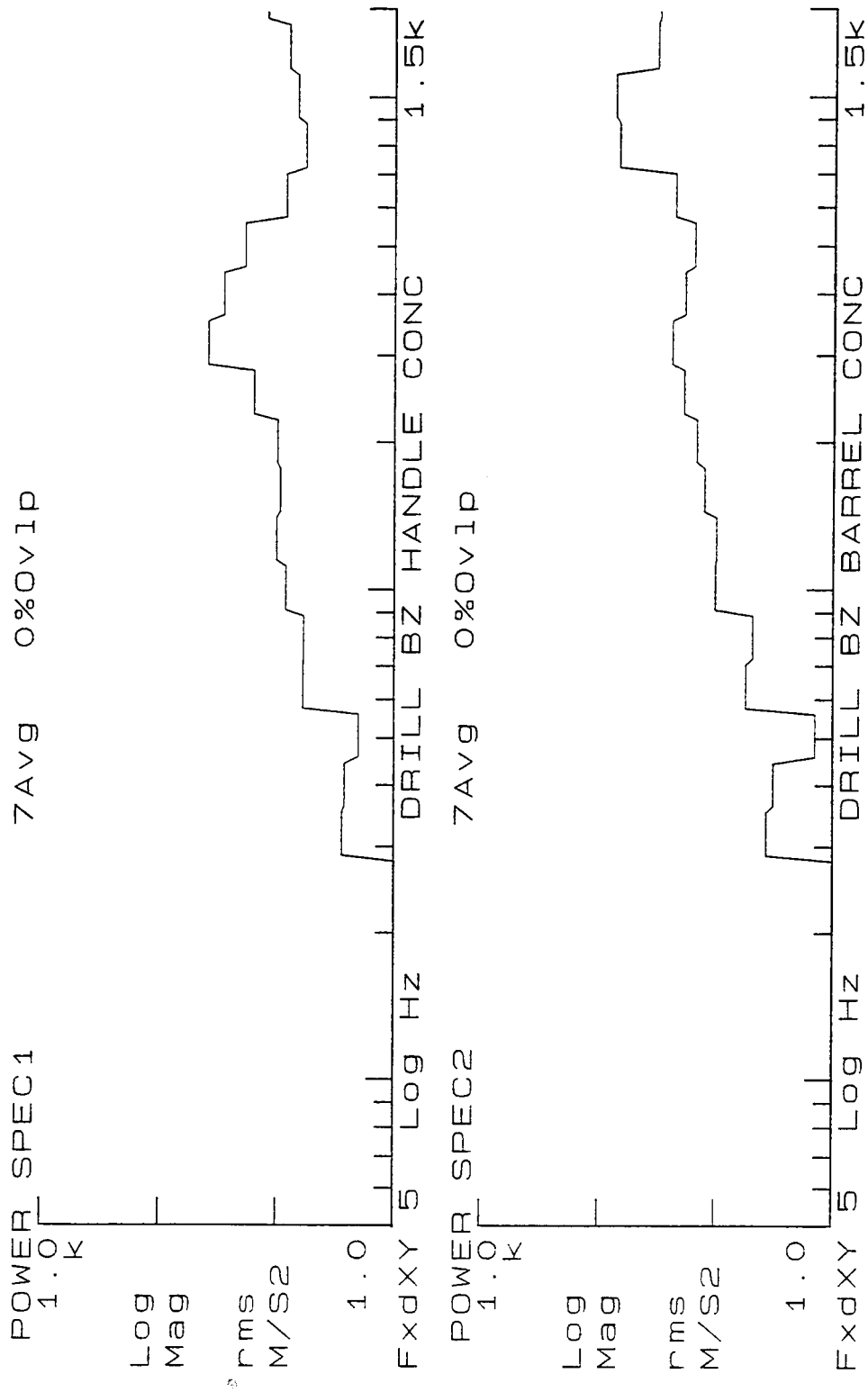


Figure 20. Sample comparison of third-octave spectra for handle versus barrel measurements.

CHAPTER IV

RESULTS

A. Maximal Vibration Location Results

The results obtained for the third-octave analysis of drills A, C, J (newer personal/refurbished), drills B, H (older personal), and drills D, E, F, G, I (rental) with the triaxial accelerometer assembly mounted along the barrel, can be found in tabular form in Appendices D and E. All results were examined from perspectives of both axis comparisons (Table 2) and material comparisons (Table 3). The tables in Appendix D and Appendix E are broken down into free runs, horizontal trials, and individual vertical trials (1-5) for each material/bit combination. In Appendix D the principal basicentric axis for each tool/material/bit combination, where measured acceleration is maximum, is indicated in bold type. Recommended maximum exposure times based on the ANSI S3.34 and ACGIH-TLV safety standards are given in number of hours per day. The principal acceleration axis based on these standards is also given in parentheses ( ) following each recommended exposure time in Appendix D. In Appendix E the material/bit combination for each tool/basicentric axis, which had maximal acceleration, is indicated in bold type. Recommended maximum exposure times based on the ANSI S3.34 and ACGIH-TLV safety standards are given in number of hours per day. The material with the highest measured acceleration based on these standards is given in parentheses ( ) following each recommended exposure time in Appendix E. These

Table 2

Sample of maximal vibration locations described using an axis-comparison basis

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 2	Concr	4.69	6.34	**8.89**	0.5-1 (Z)	<1.0 (Z)
H	Vertical 2	Concr	6.67	7.33	**10.69**	2-4 (Z)	<1.0 (Z)

Table 3

Sample of maximal vibration locations described using a material-comparison basis

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
C	Vertical 5	X	2.38	3.00	6.64	4.91	2-4 (C)	1-2 (C)
J	Vertical 5	X	7.68	4.29	4.62	7.92	2-4 (W)	1-2 (P)

results are also summarized in Appendix F which also gives the mean vertical drilling accelerations and the standard deviations of these mean values for each drill (Table 4). Examples of data plots obtained by third-octave analysis, for different drill material/bit combinations, are included in Appendix B.

B. Handle versus Barrel Comparisons

The experimental testing results (Table 5) obtained for the handle versus the barrel mounted triaxial accelerometers from drills A and B can be found in tabular form in Appendix H. Examples of data plots for handle to barrel comparisons, obtained by third octave analysis are shown in Appendix G. Based on experience, the shape of the third octave analyzed spectra follows a certain pattern (Appendix B). Any graphical acceleration data (example: Appendix C) that appeared to be deviate significantly from this pattern was assumed to be invalid. ACGIH-TLV criteria recommends less than 1 hour of maximum daily exposure for tools tests with measured rms acceleration values of 12 m/s^2 or more. For the majority of the experimental trials conducted for this study, corresponding rms acceleration values were found to be below 20 m/s^2. However, in most of the third-octave spectra which appeared to deviate significantly from the normal pattern there were corresponding rms acceleration values that were at least 100 m/s^2 or greater. No maximum recommended daily exposures times, based on the ANSI S3.34 and ACGIH-TLV standards were given for these trails. Future experimentation may provide the reason for such large spectral and numerical deviations from expected patterns.

Table 4

Sample summary of maximal vibration locations

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STD. DEV.	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
H	WOOD	X	3.62	5.46	5.88	0.34	4-8	2-4
D	WOOD	X	2.51	4.57	3.73	0.31	4-8	2-4
E	WOOD	X	2.91	3.06	3.52	0.27	4-8	4-8

Table 5

Sample of handle versus barrel accelerometer mounting location comparisons

DRILL	MATERIAL	AXIS	ACCELEROMETER MOUNTING LOCATION				MAX. RECOMMENDED EXPOSURE			
			HANDLE WT. VERT. ACCEL. (M/S^2)		BARREL WT. VERT. ACCEL. (M/S^2)		ANSI S3.34 SPECTRA (HOURS/DAY)		ACGIH-TLV CRITERIA (HOURS/DAY)	
			MEAN	ST. DEV	MEAN	ST. DEV	HANDLE	BARREL	HANDLE	BARREL
A	WOOD	X	4.58	0.344	3.70	0.104	2-4	4-8	2-4	4-8
B	WOOD	X	6.74	0.468	15.62	3.16	2-4	4-8	1-2	-
A	STEEL	X	4.10	0.263	3.53	0.251	2-4	4-8	2-4	4-8
B	STEEL	X	6.91	0.239	19.48	3.59	1-2	4-8	1-2	-

Student t-tests were performed for four randomly chosen handle versus barrel trials. The acceleration magnitudes in the Y-direction for Drill A in steel and Drill B in concrete were both significantly higher for the barrel than for the handle. The X-axis acceleration magnitude in concrete and the Z-axis acceleration magnitude for wood were both significantly higher for the handle than the barrel.

The results for the two different accelerometer mounting locations on the drill, including principal vibration axes and frequency component comparisons for Drills A and B may be summarized as follows:

***Drill A*:**

Wood

The wood bit showed similar measured accelerations in the X-direction for both the handle and barrel, with amplitudes for the handle being slightly higher and containing more low-frequency components. The Y-direction showed acceleration amplitudes for the barrel to be almost twice those for the handle. This was verified graphically by using the corresponding plotted spectra which showed greater high- and low-frequency acceleration values for the Y-axis at the barrel. The Z-direction acceleration amplitudes for wood were very similar, but the curves showed more low-frequency components for the barrel, as compared to more mid-frequencies for the handle. The principle axis was Y for the barrel and Z for the handle. Maximum recommended ANSI criteria suggest usage of 2-4 hours for this

drill and only 0.5-1 hour of usage at the barrel, indicating that the secondary cradling hand is exposed to much greater vibration amplitudes than the primary. The more conservative ACGIH-TLV standard has similar recommendations for the handle but suggests less than one hour of exposure for the cradling hand holding the barrel.

Steel

For steel the curves were similar, but the handle had slightly higher mid-frequency acceleration amplitudes in the X-direction than the barrel. The Y-direction acceleration levels for the barrel were about twice those of the handle. The curves showed more high frequency components along this axis for the barrel. The Z-axis acceleration amplitudes were about the same for steel, with the handle showing more mid-frequency components. The principle axis was Y for the barrel and Z for the handle. ANSI criteria recommends that this drill be used for a maximum of 1-2 hours for measurements at the handle and 0.5-1 hour at the barrel. Again, this means that the secondary cradling hand is exposed to much greater amplitudes than the primary, particularly in the Y-direction. ACGIH-TLV recommends maximums of 2-4 hours usage at the handle and less than one hour of usage at the barrel.

Concrete

Concrete drilling showed X-direction acceleration amplitudes that were about 1.5 times as large for the handle as they were for the barrel. The spectra showed more mid-frequency components for the handle and more high-frequency ones for the barrel. In the Y-direction acceleration amplitudes for the barrel were about twice those of the handle. The curves showed more high frequencies for the barrel. In the Z-direction acceleration amplitudes for concrete were very similar, but the curves showed more high frequencies for the barrel. The principle axis was Z for both the handle and the barrel. ANSI criteria suggests maximum usage in concrete of 0.5-1 hour at both the handle and the barrel. However, the ACGIH standard recommends less than one hour of use per day regardless of where the measurements are taken.

Plastic

Plastic had similar acceleration amplitudes and similar spectra for both locations in the X-direction. Y-direction acceleration amplitudes were approximately 1.5 times the values for those at the handle. The barrel had more high-frequency components and the handle had more low- ones. The Z-direction also showed acceleration amplitudes of approximately 1.5 times those for the handle at the barrel. However, in this direction the handle had more mid-

frequency acceleration components. The principle axis was Y for both the barrel and the handle. Both the ANSI and ACGIH-TLV standards recommend a maximum of 4-8 hours/day of exposure regardless of where measurements in plastic are taken.

***Drill B*:**

Wood

In the X-direction the results for drill B with the wood bit showed measured acceleration amplitudes at the barrel to be about three times those at the handle. The handle had more mid- and high- frequency components and the barrel, as opposed to more very high-frequency components for the barrel. For Y-axis measurements the acceleration amplitudes at the barrel were also about three times those at the handle. The spectra showed more low-, mid-, and high-frequencies at the barrel than at the handle. In the Z-direction the measured acceleration amplitudes were similar for both locations. The barrel had more low- and very high-frequency components and the handle had more middle ones. The principle axis was X for both the handle and the barrel. Maximum recommended ANSI usage is 2-4 hours/day for measurements taken at the handle and 1-2 hours/day at the barrel. ACGIH-TLV recommends that in wood this drill should only be used for a maximum of 1-2 hours for the hand at the handle or less than one hour for the cradling hand at the barrel.

Steel

X-axis acceleration amplitudes for steel were approximately three times as great at the barrel than at the handle. The handle had more low- and mid-frequency components, and the barrel had more very high ones. In the Y-direction measured acceleration amplitudes were about twice those at the handle. The barrel showed more low- and very high-frequency components. For the Z-axis, acceleration amplitudes were similar at both locations. Again, the barrel showed more low- and very high- frequency components than the handle. The principle axis was X for both the barrel and the handle. ANSI criteria suggests maximum usage of 1-2 hours for measurements taken at the handle and 0.5-1 hour/day at the barrel. ACGIH-TLV recommends 2-4 hours of exposure at the handle, but is more conservative for the barrel suggesting less than one hour of maximum usage.

Concrete

For concrete the X-axis acceleration amplitudes at the barrel, which had more very high-frequency components, were about twice those at the handle which showed more mid- and high-frequency ones. In the Y-direction measured acceleration amplitudes for the barrel were approximately three times those for the handle. The spectra for the barrel showed greater levels throughout the entire frequency range. The Z-direction acceleration amplitudes

for concrete were very similar, but the curves showed more high-frequency components for the barrel. The principle axis was X at both the barrel and the handle. ANSI recommends 0.5-1 hour/day maximum usage regardless of measurement location. The more conservative ACGIH-TLV suggests less than one hour/day regardless for either location.

Plastic

When drilling plastic, the X-axis acceleration amplitudes at the barrel were about four times that at the handle. The handle had more high-frequency components, and the barrel showed more very high frequencies. The Y-axis acceleration amplitudes at the barrel were about twice those at the handle, with the barrel showing higher accelerations throughout the whole frequency range. In the Z-direction the barrel amplitudes were about 1.5 times higher and the spectra showed more high-frequency components than for the handle. The principle axis was X at both the barrel and the handle. Maximum recommended ANSI exposure is 2-4 hours/day for measurements at the handle and 1-2 hours/day at the barrel. Maximum suggested ACGIH-TLV is 2-4 hours at the handle and less than one hour for the cradling hand at the barrel.

CHAPTER V

DISCUSSION AND CONCLUSIONS

Hand-Arm Vibration Syndrome (HAVS) is a pathological condition most prevalent in people using vibrating hand-held tools in cold environments for several hours daily over a period of time. This condition, first recognized in the early twentieth century, has now been identified among numerous groups of industrial workers. Stages of HAVS have been defined, and occupational safety standards for recommended maximum daily vibration exposure have been developed. This condition, which takes months or years to develop, has become commonly associated with the use of gasoline, electric, and pneumatic commercial tools in industrial settings.

The majority of all reported tool testing has involved tools used by workers who have developed HAVS symptoms. There is documented reported data, based on the current safety standards, which gives an indication of maximum allowable vibration exposure times for these tools. However, there appears to be a lack of such information for relatively inexpensive hobby grade tools which are designed specifically for short-term non-continuous usage.

This study focused on standard 3/8" electric drills, a tool commonly used by industrial workers and laymen alike. There are currently no reported cases of HAVS associated with this class of hand-held tools. Because of the lack of information for hobby grade tools, such as the commonly used drill, there is no way to estimate the risk factors associated with them. In addition, there is no documented evidence to date indicating the reason for the lack of

HAVS prevalence for this class of tools.

Hobby grade 3/8" electric drills are inexpensively designed and manufactured, but on the average they are used very little during the workday. Professional drills, whose costs are about five to ten times higher than those tested for this study, have multiple grips and handles padded with anti-vibration viscoelastic damping material. It is therefore assumed that they would probably be better balanced and have lower vibration levels. Since hobby grade drills do not have all these added safety features, there is a question as to why HAVS is not commonly seen in those people who use them. Is it due to low vibration levels, limited non-continuous daily exposure, or a combination of both? This study was designed to be a ground-breaking effort to provide some preliminary answers to these questions. The main objective was to compare the results to data previously found for commercial grade tools, and to identify the potential risk of HAVS development if hobby grade tools were used on a continuous long-term basis.

Tooling vibration tests were run to help identify potential risks and answer several questions. They were performed to: 1) compare measured vibration levels to the current ANSI and ACGIH-TLV safety standards, 2) compare measured vibration levels for four different common bit/material combinations, 3) determine any effects that tool age and usage might have on vibration measurements, 4) verify repeatability of experiments, 5) determine any statistical correlations that might be present from examination of the experimental data, 6) examine the most appropriate method for testing such tools, and 7) make any necessary recommendations regarding usage and exposure to vibration from these tools.

Unfortunately, in most cases, clear patterns were not evident and generalizations could

not be made. There were various results with very little semblance of order. There were even variations between vertical trials. All data plots and rms accelerations were examined from the perspectives of axis comparisons and material comparisons (Appendices D, E). Groupings of the drills by personal/refurbished and rental tools was done. The personal/refurbished ones were further grouped by age.

Although the experimental results from this research did not show clearly definable patterns and support the proposed hypotheses, they did provide some valuable information about this class of hobby grade tools. According to the data obtained in accordance with section 8.3.3.1 of ANSI standard S3.34, none of the tools in any of the materials tested here can be evaluated based on the limited amount of experimentation conducted. There are numerous variables which must be considered in evaluating such tools.

Testing was mostly done for the cradling hand, but kept the same coordinates for the handle measurements, as outlined in section 8.2 of the ANSI standard. In most cases, measurements by the barrel-mounted transducers showed much higher acceleration levels than those mounted on the handle. This probably relates to the fact that the motor is positioned under the casing along the barrel of the drill, thus creating more vibratory acceleration effects in that area. It also supports the hypothesis that the cradling hand is subject to much high acceleration amplitudes at the barrel, where they are maximum. Users of non-professional drills, such as those tested here, probably do mostly one-handed drilling, with very little need to cradle for extended periods of time. If tools such as those tested for this study are used extensively with both hands, there does appear to be the potential for development of Hand-Arm Vibration Syndrome (HAVS).

The fact that no particular patterns are clearly evident for drilling different materials does not concur with the hypothesis that concrete would show the largest vibration acceleration amplitudes, followed by steel, wood, and plastic, in order of decreasing amplitude. The drills themselves appear to matter more than the materials with the appropriate bits, which are optimized for specific materials. Based on the results obtained for barrel-mounted measurements the X-axis appears dominant, particularly in plastic. This may indicate lack of operator control due to non-symmetry of the tool and the moment created about the handle. The Z-axis was most prominent for the materials with greatest impact, particularly concrete. Plastic had lowest acceleration values in Y and Z directions. It was most uniform and therefore least likely to bind. Steel, on the other hand, which had highest acceleration values in Y and Z directions, also had a large propensity to bind.

The only conclusion made concerning tool age and usage is that older drills appear to be less consistent than newer/refurbished ones. It is possible that as a tool is used over time the inner mechanism begins to loosen, thus creating separate vibrations within the drills themselves. This could help to explain inconsistencies observed with the data. The condition of each tool appears to be critical to measured acceleration levels. Worn out bearings and other internal worn components could affect the results and increase the amount of vibration measured.

The mean value of the five vertical trials for each material/bit combination tested was used for purposes of statistical analysis. For some of the drills tested and some of the material/bit combinations used, the standard deviations of the vertical were very large compared to the means. In some cases they were larger than the mean vertical values by

about 20% or more. This large amount of scatter means there is a large range of values and inconsistency for the five vertical trials. This is surprising, because it was expected that most of the drills tested would show results that verified repeatability. In future research, it is suggested that longer data samples might need to be taken and/or more averages calculated during analysis.

Since there is such a wide variation in standard deviations, it is recommended that the vibration acceleration amplitude levels for tools may need to be checked at the specific workplace where they may be used. Comparison of the values of horizontal trials with their mean vertical counterparts showed that in most cases, they were within 20% of the calculated mean values for the vertical trials. This suggests that for workplace testing purposes vertical drilling should be sufficient.

In general, there is no pattern to show tremendous differences between horizontal and vertical drilling. However, certain specific tools might have larger variations than others. Since there is less control when drilling in the horizontal direction, there is more variation in measured acceleration values. The ratio of horizontal drilling to vertical drilling was usually larger, due to the fact that a person can apply greater force vertically because of their body weight and the mass of the drill acting in the same direction as the tool. The different drills tested here had different masses. In addition, the amount of force applied by the operator may also skew results in one direction or the other.

Feed force is applied to the material by a worker pushing on the tool normal to the wokpiece during drilling. An inexperienced tool operator may apply too much force to the workpiece. However, a more experienced tool operator actually lets the tool do the work

(Personal communication with D.E. Wasserman, 1997). The main testing for these experiments was performed by a 155 lb, 6'0" tall man with small wrists and forearms. When another person who was shorter with larger wrists and forearms attempted to duplicate some of the measurements, different acceleration values and vibration spectra were obtained. When the original tool operator repeated the experiment himself, however, the results obtained were very similar to the original data. This suggests that since the results may be altered due to size and density of the worker's arms, the amount of vertical feed force applied varies, and therefore body structure does appear to play a key role in the amount of vibration measured. The amount of grip force the operator applies to the tool at the worker-tool interface while drilling could also affect measured results, as well as the amount of vibration absorbed by the worker due to coupling with the tool.

Another factor that may have affected consistency was the fact that drilling was not completely continuous. During the two-minute testing period for each trial, several holes were drilled, with the tool going through a very brief period where no work was done each time a new hole was started. Therefore, during this period of movement from one hole to another acceleration values may have been changing.

There are also several miscellaneous factors that could cause variations in measured acceleration values. These include rotational speed, material properties, transducer/tool coupling, and segments of data used for analysis. Since the rotational speeds for these tools were unknown, that may have also affected results because of faster or slower drilling. In future testing they should be monitored and determined. Material properties such as hardness and elasticity of the materials may be important. These could affect drilling time, binding, and

amount of impact. The triaxial accelerometer assembly was attached to the drill using a modified hose clamp assembly. It is possible that the tightness of the hose clamp band could affect the amount of coupling between the transducer and the tool. Lastly, since recorded data is non-periodic and there are very brief time periods of no-load conditions during hole changes, the segment of the data chosen for third-octave analysis could affect measured acceleration values and plotted vibration spectra.

According to the experimental data obtained, none of these tools can be adequately evaluated based only on the results presented here. Student t-tests performed for randomly chosen handle versus barrel mounted accelerometer measurements showed that statistical significance does exist between the two mounting locations. Further research should include a multi-factorial statistical analysis that takes into account several factors at once.

However, the results of this study does provide a measure of usability based on current safety standards. Based on testing performed for this study and on the ANSI S3.34 safety standard, it appears that most 3/8" electric hobby grade drills can be safely used for about 1-2 hours. It is possible that taking longer data samples would have changed the amount of standard deviation. Taking more averages might also affect the results. This set of 3/8" hobby grade drills can be looked at as a group, but there is obviously a need to check specific tools at a specific workplace with a specific operator using them.

It is clear from this research that all 3/8" drills are "not created equal". Each one appeared to have its own personality. There is definitely some potential risk of damage. The

amount of vibration to which a worker is exposed depends on several factors, and testing a single tool by itself will probably not give an accurate indication of the general trend for a class of those tools.

CHAPTER VII

RECOMMENDATIONS

In order to enhance the research conducted for this thesis, several suggestions can be made regarding future testing of 3/8" electric drills or similar hobby grade tools. This section addresses potential concerns and recommended improvements for any future experimentation from which researchers and readers of this study might benefit. The experiments conducted here were designed to be an initial effort to look at tools which are not commonly associated with HAVS, but could be potential sources of damage. It could prove useful in future research to perform similar testing with professional grade drills and compare the results to those obtained here and in future experimentation with hobby grade tools.

It is quite obvious from the experimental vibration acceleration data that in order to obtain the most accurate and consistent results, specific tools need to be tested with the material/bit combinations in the workplaces where they will be used, by the people who will be using them. During experiments, the operator should use both hands, especially if two-handed drilling is the norm, while measurements are taken. Two triaxial accelerometer assemblies should be used for testing: one mounted at the handle and the other on the barrel where cradling occurs. The same coordinate system should be used in both locations for consistency. Six channels of data (three for each triaxial assembly) should be taken simultaneously with the DAT recorder.

Based on the results presented here, there appears to be very little need for horizontal

drilling. Therefore, testing should probably include several vertical trials for each experiment conducted. It is possible that the use of longer data samples during testing and more averages during analysis might help to produce more consistent results with smaller standard deviations and less scatter. This in turn might result in a smaller range of measured values with less deviation. In addition, during analysis by the signal analyzer it might be helpful to obtain each time average used to generate the Fourier spectrum from different sections of the recorded data, instead of averaging based on one continuous section of the DAT recorded tape. This could help to reduce any potential bias that might have presented itself during the experiments conducted here.

During future experimentation some experimentation with adjustments to the hose clamp band might help to clarify whether this is significant enough to affect transducer/tool coupling and thus skew results. Determining tool rotational speed and specific material properties might also prove helpful. A multi-factorial statistical analysis which simultaneously considers several factors which could affect measured acceleration values would be beneficial for future studies. Such studies should also attempt to narrow the focus of the research. A larger number of drills used upon one or two different materials for several vertical drilling trials would be one way to do this. Because the difference in mounting location appears to be statistically significant, future research should also incorporate handle and barrel mounted triaxial accelerometer assemblies for all two-handed drill testing.

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APPENDICES

Appendix A

This appendix contains hardcopy printouts of autosequences programmed into the HP 3562A dynamic signal analyzer. These autosequences were used to set up the analyzer and to plot the third-octave spectra stored on floppy disk.

Auto Sequence 1 110 Keys Left

Display ON Label: ASETUP

```
1  A B
2  MEAS MODE: LOG RES
3  SELECT MEAS: FREQ RESP
4  SELECT MEAS: CH 1&2 ACTIVE
5  AVG: NUMBER AVGS 7
6  AVG: STABLE (MEAN)
7  FREQ (SPAN): START FREQ 5 Hz
8  SOURCE: SOURCE OFF
9  RANGE: CHAN 1 RANGE 5 V
10 RANGE: CHAN 2 RANGE 5 V
11 ICPL: CHAN1 AC DC (1/O): FLOAT CHAN1
12 ICPL: CHAN2 AC DC (1/O): FLOAT CHAN2
13 ENGR UNITS: EU VAL CHAN1 1.02 mV/EU
14 ENGR UNITS: EU VAL CHAN2 1.02 mV/EU
15 ENGR UNITS: EU LBL CHAN1 M/S2
16 ENGR UNITS: EU LBL CHAN2 M/S2
17 COORD: MAG (LOG)
18 SCALE: X FIXD SCALE 5, 1500 Hz
19 SCALE: Y FIXD SCALE 1, 1000 EU2
```

```
                    Auto Sequence 3  108 Keys Left
Display ON   Label:  FRPLOT

  1   PLOT:  SELECT DATA:  DATA & ANNOT
  2   PLOT:  SELECT DATA:  TICK MARKS
  3   PLOT:  SELECT PENS:  GRID PEN 1
  4   PLOT:  SELECT PENS:  TRACE A PEN 3
  5   PLOT:  SELECT PENS:  TRACE B PEN 4
  6   PLOT:  SELECT PENS:  ANNOT A PEN 1
  7   PLOT:  SPEED  F  S   (1/0)  0
  8   PLOT:  LINE TYPES:  SOLID LINES
  9   PLOT:  PAGING CONTRL:  NO PAGING
  10  PLOT: PCTL:  CUT PG ON OFF  (1/0)  0
  11  PLOT:  PLOT LIMITS:  PLOT AREA
  12  PLOT: PLIM: ULIM:  SET P1 LWR LF 770, 1170
  13  PLOT: PLIM: ULIM: SEP2 UPR RT 9760, 6930
  14  PLOT: PLIM:  ROT 90 ON OFF  (1/0)  0
  15  A
  16  SINGLE
  17  PLOT:  START PLOT
  18  B
  19  PLOT:  SELECT DATA:  DATA ONLY
  20  PLOT:  START PLOT
```

Auto Sequence 3 108 Keys Left

Display ON Label: HPLOT

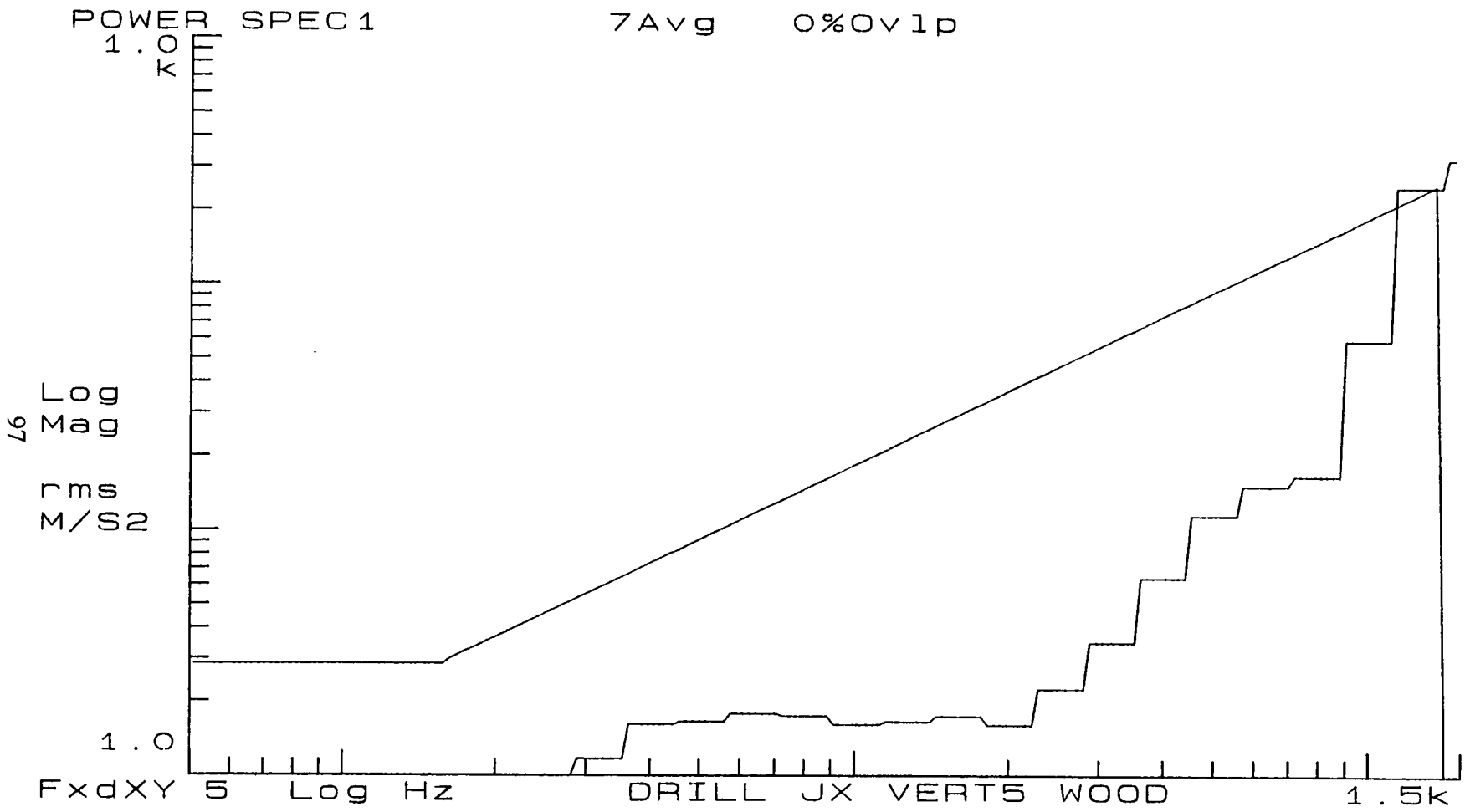
```
 1  PLOT:  SELECT DATA:  DATA & ANNOT
 2  PLOT:  SELECT DATA:  TICK MARKS
 3  PLOT:  SELECT PENS:  GRID PEN 1
 4  PLOT:  SELECT PENS:  TRACE A PEN 1
 5  PLOT:  SELECT PENS:  TRACE B PEN 4
 6  PLOT:  SELECT PENS:  ANNOT A PEN 1
 7  PLOT:  SPEED  F  S  (1/0) 0
 8  PLOT:  LINE TYPES:  SOLID LINES
 9  PLOT:  PAGING CONTRL:  NO PAGING
10  PLOT: PCTL:  CUT PG ON OFF  (1/0)  0
11  PLOT:  PLOT LIMITS:  PLOT AREA
12  PLOT: PLIM: ULIM:  SET P1 LWR LF 770, 1170
13  PLOT: PLIM: ULIM: SEP2 UPR RT 9760, 6930
14  PLOT: PLIM:  ROT 90 ON OFF  (1/0)  0
15  A
16  SINGLE
17  PLOT:  START PLOT
18  B
19  PLOT:  SELECT DATA:  DATA ONLY
20  PLOT:  START PLOT
```

```
                    Auto Sequence 3  108 Keys Left
Display ON   Label:  VPLOT

  1   PLOT:  SELECT DATA:  DATA & ANNOT
  2   PLOT:  SELECT DATA:  TICK MARKS
  3   PLOT:  SELECT PENS:  GRID PEN 1
  4   PLOT:  SELECT PENS:  TRACE A PEN 2
  5   PLOT:  SELECT PENS:  TRACE B PEN 4
  6   PLOT:  SELECT PENS:  ANNOT A PEN 1
  7   PLOT:  SPEED  F  S   (1/0)  0
  8   PLOT:  LINE TYPES:  SOLID LINES
  9   PLOT:  PAGING CONTRL:  NO PAGING
  10  PLOT: PCTL:  CUT PG ON OFF  (1/0)  0
  11  PLOT:  PLOT LIMITS:  PLOT AREA
  12  PLOT: PLIM: ULIM:  SET P1 LWR LF 770, 1170
  13  PLOT: PLIM: ULIM: SEP2 UPR RT 9760, 6930
  14  PLOT: PLIM:  ROT 90 ON OFF  (1/0)  0
  15  A
  16  SINGLE
  17  PLOT:  START PLOT
  18  B
  19  PLOT:  SELECT DATA:  DATA ONLY
  20  PLOT:  START PLOT
```

Appendix B

This appendix contains examples of third-octave spectra obtained from recorded acceleration data for different tool/material/bit combinations. The ANSI standard exposure zones are superimposed on the plots to determine if, and by how much, the standard may have been exceeded.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7Avg
0%Ovlp
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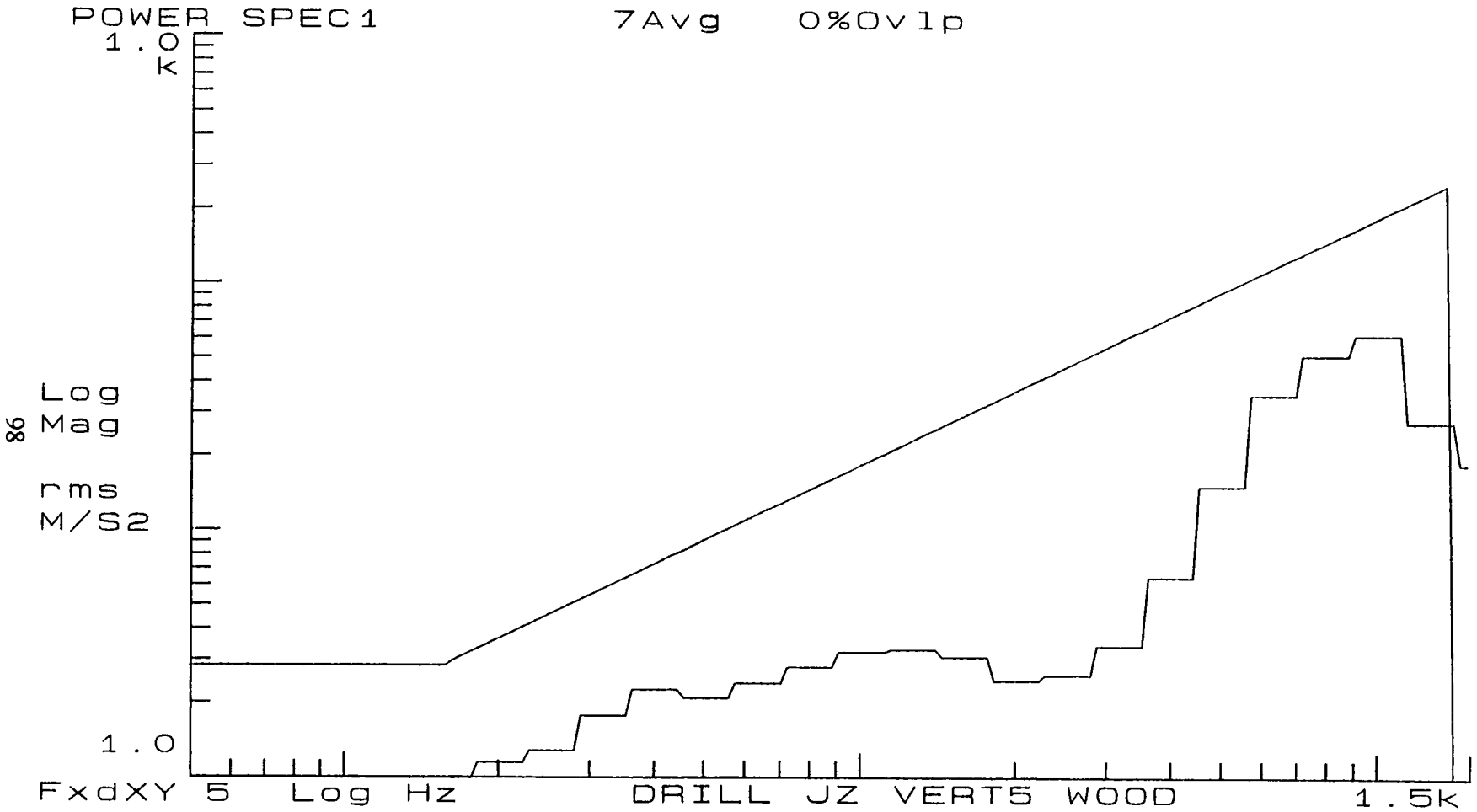
k
Log
Mag
rms
M/S2
1.0
FxdXY 5
Log Hz
DRILL JX VERT5 WOOD
1.5k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Log
Mag
rms
M/S2
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Log Hz
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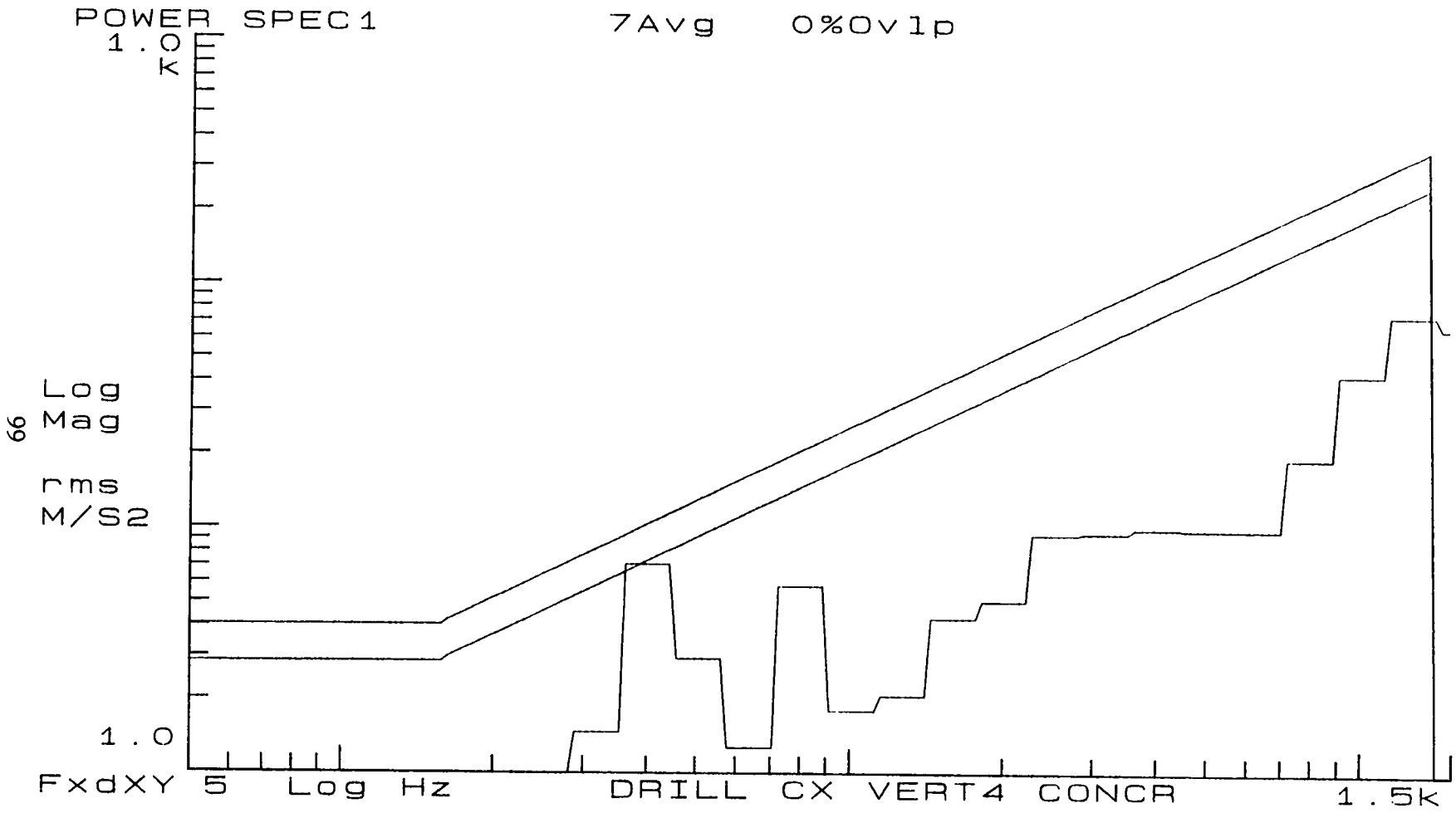
1.5k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7Avg
0%Ovlp
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k
Log
Mag
rms
M/S2
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FxdXY 5
Log Hz
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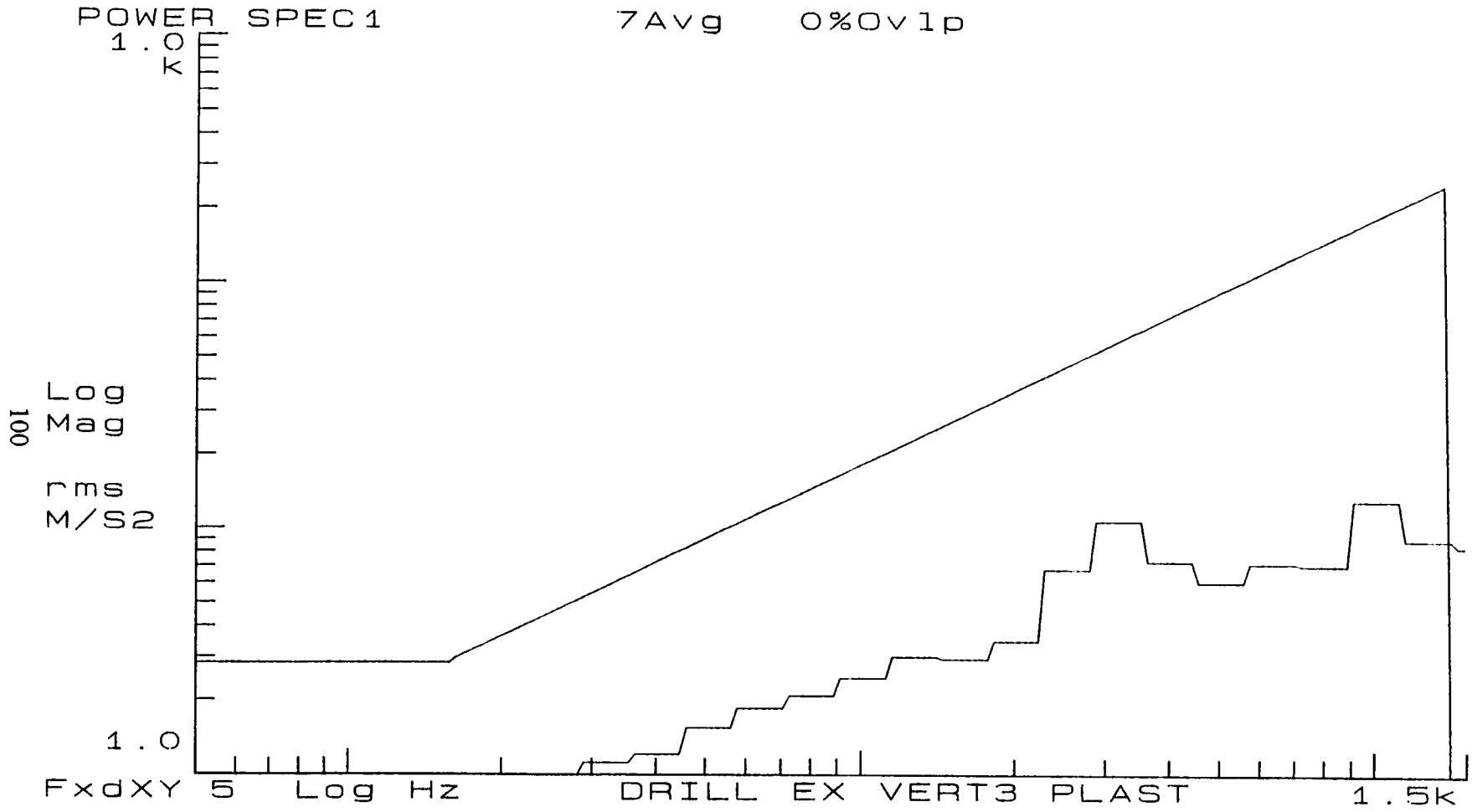
1.5k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k
Log
Mag
rms
M/S2
1.0
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Log Hz
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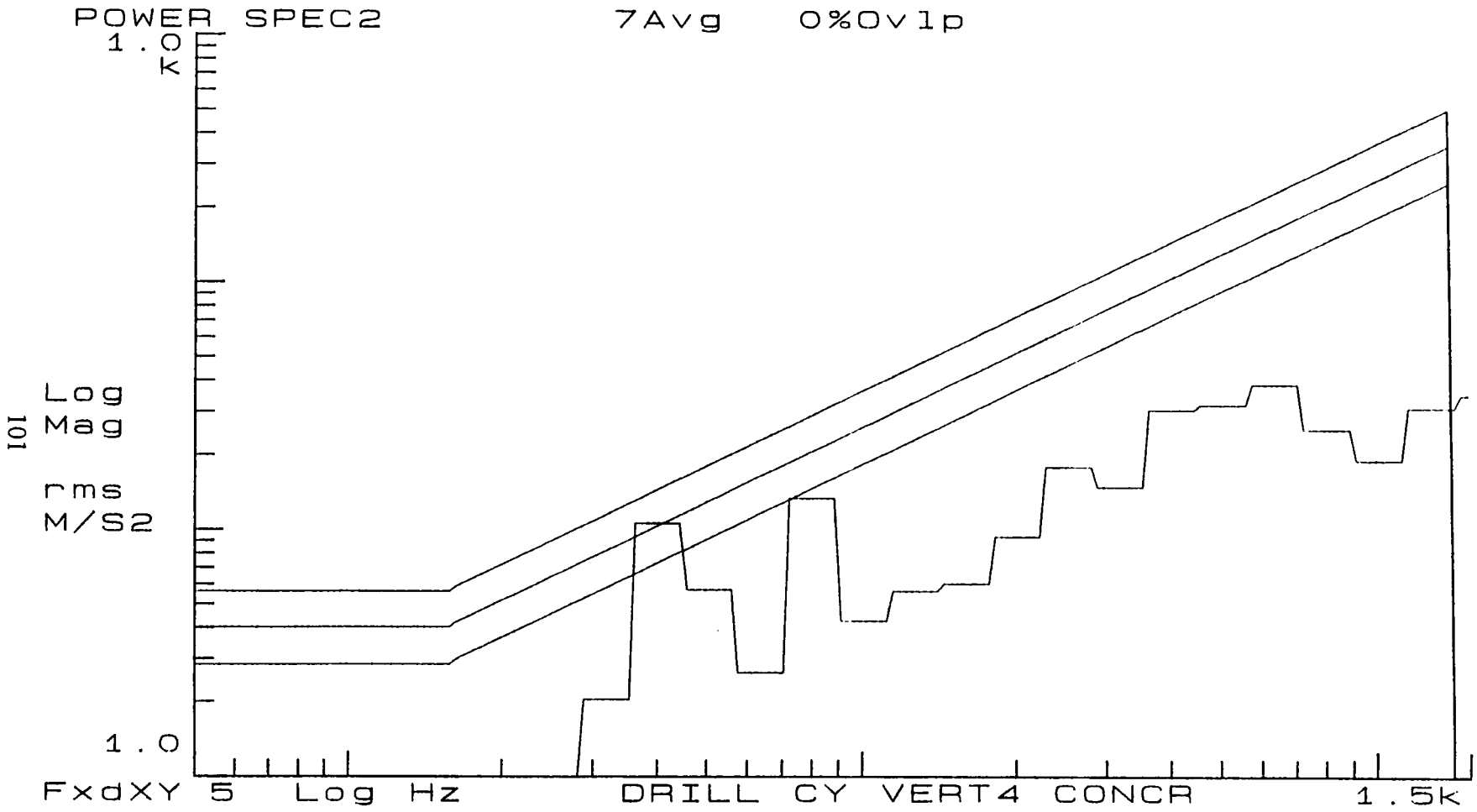
1.5k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Log
Mag
rms
M/S2
1.0
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Log Hz
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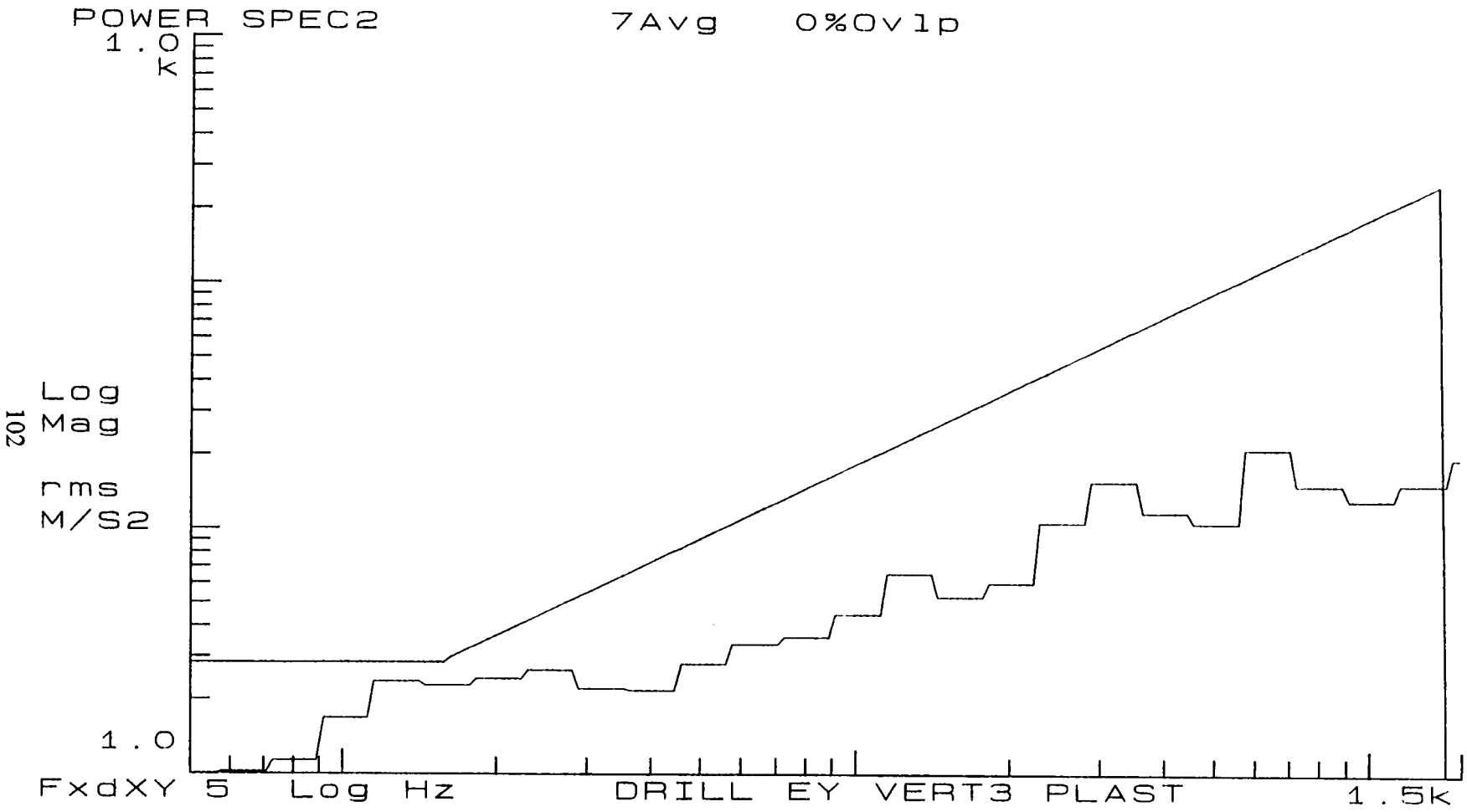
1.5k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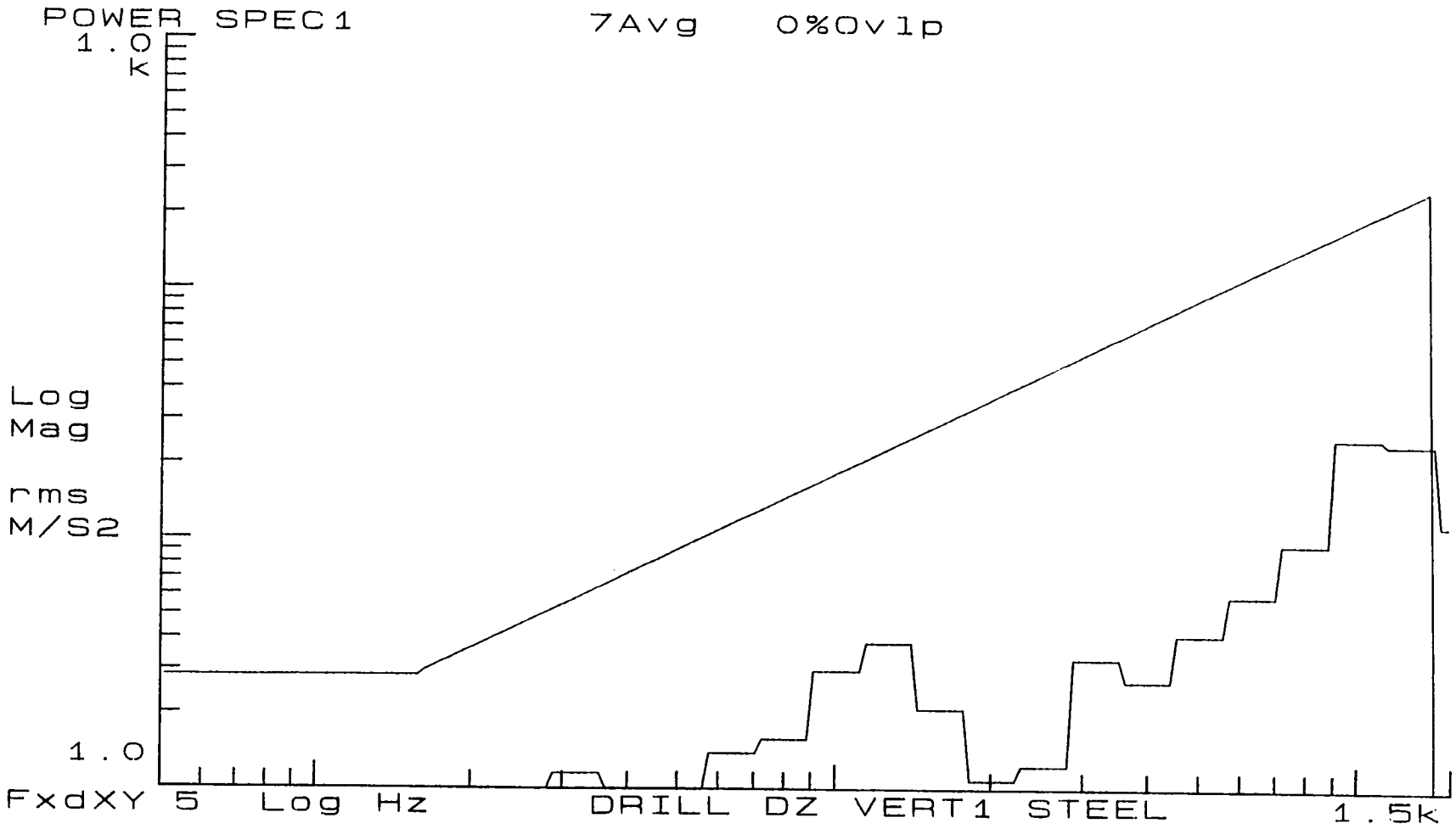
0%Ovlp
1.0
k
Log
Mag
rms
M/S2
1.0
FxdXY 5
Log Hz
DRILL EY VERT3 PLAST
1.5k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k
Log
Mag
rms
M/S2
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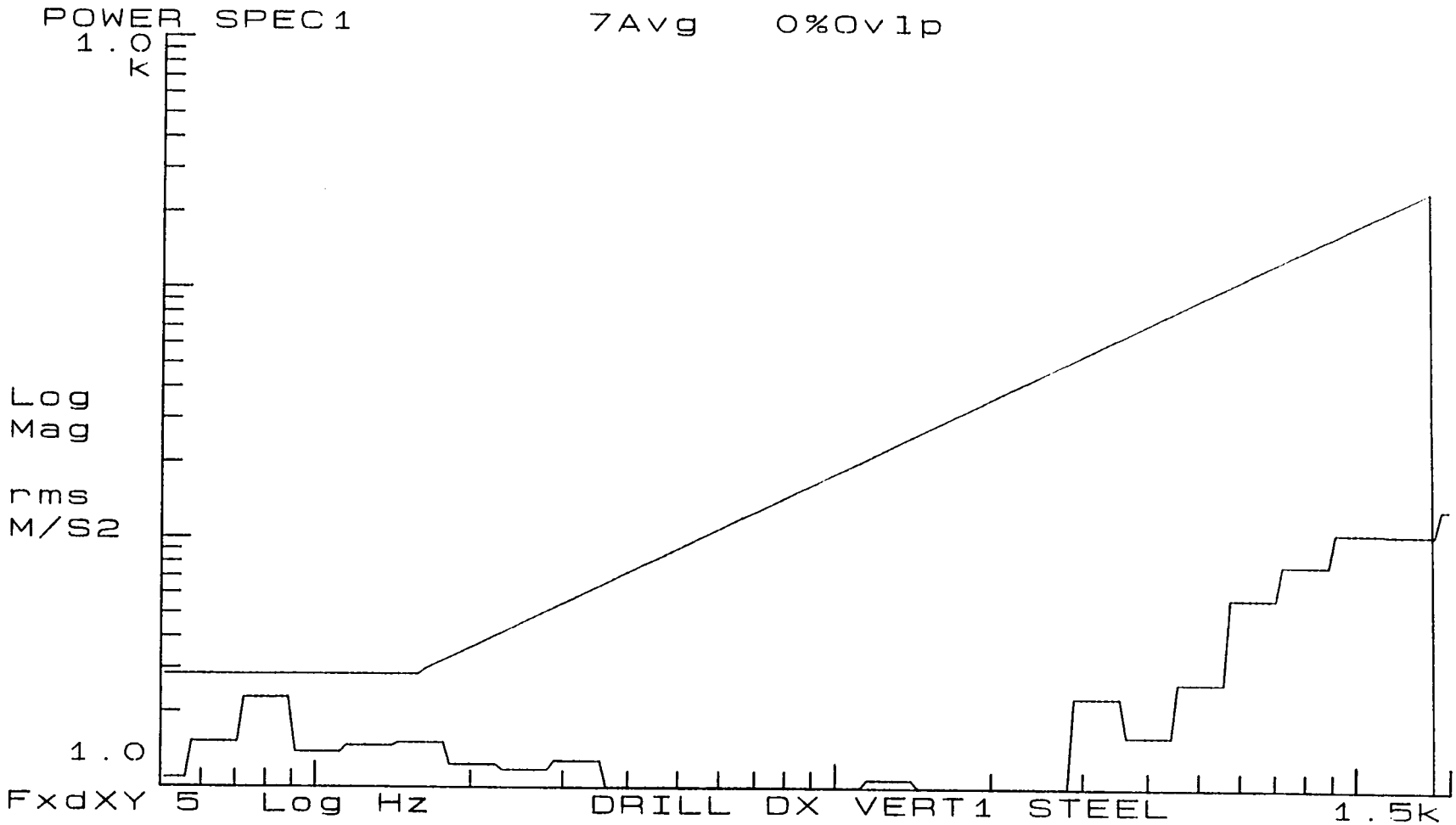
Log Hz
DRILL DZ VERT1 STEEL
1.5k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0%Ovlp
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k
Log
Mag
rms
M/S2
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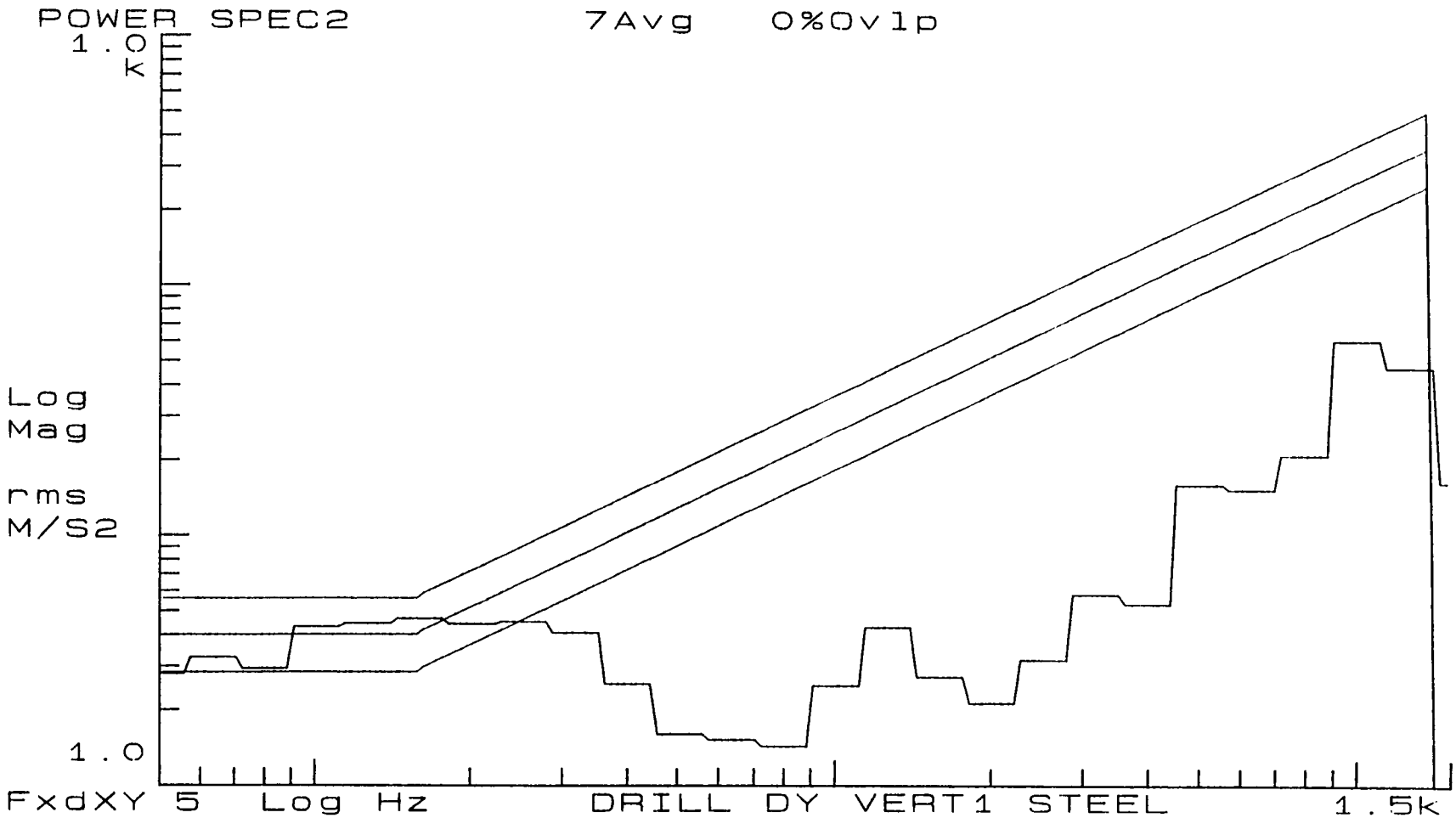
FxdXY
5
Log Hz
DRILL DX VERT1 STEEL
1.5k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Log
Mag
rms
M/S2
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Log Hz
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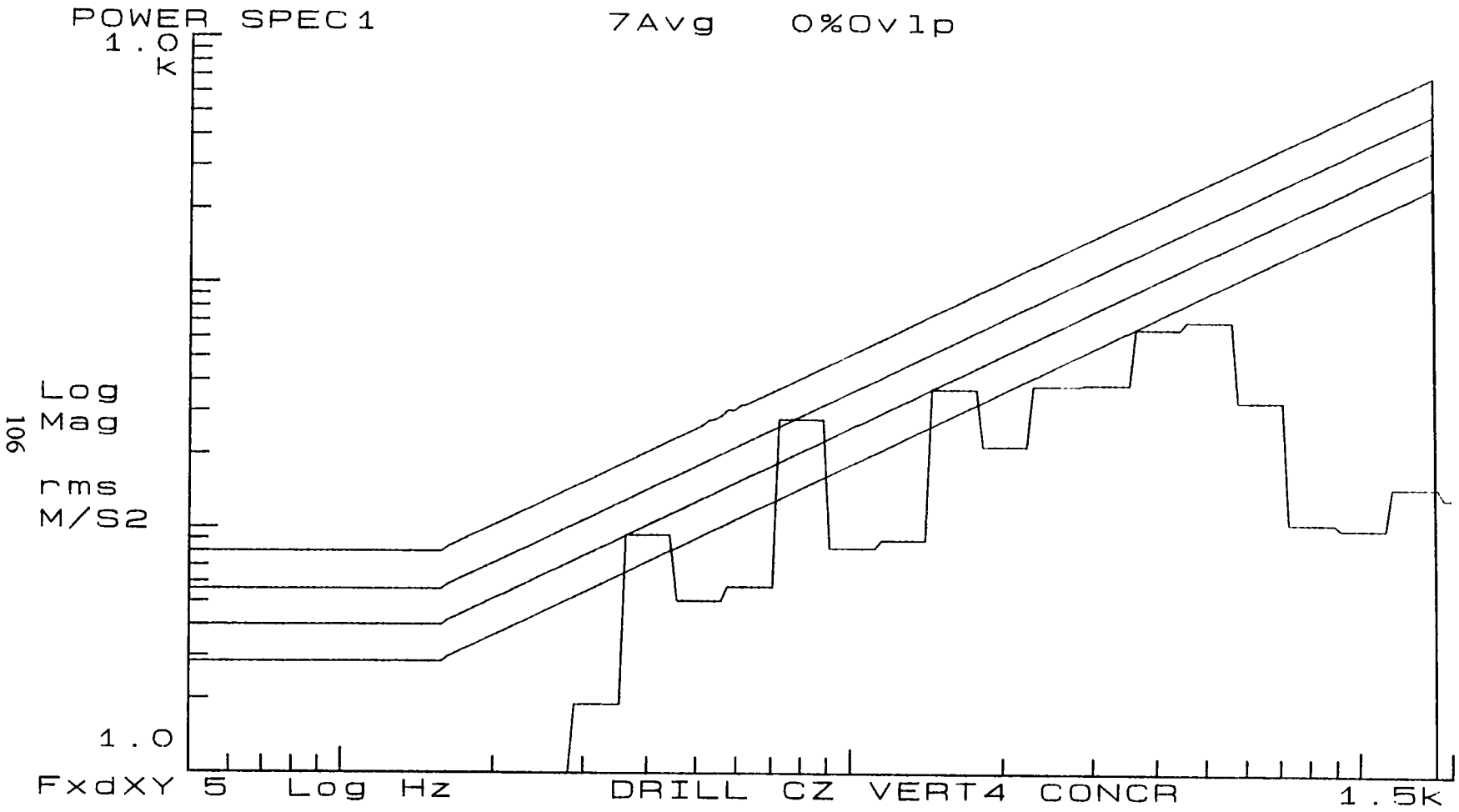
1.5k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k
Log
Mag
rms
M/S2
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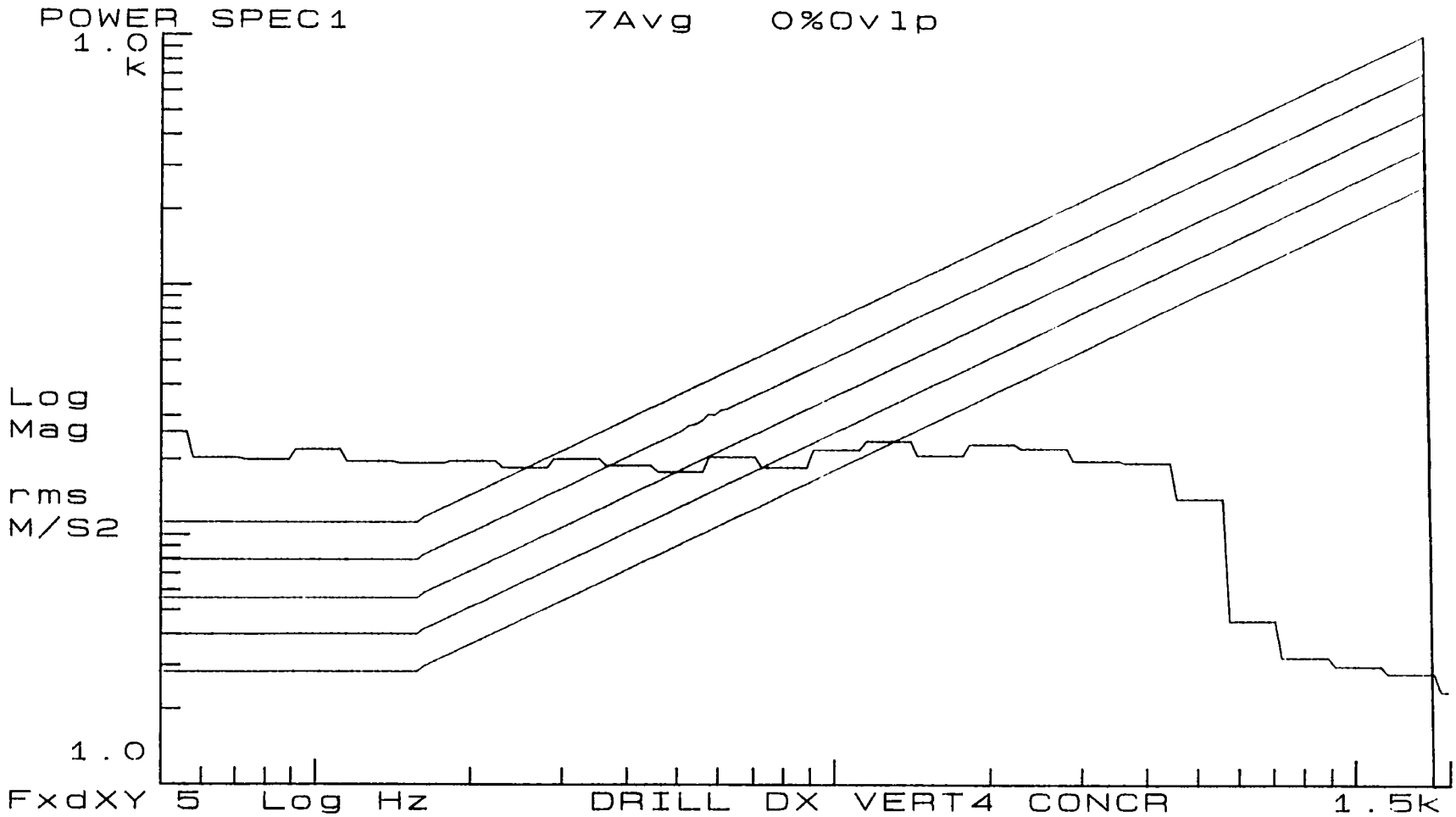
FxdXY 5
Log Hz
DRILL CZ VERT4 CONCR
1.5k

Appendix C

This appendix contains examples of third-octave spectra obtained from recorded acceleration data that appear to be grossly incorrect, have tremendous deviations from mean values, and far exceed ANSI recommended exposure zones. Data such as this was assumed to be invalid. The corresponding rms acceleration values for these plots exceeded mean acceleration values by a factor of 3 or more.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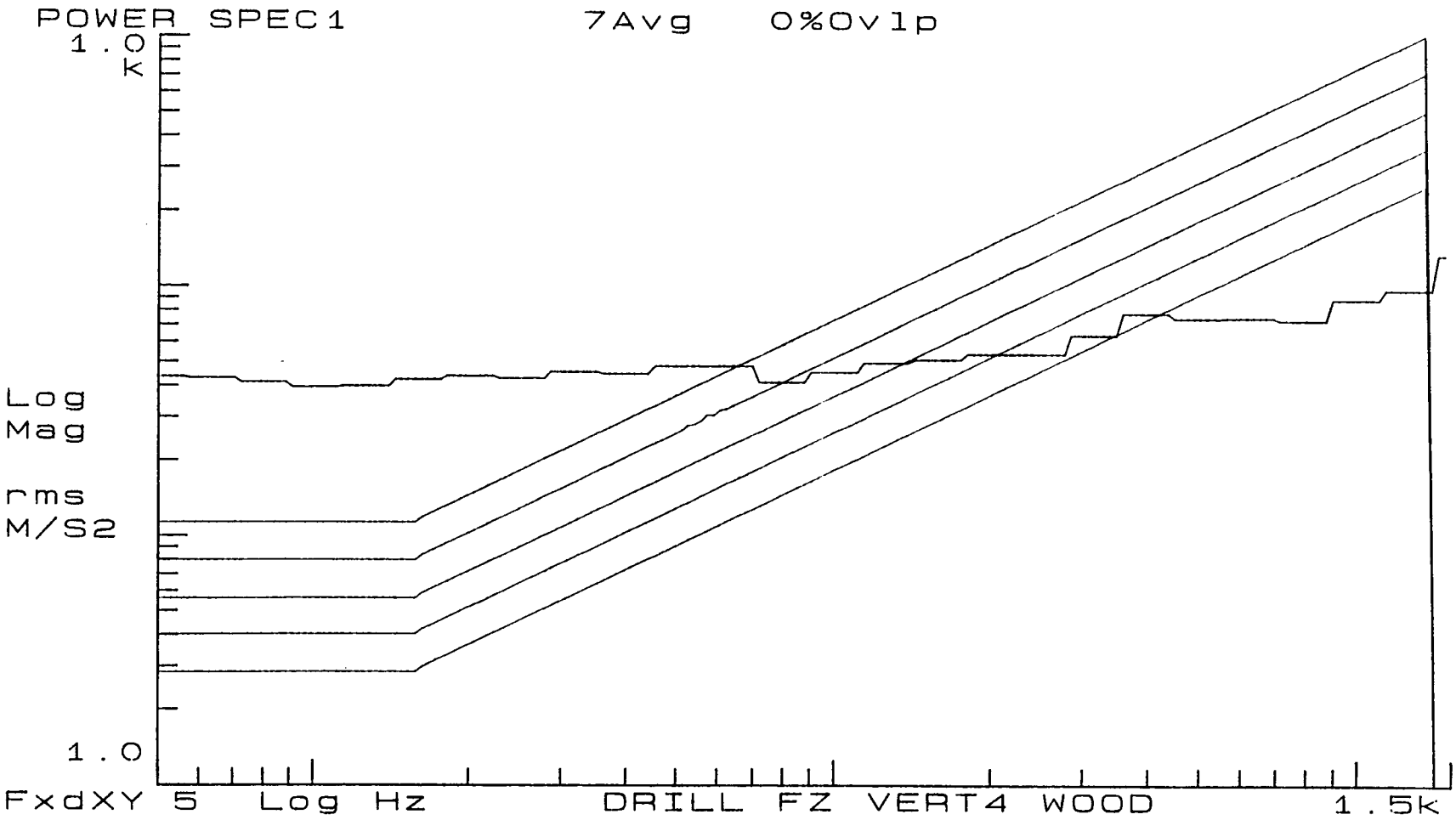
k
Log
Mag
rms
M/S2
1.0
FxdXY
5
Log Hz
DRILL DX VERT4 CONCR
1.5k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0%Ovlp
1.0
k
Log
Mag
rms
M/S2
1.0
FxdXY 5
Log Hz
DRILL FZ VERT4 WOOD
1.5k

Appendix D

This appendix contains the results, in tabular form for "free run" drilling, horizontal drilling experiments, and vertical drilling experiments conducted for each bit/material combination. The principal axes of acceleration are given in bold type and also in parentheses ( ) following recommended maximum exposure times.

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Free Run	Wood	1.93	**2.93**	0.98	N/A	N/A
C	Free Run	Wood	0.68	1.09	**1.21**	N/A	N/A
J	Free Run	Wood	1.04	**1.45**	1.10	N/A	N/A
B	Free Run	Wood	**3.83**	3.75	2.45	N/A	N/A
H	Free Run	Wood	**3.62**	3.48	2.15	N/A	N/A
D	Free Run	Wood	**2.51**	1.66	0.88	N/A	N/A
E	Free Run	Wood	2.91	5.37	**10.38**	N/A	N/A
F	Free Run	Wood	1.55	**1.82**	0.69	N/A	N/A
G	Free Run	Wood	1.62	**2.26**	0.90	N/A	N/A
I	Free Run	Wood	7.18	10.02	**11.39**	N/A	N/A

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Free Run	Steel	2.36	**3.46**	1.39	N/A	N/A
C	Free Run	Steel	0.79	**1.29**	1.19	N/A	N/A
J	Free Run	Steel	1.01	**1.17**	0.84	N/A	N/A
B	Free Run	Steel	2.51	**3.13**	1.66	N/A	N/A
H	Free Run	Steel	3.19	3.37	**4.49**	N/A	N/A
D	Free Run	Steel	**2.24**	1.19	0.74	N/A	N/A
E	Free Run	Steel	2.31	4.87	**6.30**	N/A	N/A
F	Free Run	Steel	**2.04**	1.69	-	N/A	N/A
G	Free Run	Steel	**1.64**	1.53	1.13	N/A	N/A
I	Free Run	Steel	12.14	14.77	**18.05**	N/A	N/A

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Free Run	Concr	1.85	**3.49**	1.91	N/A	N/A
C	Free Run	Concr	0.84	**1.59**	1.46	N/A	N/A
J	Free Run	Concr	**2.49**	1.83	0.93	N/A	N/A
B	Free Run	Concr	2.88	**2.89**	1.84	N/A	N/A
H	Free Run	Concr	5.80	7.19	**12.43**	N/A	N/A
D	Free Run	Concr	**2.12**	1.35	0.69	N/A	N/A
E	Free Run	Concr	3.90	8.31	**15.13**	N/A	N/A
F	Free Run	Concr	1.90	**2.12**	1.76	N/A	N/A
G	Free Run	Concr	2.55	2.52	**2.92**	N/A	N/A
I	Free Run	Concr	12.63	13.19	**18.77**	N/A	N/A

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Free Run	Plast	2.97	**4.18**	1.18	N/A	N/A
C	Free Run	Plast	1.33	**1.68**	1.08	N/A	N/A
J	Free Run	Plast	1.34	**1.43**	1.10	N/A	N/A
B	Free Run	Plast	3.59	3.23	**3.66**	N/A	N/A
H	Free Run	Plast	**4.36**	4.13	2.37	N/A	N/A
D	Free Run	Plast	-	**1.34**	0.65	N/A	N/A
E	Free Run	Plast	0.84	4.42	**6.50**	N/A	N/A
F	Free Run	Plast	**1.77**	1.49	0.71	N/A	N/A
G	Free Run	Plast	1.79	**2.22**	0.86	N/A	N/A
I	Free Run	Plast	5.87	8.77	**9.28**	N/A	N/A

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Horizontal	Wood	2.15	**5.06**	2.89	4-8 (Y)	2-4 (Y)
C	Horizontal	Wood	2.04	**3.63**	3.59	4-8 (Y)	4-8 (Y)
J	Horizontal	Wood	5.60	**8.88**	2.74	4-8 (Y)	<1.0 (Y)
B	Horizontal	Wood	5.40	**6.84**	4.19	4-8 (Y)	1-2 (Y)
H	Horizontal	Wood	**5.46**	5.44	3.83	4-8 (Y)	2-4 (X)
D	Horizontal	Wood	4.57	**8.71**	2.96	1-2 (Y)	<1.0 (Y)
E	Horizontal	Wood	3.06	6.53	**9.16**	2-4 (Z)	<1.0 (Z)
F	Horizontal	Wood	11.39	**16.34**	-	4-8 (Y)	0 (Y)
G	Horizontal	Wood	**4.79**	4.49	2.23	4-8 (Y)	2-4 (X)
I	Horizontal	Wood	7.87	10.39	**11.96**	1-2 (Z)	<1.0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Horizontal	Steel	5.00	4.45	**6.66**	1-2 (Z)	1-2 (Z)
C	Horizontal	Steel	2.10	**3.65**	2.53	4-8 (Y)	4-8 (Y)
J	Horizontal	Steel	3.55	**6.00**	2.44	4-8 (Y)	2-4 (Y)
B	Horizontal	Steel	4.77	**4.96**	3.69	4-8 (Y)	2-4 (Y)
H	Horizontal	Steel	5.09	**5.11**	4.35	4-8 (Y)	2-4 (Y)
D	Horizontal	Steel	**5.15**	3.08	2.21	4-8 (Y)	2-4 (X)
E	Horizontal	Steel	2.92	5.60	**10.27**	2-4 (Z)	<1.0 (Z)
F	Horizontal	Steel	10.27	**10.99**	-	4-8 (Y)	<1.0 (Y)
G	Horizontal	Steel	**3.78**	2.70	2.17	4-8 (Y)	4-8 (X)
I	Horizontal	Steel	11.65	14.63	**17.94**	0.5-1 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Horizontal	Concr	5.05	6.30	**9.93**	0.5-1 (Z)	<1.0 (Z)
C	Horizontal	Concr	4.33	7.85	**8.88**	0.5-1 (Y)	<1.0 (Z)
J	Horizontal	Concr	3.72	**5.65**	4.20	4-8 (Y)	2-4 (Y)
B	Horizontal	Concr	7.06	-	**8.24**	2-4 (Z)	<1.0 (Z)
H	Horizontal	Concr	7.11	6.41	**7.98**	2-4 (Z)	1-2 (Z)
D	Horizontal	Concr	4.60	4.15	**5.31**	4-8 (Z)	2-4 (Z)
E	Horizontal	Concr	5.05	8.51	**14.79**	1-2 (Z)	0 (Z)
F	Horizontal	Concr	9.61	**14.13**	6.26	1-2 (Y)	0 (Y)
G	Horizontal	Concr	4.42	4.21	**6.73**	4-8 (Z)	1-2 (Z)
I	Horizontal	Concr	9.26	11.39	**14.78**	1-2 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Horizontal	Plast	3.87	**5.44**	4.22	2-4 (Z)	2-4 (Y)
C	Horizontal	Plast	4.73	**4.86**	4.77	4-8 (Y)	2-4 (Y)
J	Horizontal	Plast	5.76	**7.69**	1.87	1-2 (Y)	1-2 (Y)
B	Horizontal	Plast	**9.63**	8.18	5.28	4-8 (Y)	<1.0 (X)
H	Horizontal	Plast	**8.67**	5.93	3.64	4-8 (Y)	<1.0 (X)
D	Horizontal	Plast	-	**9.25**	1.57	0.5-1 (Y)	<1.0 (Y)
E	Horizontal	Plast	2.97	6.70	**9.01**	4-8 (Z)	<1.0 (Z)
F	Horizontal	Plast	12.48	**18.00**	5.35	1-2 (Y)	0 (Y)
G	Horizontal	Plast	2.87	**4.83**	1.33	4-8 (Y)	2-4 (Y)
I	Horizontal	Plast	6.03	**8.73**	7.32	4-8 (Z)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 1	Wood	2.37	**4.98**	4.03	2-4 (Y)	2-4 (Y)
C	Vertical 1	Wood	2.37	3.84	**4.93**	4-8 (Z)	2-4 (Z)
J	Vertical 1	Wood	4.32	**8.35**	3.20	2-4 (Y)	<1.0 (Y)
B	Vertical 1	Wood	7.27	**8.16**	5.32	1-2 (Y)	<1.0 (Y)
H	Vertical 1	Wood	6.31	**6.56**	3.89	4-8 (Y)	1-2 (Y)
D	Vertical 1	Wood	4.21	**7.27**	2.71	1-2 (Y)	1-2 (Y)
E	Vertical 1	Wood	3.13	7.36	**9.04**	2-4 (Z)	<1.0 (Z)
F	Vertical 1	Wood	10.04	**16.03**	11.57	1-2 (Z)	0 (Y)
G	Vertical 1	Wood	2.48	**5.70**	1.93	2-4 (Y)	2-4 (Y)
I	Vertical 1	Wood	6.66	**10.31**	10.02	2-4 (Z)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 1	Steel	2.36	3.46	**4.60**	2-4 (Z)	2-4 (Z)
C	Vertical 1	Steel	3.11	5.40	**5.65**	4-8 (Z)	2-4 (Z)
J	Vertical 1	Steel	5.11	**5.56**	2.36	4-8 (Y)	2-4 (Y)
B	Vertical 1	Steel	6.99	**8.53**	4.44	2-4 (Y)	<1.0 (Y)
H	Vertical 1	Steel	5.97	**6.02**	3.69	4-8 (Y)	1-2 (Y)
D	Vertical 1	Steel	6.34	**10.67**	2.33	1-2 (Y)	<1.0 (Y)
E	Vertical 1	Steel	2.53	5.26	**5.70**	4-8 (Z)	2-4 (Z)
F	Vertical 1	Steel	**13.60**	12.70	-	4-8 (Y)	0 (X)
G	Vertical 1	Steel	**7.90**	3.87	4.53	4-8 (Y)	4-8 (X)
I	Vertical 1	Steel	10.90	13.16	**13.90**	1-2 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 1	Concr	4.65	5.73	**6.86**	2-4 (Z)	1-2 (Z)
C	Vertical 1	Concr	4.65	6.87	**8.00**	1-2 (Z)	1-2 (Z)
J	Vertical 1	Concr	**6.26**	6.00	3.13	4-8 (Y)	1-2 (X)
B	Vertical 1	Concr	5.25	-	**5.39**	4-8 (Z)	2-4 (Z)
H	Vertical 1	Concr	6.87	7.57	**10.74**	1-2 (Z)	0 (Z)
D	Vertical 1	Concr	5.33	**10.08**	3.73	<0.5 (Y)	<1.0 (Y)
E	Vertical 1	Concr	5.24	8.73	**13.85**	1-2 (Z)	0 (Z)
F	Vertical 1	Concr	12.34	**15.42**	8.28	1-2 (Y)	0 (Y)
G	Vertical 1	Concr	4.18	**4.46**	-	4-8 (Y)	2-4 (Y)
I	Vertical 1	Concr	10.51	12.41	**15.03**	1-2 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 1	Plast	1.86	**5.39**	2.12	4-8 (Y)	2-4 (Y)
C	Vertical 1	Plast	**4.76**	4.19	3.86	4-8 (Y)	2-4 (X)
J	Vertical 1	Plast	7.65	**8.44**	1.82	2-4 (Y)	<1.0 (Y)
B	Vertical 1	Plast	9.71	**10.93**	9.28	4-8 (Y)	<1.0 (Y)
H	Vertical 1	Plast	**8.47**	5.55	3.18	4-8 (Y)	<1.0 (X)
D	Vertical 1	Plast	-	**4.98**	1.59	2-4 (Y)	2-4 (Y)
E	Vertical 1	Plast	2.59	5.48	**6.96**	4-8 (Z)	1-2 (Z)
F	Vertical 1	Plast	6.68	**10.10**	3.62	4-8 (Y)	<1.0 (Y)
G	Vertical 1	Plast	3.25	**4.93**	1.73	4-8 (Y)	2-4 (Y)
I	Vertical 1	Plast	5.24	**7.81**	5.62	4-8 (Y)	1-2 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 2	Wood	2.16	**4.55**	4.13	4-8 (Y)	2-4 (Y)
C	Vertical 2	Wood	2.55	4.24	**5.40**	2-4 (Z)	2-4 (Y)
J	Vertical 2	Wood	3.66	**7.32**	4.82	2-4 (Y)	1-2 (Y)
B	Vertical 2	Wood	5.48	**7.09**	4.18	2-4 (Y)	1-2 (Y)
H	Vertical 2	Wood	5.78	**7.32**	3.76	2-4 (Y)	1-2 (Y)
D	Vertical 2	Wood	3.79	**7.96**	3.13	1-2 (Y)	1-2 (Y)
E	Vertical 2	Wood	3.72	9.06	**12.63**	1-2 (Z)	0 (Z)
F	Vertical 2	Wood	11.00	**12.65**	-	1-2 (Y)	0 (Y)
G	Vertical 2	Wood	3.85	**6.87**	2.29	2-4 (Y)	1-2 (Y)
I	Vertical 2	Wood	8.10	**13.00**	10.97	1-2 (Y)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 2	Steel	5.52	4.53	**10.52**	0.5-1 (Z)	<1.0 (Z)
C	Vertical 2	Steel	3.01	**4.93**	3.00	4-8 (Y)	2-4 (Y)
J	Vertical 2	Steel	5.22	**7.69**	2.10	2-4 (Y)	1-2 (Y)
B	Vertical 2	Steel	7.87	**12.16**	5.71	1-2 (Y)	0 (Y)
H	Vertical 2	Steel	**5.27**	4.98	4.22	4-8 (Z)	2-4 (X)
D	Vertical 2	Steel	5.96	**7.32**	2.04	1-2 (Y)	1-2 (Y)
E	Vertical 2	Steel	3.28	7.03	**9.83**	2-4 (Z)	<1.0 (Z)
F	Vertical 2	Steel	12.08	**15.88**	4.68	2-4 (0)	0 (Y)
G	Vertical 2	Steel	3.56	**4.13**	1.73	4-8 (Y)	2-4 (Y)
I	Vertical 2	Steel	9.98	12.80	**13.52**	1-2 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 2	Concr	4.69	6.34	**8.89**	0.5-1 (Z)	<1.0 (Z)
C	Vertical 2	Concr	4.51	7.34	**10.86**	1-2 (Y)	<1.0 (Z)
J	Vertical 2	Concr	3.97	**6.72**	3.63	2-4 (Y)	1-2 (Y)
B	Vertical 2	Concr	8.46	-	**8.60**	4-8 (Z)	<1.0 (Z)
H	Vertical 2	Concr	6.67	7.33	**10.69**	2-4 (Z)	<1.0 (Z)
D	Vertical 2	Concr	5.25	**7.50**	3.72	0.5-1 (Y)	1-2 (Y)
E	Vertical 2	Concr	6.22	11.32	**17.02**	1-2 (Z)	0 (Z)
F	Vertical 2	Concr	11.26	**13.09**	5.34	0.5-1 (Y)	0 (Y)
G	Vertical 2	Concr	3.50	**4.39**	3.74	4-8 (Z)	2-4 (Y)
I	Vertical 2	Concr	10.13	13.69	**15.42**	1-2 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 2	Plast	2.42	**6.42**	2.51	4-8 (Y)	1-2 (Y)
C	Vertical 2	Plast	4.74	**5.03**	3.68	4-8 (Y)	2-4 (Y)
J	Vertical 2	Plast	8.05	**9.71**	2.29	1-2 (Y)	<1.0 (Y)
B	Vertical 2	Plast	**9.80**	9.04	6.09	2-4 (Y)	<1.0 (X)
H	Vertical 2	Plast	4.29	**4.52**	3.04	4-8 (Z)	2-4 (Y)
D	Vertical 2	Plast	-	**7.75**	6.96	1-2 (Y)	1-2 (Y)
E	Vertical 2	Plast	2.97	6.49	**9.41**	1-2 (Z)	<1.0 (Z)
F	Vertical 2	Plast	7.80	**15.68**	5.05	2-4 (Y)	0 (Y)
G	Vertical 2	Plast	**6.74**	4.81	2.33	4-8 (Y)	1-2 (X)
I	Vertical 2	Plast	6.22	**8.83**	6.92	4-8 (Z)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 3	Wood	2.18	**4.80**	3.96	2-4 (Y)	2-4 (Y)
C	Vertical 3	Wood	2.35	3.95	**5.53**	2-4 (Z)	2-4 (Z)
J	Vertical 3	Wood	4.31	**10.12**	3.14	1-2 (Y)	<1.0 (Y)
B	Vertical 3	Wood	6.42	**8.38**	4.52	1-2 (Y)	<1.0 (Y)
H	Vertical 3	Wood	6.16	**8.42**	3.04	2-4 (Y)	<1.0 (Y)
D	Vertical 3	Wood	3.65	**10.41**	3.54	0.5-1 (Y)	<1.0 (Y)
E	Vertical 3	Wood	3.80	8.83	**12.89**	1-2 (Z)	0 (Z)
F	Vertical 3	Wood	8.41	**12.68**	-	2-4 (Y)	0 (Y)
G	Vertical 3	Wood	3.99	**6.40**	2.53	2-4 (Y)	1-2 (Y)
I	Vertical 3	Wood	7.33	**11.52**	10.56	2-4 (Z)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 3	Steel	4.55	4.23	**10.65**	<0.5 (Z)	<1.0 (Z)
C	Vertical 3	Steel	3.22	6.21	**6.24**	0.5-1 (Z)	1-2 (Z)
J	Vertical 3	Steel	3.56	**7.29**	2.30	4-8 (Y)	1-2 (Y)
B	Vertical 3	Steel	6.34	**8.75**	4.31	4-8 (Y)	<1.0 (Y)
H	Vertical 3	Steel	5.11	**5.29**	4.79	2-4 (Z)	2-4 (Y)
D	Vertical 3	Steel	**6.14**	3.84	1.46	4-8 (Y)	1-2 (X)
E	Vertical 3	Steel	3.03	6.18	**9.00**	2-4 (Z)	<1.0 (Z)
F	Vertical 3	Steel	9.62	**15.94**	5.31	2-4 (Y)	0 (Y)
G	Vertical 3	Steel	**10.10**	4.70	5.31	4-8 (Z)	<1.0 (X)
I	Vertical 3	Steel	9.92	13.54	**13.71**	1-2 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 3	Concr	4.10	6.98	**7.95**	1-2 (Z)	1-2 (Z)
C	Vertical 3	Concr	4.62	6.86	**10.85**	0.5-1 (Z)	<1.0 (Z)
J	Vertical 3	Concr	4.60	**7.32**	3.93	1-2 (Y)	1-2 (Y)
B	Vertical 3	Concr	**9.59**	-	8.02	4-8 (Z)	<1.0 (X)
H	Vertical 3	Concr	7.02	7.69	**7.87**	2-4 (Z)	1-2 (Z)
D	Vertical 3	Concr	-	**5.98**	3.39	1-2 (Y)	2-4 (Y)
E	Vertical 3	Concr	5.93	9.66	**15.88**	1-2 (Z)	0 (Z)
F	Vertical 3	Concr	13.27	**12.64**	6.02	1-2 (Y)	0 (Y)
G	Vertical 3	Concr	4.73	**5.63**	4.19	2-4 (Y)	2-4 (Y)
I	Vertical 3	Concr	10.0	14.04	**15.32**	0.5-1 (Y)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 3	Plast	2.60	**6.68**	2.23	4-8 (Y)	1-2 (Y)
C	Vertical 3	Plast	**4.49**	4.10	3.48	4-8 (Z)	2-4 (X)
J	Vertical 3	Plast	7.39	**11.97**	2.28	2-4 (Y)	<1.0 (Y)
B	Vertical 3	Plast	7.93	**8.95**	4.36	2-4 (Y)	<1.0 (Y)
H	Vertical 3	Plast	**7.62**	5.60	3.03	4-8 (Y)	1-2 (X)
D	Vertical 3	Plast	-	**6.14**	1.74	1-2 (Y)	1-2 (Y)
E	Vertical 3	Plast	3.01	6.86	**9.52**	2-4 (Z)	<1.0 (Z)
F	Vertical 3	Plast	8.24	**11.48**	4.72	4-8 (Y)	<1.0 (Y)
G	Vertical 3	Plast	3.38	**4.35**	1.81	4-8 (Y)	2-4 (Y)
I	Vertical 3	Plast	6.91	**8.52**	6.85	4-8 (Z)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOUS/DAY)
A	Vertical 4	Wood	2.43	**6.59**	3.79	2-4 (Y)	1-2 (Y)
C	Vertical 4	Wood	2.39	4.06	**4.95**	4-8 (Z)	2-4 (Z)
J	Vertical 4	Wood	7.53	**9.38**	3.15	2-4 (Y)	<1.0 (Y)
B	Vertical 4	Wood	5.06	**8.44**	4.94	2-4 (Y)	<1.0 (Y)
H	Vertical 4	Wood	5.63	**9.28**	4.38	1-2 (Y)	<1.0 (Y)
D	Vertical 4	Wood	3.65	**9.84**	3.05	0.5-1 (Y)	<1.0 (Y)
E	Vertical 4	Wood	3.55	**9.17**	-	1-2 (Y)	<1.0 (Y)
F	Vertical 4	Wood	8.88	**12.18**	-	2-4 (Y)	0 (Y)
G	Vertical 4	Wood	3.18	**6.47**	2.32	2-4 (Y)	1-2 (Y)
I	Vertical 4	Wood	5.24	**9.39**	7.44	2-4 (Y)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 4	Steel	3.59	5.05	**10.65**	<0.5 (Z)	<1.0 (Z)
C	Vertical 4	Steel	3.42	6.40	**7.86**	0.5-1 (Z)	1-2 (Z)
J	Vertical 4	Steel	4.57	**7.27**	2.11	2-4 (Y)	1-2 (Y)
B	Vertical 4	Steel	7.42	**11.14**	4.67	2-4 (Y)	<1.0 (Y)
H	Vertical 4	Steel	6.04	**6.66**	4.20	4-8 (Y)	1-2 (Y)
D	Vertical 4	Steel	**5.80**	3.59	1.82	4-8 (Y)	2-4 (X)
E	Vertical 4	Steel	2.94	6.77	**8.10**	4-8 (Z)	<1.0 (Z)
F	Vertical 4	Steel	10.65	**15.10**	5.18	2-4 (Y)	0 (Y)
G	Vertical 4	Steel	**3.95**	3.39	2.28	4-8 (Y)	4-8 (X)
I	Vertical 4	Steel	8.58	**11.68**	10.64	2-4 (Z)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 4	Concr	5.12	6.13	**10.46**	1-2 (Z)	<1.0 (Z)
C	Vertical 4	Concr	4.11	6.94	**10.10**	0.5-1 (Z)	<1.0 (Z)
J	Vertical 4	Concr	4.24	**7.18**	3.93	4-8 (Y)	1-2 (Y)
B	Vertical 4	Concr	7.71	-	**8.98**	4-8 (Z)	<1.0 (Z)
H	Vertical 4	Concr	**6.74**	6.21	6.66	4-8 (Z)	1-2 (X)
D	Vertical 4	Concr	-	**6.65**	4.13	1-2 (Y)	1-2 (Y)
E	Vertical 4	Concr	5.96	11.42	**16.22**	0.5-1 (Z)	0 (Z)
F	Vertical 4	Concr	12.00	**15.77**	6.07	<0.5 (Y)	0 (Y)
G	Vertical 4	Concr	3.91	**5.48**	4.13	1-2 (Y)	2-4 (Y)
I	Vertical 4	Concr	10.05	12.50	**15.11**	1-2 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 4	Plast	2.74	**6.66**	2.35	4-8 (Y)	1-2 (Y)
C	Vertical 4	Plast	**5.72**	5.27	3.91	4-8 (Y)	2-4 (X)
J	Vertical 4	Plast	6.23	**12.83**	2.15	2-4 (Y)	0 (Y)
B	Vertical 4	Plast	**11.56**	8.40	5.45	4-8 (Y)	<1.0 (X)
H	Vertical 4	Plast	**8.13**	6.94	3.41	4-8 (Y)	<1.0 (X)
D	Vertical 4	Plast	-	**6.46**	2.16	1-2 (Y)	1-2 (Y)
E	Vertical 4	Plast	3.17	6.57	**11.29**	1-2 (Z)	<1.0 (Z)
F	Vertical 4	Plast	6.18	**10.22**	5.06	4-8 (Z)	<1.0 (Y)
G	Vertical 4	Plast	4.28	**7.28**	2.04	1-2 (Y)	1-2 (Y)
I	Vertical 4	Plast	6.78	**9.56**	8.05	4-8 (Z)	<1.0 (Y)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 5	Wood	2.40	**5.36**	4.66	2-4 (Z)	2-4 (Y)
C	Vertical 5	Wood	2.38	4.22	**4.83**	4-8 (Z)	2-4 (Z)
J	Vertical 5	Wood	7.68	**16.11**	3.56	0.5-1 (Y)	0 (Y)
B	Vertical 5	Wood	6.48	**9.27**	6.07	2-4 (Y)	<1.0 (Y)
H	Vertical 5	Wood	5.54	**8.95**	3.44	2-4 (Y)	<1.0 (Y)
D	Vertical 5	Wood	3.36	**5.93**	2.58	2-4 (Y)	2-4 (Y)
E	Vertical 5	Wood	3.40	9.59	**10.83**	1-2 (Y)	<1.0 (Z)
F	Vertical 5	Wood	12.09	**12.42**	-	1-2 (Y)	0 (Y)
G	Vertical 5	Wood	3.17	**7.53**	2.60	1-2 (Y)	1-2 (Y)
I	Vertical 5	Wood	7.84	10.95	**10.96**	2-4 (Z)	<1.0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 5	Steel	3.44	4.67	**10.13**	0.5-1 (Z)	<1.0 (Z)
C	Vertical 5	Steel	3.00	5.01	**6.28**	1-2 (Z)	1-2 (Z)
J	Vertical 5	Steel	4.29	**9.09**	2.49	4-8 (Y)	<1.0 (Y)
B	Vertical 5	Steel	6.82	**11.41**	4.53	1-2 (Y)	<1.0 (Y)
H	Vertical 5	Steel	**5.43**	5.29	4.72	4-8 (Z)	2-4 (X)
D	Vertical 5	Steel	4.53	**6.21**	1.69	2-4 (Y)	1-2 (Y)
E	Vertical 5	Steel	2.91	-	7.80	4-8 (Z)	1-2 (Z)
F	Vertical 5	Steel	10.45	**13.75**	5.20	4-8 (Y)	0 (Y)
G	Vertical 5	Steel	2.65	**3.70**	1.41	4-8 (Y)	4-8 (Y)
I	Vertical 5	Steel	7.28	9.96	**10.98**	2-4 (Z)	<1.0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM REQUIRED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 5	Concr	5.50	5.47	**5.84**	2-4 (Z)	2-4 (Z)
C	Vertical 5	Concr	6.64	11.79	**14.52**	0.5-1 (Z)	0 (Z)
J	Vertical 5	Concr	4.62	**7.47**	3.83	4-8 (Y)	1-2 (Y)
B	Vertical 5	Concr	**8.00**	-	7.80	4-8 (Z)	1-2 (X)
H	Vertical 5	Concr	**5.77**	5.76	5.62	4-8 (Z)	2-4 (X)
D	Vertical 5	Concr	-	-	**4.72**	4-8 (Z)	2-4 (Z)
E	Vertical 5	Concr	5.44	9.84	**14.93**	1-2 (Z)	0 (Z)
F	Vertical 5	Concr	**14.71**	13.91	6.14	1-2 (Y)	0 (Z)
G	Vertical 5	Concr	**8.47**	4.66	5.49	4-8 (Z)	<1.0 (X)
I	Vertical 5	Concr	8.31	10.53	**12.55**	1-2 (Z)	0 (Z)

DRILL	TRIAL TYPE	MATERIAL	DIRECTION OF MEASUREMENT			MAXIMUM RECOMMENDED EXPOSURE	
			X-AXIS WT. ACC. (M/S^2)	Y-AXIS WT. ACC. (M/S^2)	Z-AXIS WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 5	Plast	2.55	**6.34**	2.37	4-8 (Y)	1-2 (Y)
C	Vertical 5	Plast	**4.91**	4.78	4.14	4-8 (Y)	2-4 (X)
J	Vertical 5	Plast	7.92	**9.97**	2.10	4-8 (Y)	<1.0 (Y)
B	Vertical 5	Plast	8.72	**9.67**	7.13	4-8 (Y)	<1.0 (Y)
H	Vertical 5	Plast	6.92	**7.49**	3.53	4-8 (Y)	1-2 (Y)
D	Vertical 5	Plast	-	6.85	1.81	1-2 (Y)	1-2 (Y)
E	Vertical 5	Plast	4.05	8.81	**14.21**	1-2 (Z)	0 (Z)
F	Vertical 5	Plast	9.91	**14.18**	5.71	2-4 (Y)	0 (Y)
G	Vertical 5	Plast	3.13	**4.93**	1.54	4-8 (Y)	2-4 (Y)
I	Vertical 5	Plast	6.74	**9.68**	6.82	4-8 (Y)	<1.0 (Y)

Appendix E

This appendix contains the results, in tabular form for "free run" drilling, horizontal drilling experiments, and vertical drilling experiments conducted for each bit/material combination. The materials with the greatest rms acceleration amplitudes are given in bold type and also in parentheses ( ) following recommended maximum exposure times.

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Free Run	X	1.93	2.36	1.85	**2.97**	N/A	N/A
C	Free Run	X	0.68	0.79	0.84	**1.33**	N/A	N/A
J	Free Run	X	1.04	1.01	**2.49**	1.34	N/A	N/A
B	Free Run	X	**3.83**	2.51	2.88	3.59	N/A	N/A
H	Free Run	X	3.62	3.19	**5.80**	4.36	N/A	N/A
D	Free Run	X	**2.51**	2.24	2.12	-	N/A	N/A
E	Free Run	X	2.91	2.31	**3.90**	0.84	N/A	N/A
F	Free Run	X	1.55	**2.04**	1.90	1.77	N/A	N/A
G	Free Run	X	1.62	1.64	**2.55**	1.79	N/A	N/A
I	Free Run	X	7.18	12.14	**12.63**	5.87	N/A	N/A

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Free Run	Y	2.93	3.46	3.49	**4.18**	N/A	N/A
C	Free Run	Y	1.09	1.29	1.59	**1.68**	N/A	N/A
J	Free Run	Y	1.45	1.17	**1.83**	1.43	N/A	N/A
B	Free Run	Y	**3.75**	3.13	2.89	3.23	N/A	N/A
H	Free Run	Y	3.48	3.37	**7.19**	4.13	N/A	N/A
D	Free Run	Y	**1.66**	1.19	1.35	1.34	N/A	N/A
E	Free Run	Y	5.37	4.87	**8.31**	4.42	N/A	N/A
F	Free Run	Y	1.82	1.69	**2.12**	1.49	N/A	N/A
G	Free Run	Y	2.26	1.53	**2.52**	2.22	N/A	N/A
I	Free Run	Y	10.02	**14.77**	13.19	8.77	N/A	N/A

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Free Run	Z	0.98	1.39	**1.91**	1.18	N/A	N/A
C	Free Run	Z	1.21	1.19	**1.46**	1.08	N/A	N/A
J	Free Run	Z	**1.10**	0.84	0.93	**1.10**	N/A	N/A
B	Free Run	Z	2.45	1.66	1.84	**3.66**	N/A	N/A
H	Free Run	Z	2.15	4.49	**12.43**	2.37	N/A	N/A
D	Free Run	Z	**0.88**	0.74	0.69	0.65	N/A	N/A
E	Free Run	Z	10.38	6.30	**15.13**	6.50	N/A	N/A
F	Free Run	Z	0.69	-	**1.76**	0.71	N/A	N/A
G	Free Run	Z	0.90	1.13	**2.92**	0.86	N/A	N/A
I	Free Run	Z	11.39	18.05	**18.77**	9.28	N/A	N/A

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Horizontal	X	2.15	5.00	**5.05**	3.87	4-8 (C)	2-4 (C)
C	Horizontal	X	2.04	2.10	4.33	**4.73**	2-4 (C)	2-4 (P)
J	Horizontal	X	5.60	3.55	3.72	**5.76**	4-8 (C)	2-4 (P)
B	Horizontal	X	5.40	4.77	7.06	**9.63**	4-8 (C)	<1.0 (P)
H	Horizontal	X	5.46	5.09	7.11	**8.67**	2-4 (C)	<1.0 (P)
D	Horizontal	X	4.57	**5.15**	4.60	-	4-8 (C)	2-4 (S)
E	Horizontal	X	3.06	2.92	**5.05**	2.97	4-8 (C)	2-4 (C)
F	Horizontal	X	11.39	10.27	9.61	**12.48**	4-8 (C)	0 (P)
G	Horizontal	X	**4.79**	3.78	4.42	2.87	4-8 (C)	2-4 (W)
I	Horizontal	X	7.87	**11.65**	9.26	6.03	2-4 (S)	<1.0 (S)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Horizontal	Y	5.06	4.45	**6.30**	5.44	2-4 (C)	1-2 (C)
C	Horizontal	Y	3.63	3.65	**7.85**	4.86	0.5-1 (C)	1-2 (C)
J	Horizontal	Y	**8.88**	6.00	5.65	7.69	4-8 (C)	<1.0 (W)
B	Horizontal	Y	6.84	4.96	-	**8.18**	4-8 (P)	<1.0 (P)
H	Horizontal	Y	5.44	5.11	**6.41**	5.93	4-8 (C)	1-2 (C)
D	Horizontal	Y	8.71	3.08	4.15	**9.25**	0.5-1 (P)	<1.0 (P)
E	Horizontal	Y	6.53	5.60	**8.51**	6.70	1-2 (C)	<1.0 (C)
F	Horizontal	Y	16.34	10.99	14.13	**18.00**	1-2 (P)	0 (P)
G	Horizontal	Y	4.49	2.70	4.21	**4.83**	4-8 (C)	2-4 (P)
I	Horizontal	Y	10.39	**14.63**	11.39	8.73	1-2 (S)	0 (S)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Horizontal	Z	2.89	6.66	**9.93**	4.22	0.5-1 (C)	<1.0 (C)
C	Horizontal	Z	3.59	2.53	**8.88**	4.77	2-4 (C)	<1.0 (C)
J	Horizontal	Z	2.74	2.44	**4.20**	1.87	4-8 (C)	2-4 (C)
B	Horizontal	Z	4.19	3.69	**8.24**	5.28	2-4 (C)	<1.0 (C)
H	Horizontal	Z	3.83	4.35	**7.98**	3.64	2-4 (C)	1-2 (C)
D	Horizontal	Z	2.96	2.21	**5.31**	1.57	4-8 (C)	2-4 (C)
E	Horizontal	Z	9.16	10.27	**14.79**	9.01	1-2 (C)	0 (C)
F	Horizontal	Z	-	-	**6.26**	5.35	2-4 (C)	1-2 (C)
G	Horizontal	Z	2.23	2.17	**6.73**	1.33	4-8 (C)	1-2 (C)
I	Horizontal	Z	11.96	**17.94**	14.78	7.32	0.5-1 (S)	0 (S)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 1	X	2.37	2.36	**4.65**	1.86	2-4 (C)	2-4 (C)
C	Vertical 1	X	2.37	3.11	4.65	**4.76**	2-4 (C)	2-4 (P)
J	Vertical 1	X	4.32	5.11	6.26	**7.65**	4-8 (C)	1-2 (P)
B	Vertical 1	X	7.27	6.99	5.25	**9.71**	4-8 (C)	<1.0 (P)
H	Vertical 1	X	6.31	5.97	6.87	**8.47**	4-8 (C)	<1.0 (P)
D	Vertical 1	X	4.21	**6.34**	5.33	-	4-8 (C)	1-2 (S)
E	Vertical 1	X	3.13	2.53	**5.24**	2.59	4-8 (C)	2-4 (C)
F	Vertical 1	X	10.04	**13.60**	12.34	6.68	4-8 (C)	0 (S)
G	Vertical 1	X	2.48	**7.90**	4.18	3.25	4-8 (C)	1-2 (S)
I	Vertical 1	X	6.66	**10.90**	10.51	5.24	2-4 (C)	<1.0 (S)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 1	Y	4.98	3.46	**5.73**	5.39	2-4 (C)	2-4 (C)
C	Vertical 1	Y	3.84	5.40	**6.87**	4.19	1-2 (C)	1-2 (C)
J	Vertical 1	Y	8.35	5.56	6.00	**8.44**	2-4 (W)	<1.0 (P)
B	Vertical 1	Y	8.16	8.53	-	**10.93**	1-2 (W)	<1.0 (P)
H	Vertical 1	Y	6.56	6.02	**7.57**	5.55	2-4 (C)	1-2 (C)
D	Vertical 1	Y	7.27	**10.67**	10.08	4.98	0 (C)	<1.0 (S)
E	Vertical 1	Y	7.36	5.26	**8.73**	5.48	2-4 (C)	<1.0 (C)
F	Vertical 1	Y	**16.03**	12.70	15.42	10.10	1-2 (C)	0 (W)
G	Vertical 1	Y	**5.70**	3.87	4.46	4.93	2-4 (W)	2-4 (W)
I	Vertical 1	Y	10.31	**13.16**	12.41	7.81	1-2 (S)	0 (S)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 1	Z	4.03	4.60	**6.86**	2.12	2-4 (C)	1-2 (C)
C	Vertical 1	Z	4.93	5.65	**8.00**	3.86	1-2 (C)	1-2 (C)
J	Vertical 1	Z	**3.20**	2.36	3.13	1.82	4-8 (C)	4-8 (W)
B	Vertical 1	Z	5.32	4.44	5.39	**9.28**	4-8 (C)	<1.0 (P)
H	Vertical 1	Z	3.89	3.69	**10.74**	3.18	1-2 (C)	0 (C)
D	Vertical 1	Z	2.71	2.33	**3.73**	1.59	4-8 (C)	4-8 (C)
E	Vertical 1	Z	9.04	5.70	**13.85**	6.96	1-2 (C)	0 (C)
F	Vertical 1	Z	**11.57**	-	8.28	3.62	1-2 (W)	<1.0 (W)
G	Vertical 1	Z	1.93	**4.53**	-	1.73	4-8 (W)	4-8 (S)
I	Vertical 1	Z	10.02	13.90	**15.03**	5.62	1-2 (C)	0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 2	X	2.16	**5.52**	4.69	2.42	2-4 (S)	2-4 (S)
C	Vertical 2	X	2.55	3.01	4.51	**4.74**	2-4 (C)	2-4 (P)
J	Vertical 2	X	3.66	5.22	3.97	**8.05**	4-8 (C)	<1.0 (P)
B	Vertical 2	X	5.48	7.87	8.46	**9.80**	4-8 (C)	<1.0 (P)
H	Vertical 2	X	5.78	5.27	**6.67**	4.29	2-4 (C)	1-2 (C)
D	Vertical 2	X	3.79	**5.96**	5.25	-	4-8 (C)	2-4 (S)
E	Vertical 2	X	3.72	3.28	**6.22**	2.97	4-8 (C)	1-2 (C)
F	Vertical 2	X	11.00	**12.08**	11.26	7.80	4-8 (C)	0 (S)
G	Vertical 2	X	3.85	3.56	3.50	**6.74**	4-8 (C)	1-2 (P)
I	Vertical 2	X	8.10	9.98	**10.13**	6.22	2-4 (C)	<1.0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 2	Y	4.55	4.53	6.34	**6.42**	1-2 (C)	1-2 (P)
C	Vertical 2	Y	4.24	4.93	**7.34**	5.03	1-2 (C)	1-2 (C)
J	Vertical 2	Y	7.32	7.69	6.72	**9.71**	1-2 (P)	<1.0 (P)
B	Vertical 2	Y	7.09	**12.16**	-	9.04	1-2 (S)	0 (S)
H	Vertical 2	Y	7.32	4.98	**7.33**	4.52	2-4 (W)	1-2 (C)
D	Vertical 2	Y	**7.96**	7.32	7.50	7.75	0.5-1 (C)	1-2 (W)
E	Vertical 2	Y	9.06	7.03	**11.32**	6.49	1-2 (C)	<1.0 (C)
F	Vertical 2	Y	12.65	**15.88**	13.09	15.68	0.5-1 (C)	0 (S)
G	Vertical 2	Y	**6.87**	4.13	4.39	4.81	2-4 (W)	1-2 (W)
I	Vertical 2	Y	13.00	12.80	**13.69**	8.83	1-2 (W)	0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 2	Z	4.13	**10.52**	8.89	2.51	0.5-1 (C)	<1.0 (S)
C	Vertical 2	Z	5.40	3.00	**10.86**	3.68	2-4 (C)	<1.0 (C)
J	Vertical 2	Z	**4.82**	2.10	3.63	2.29	4-8 (W)	2-4 (W)
B	Vertical 2	Z	4.18	5.71	**8.60**	6.09	4-8 (C)	<1.0 (C)
H	Vertical 2	Z	3.76	4.22	**10.69**	3.04	2-4 (C)	<1.0 (C)
D	Vertical 2	Z	3.13	2.04	3.72	**6.96**	4-8 (C)	1-2 (P)
E	Vertical 2	Z	12.63	9.83	**17.02**	9.41	1-2 (C)	0 (C)
F	Vertical 2	Z	-	4.68	**5.34**	5.05	4-8 (C)	2-4 (C)
G	Vertical 2	Z	2.29	1.73	**3.74**	2.33	4-8 (C)	4-8 (C)
I	Vertical 2	Z	10.97	13.52	**15.42**	6.92	1-2 (C)	0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 3	X	2.18	**4.55**	4.10	2.60	2-4 (C)	2-4 (S)
C	Vertical 3	X	2.35	3.22	**4.62**	4.49	2-4 (C)	2-4 (C)
J	Vertical 3	X	4.31	3.56	4.60	**7.39**	4-8 (C)	1-2 (P)
B	Vertical 3	X	6.42	6.34	**9.59**	7.93	4-8 (C)	<1.0 (C)
H	Vertical 3	X	6.16	5.11	7.02	**7.62**	4-8 (C)	1-2 (P)
D	Vertical 3	X	3.65	**6.14**	-	-	4-8 (S)	1-2 (S)
E	Vertical 3	X	3.80	3.03	**5.93**	3.01	4-8 (C)	2-4 (C)
F	Vertical 3	X	8.41	9.62	**13.27**	8.24	4-8 (C)	0 (C)
G	Vertical 3	X	3.99	**10.10**	4.73	3.38	4-8 (S)	<1.0 (S)
I	Vertical 3	X	7.33	9.92	**10.0**	6.91	2-4 (C)	<1.0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 3	Y	4.80	4.23	**6.98**	6.68	1-2 (C)	1-2 (C)
C	Vertical 3	Y	3.95	6.21	**6.86**	4.10	1-2 (C)	1-2 (C)
J	Vertical 3	Y	10.12	7.29	7.32	**11.97**	1-2 (C)	<1.0 (P)
B	Vertical 3	Y	8.38	8.75	-	8.95	1-2 (W)	<1.0 (P)
H	Vertical 3	Y	**8.42**	5.29	7.69	5.60	2-4 (C)	<1.0 (W)
D	Vertical 3	Y	**10.41**	3.84	5.98	6.14	0.5-1 (W)	<1.0 (W)
E	Vertical 3	Y	8.83	6.18	**9.66**	6.86	2-4 (C)	<1.0 (C)
F	Vertical 3	Y	12.68	**15.94**	12.64	11.48	1-2 (C)	O (S)
G	Vertical 3	Y	**6.40**	4.70	5.63	4.35	2-4 (C)	1-2 (W)
I	Vertical 3	Y	11.52	13.54	**14.04**	8.52	0.5-1 (C)	0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 3	Z	3.96	**10.65**	7.95	2.23	0 (S)	<1.0 (S)
C	Vertical 3	Z	5.53	6.24	**10.85**	3.48	0.5-1 (C)	<1.0 (C)
J	Vertical 3	Z	3.14	2.30	**3.93**	2.28	4-8 (C)	4-8 (C)
B	Vertical 3	Z	4.52	4.31	**8.02**	4.36	4-8 (C)	<1.0 (C)
H	Vertical 3	Z	3.04	4.79	**7.87**	3.03	2-4 (C)	1-2 (C)
D	Vertical 3	Z	**3.54**	1.46	3.39	1.74	4-8 (C)	4-8 (W)
E	Vertical 3	Z	12.89	9.00	**15.88**	9.52	1-2 (C)	0 (C)
F	Vertical 3	Z	-	5.31	**6.02**	4.72	4-8 (C)	1-2 (C)
G	Vertical 3	Z	2.53	**5.31**	4.19	1.81	4-8 (S)	2-4 (S)
I	Vertical 3	Z	10.56	13.71	**15.32**	6.85	1-2 (C)	0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 4	X	2.43	3.59	**5.12**	2.74	4-8 (C)	2-4 (C)
C	Vertical 4	X	2.39	3.42	4.11	**5.72**	2-4 (C)	2-4 (P)
J	Vertical 4	X	**7.53**	4.57	4.24	6.23	4-8 (C)	1-2 (W)
B	Vertical 4	X	5.06	7.42	7.71	**11.56**	4-8 (C)	<1.0 (P)
H	Vertical 4	X	5.63	6.04	6.74	**8.13**	4-8 (C)	<1.0 (P)
D	Vertical 4	X	3.65	**5.80**	-	-	4-8 (S)	2-4 (S)
E	Vertical 4	X	3.55	2.94	**5.96**	3.17	4-8 (C)	2-4 (C)
F	Vertical 4	X	8.88	10.65	**12.00**	6.18	4-8 (C)	<1.0 (C)
G	Vertical 4	X	3.18	3.95	3.91	**4.28**	4-8 (C)	2-4 (P)
I	Vertical 4	X	5.24	8.58	**10.05**	6.78	2-4 (C)	<1.0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 4	Y	6.59	5.05	6.13	**6.66**	2-4 (C)	1-2 (P)
C	Vertical 4	Y	4.06	6.40	**6.94**	5.27	1-2 (C)	1-2 (C)
J	Vertical 4	Y	9.38	7.27	7.18	**12.83**	2-4 (W)	0 (P)
B	Vertical 4	Y	8.44	**11.14**	-	8.40	2-4 (W)	<1.0 (S)
H	Vertical 4	Y	**9.28**	6.66	6.21	6.94	1-2 (W)	<1.0 (W)
D	Vertical 4	Y	**9.84**	3.59	6.65	6.46	0.5-1 (W)	<1.0 (W)
E	Vertical 4	Y	9.17	6.77	**11.42**	6.57	1-2 (C)	<1.0 (C)
F	Vertical 4	Y	12.18	15.10	**15.77**	10.22	<0.5 (C)	0 (C)
G	Vertical 4	Y	6.47	3.39	5.48	**7.28**	1-2 (P)	1-2 (P)
I	Vertical 4	Y	9.39	11.68	**12.50**	9.56	2-4 (C)	0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 4	Z	3.79	**10.65**	10.46	2.35	<0.5 (S)	<1.0 (S)
C	Vertical 4	Z	4.95	7.86	**10.10**	3.91	0.5-1 (C)	<1.0 (C)
J	Vertical 4	Z	3.15	2.11	**3.93**	2.15	4-8 (C)	4-8 (C)
B	Vertical 4	Z	4.94	4.67	**8.98**	5.45	4-8 (C)	<1.0 (C)
H	Vertical 4	Z	4.38	4.20	**6.66**	3.41	4-8 (C)	1-2 (C)
D	Vertical 4	Z	3.05	1.82	**4.13**	2.16	4-8 (C)	2-4 (C)
E	Vertical 4	Z	-	8.10	**16.22**	11.29	0.5-1 (C)	0 (C)
F	Vertical 4	Z	-	5.18	**6.07**	5.06	4-8 (C)	1-2 (C)
G	Vertical 4	Z	2.32	2.28	**4.13**	2.04	4-8 (C)	2-4 (C)
I	Vertical 4	Z	7.44	10.64	**15.11**	8.05	1-2 (C)	0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 5	X	2.40	3.44	**5.50**	2.55	4-8 (C)	2-4 (C)
C	Vertical 5	X	2.38	3.00	**6.64**	4.91	2-4 (C)	1-2 (C)
J	Vertical 5	X	7.68	4.29	4.62	**7.92**	2-4 (W)	1-2 (P)
B	Vertical 5	X	6.48	6.82	8.00	**8.72**	4-8 (C)	<1.0 (P)
H	Vertical 5	X	5.54	5.43	5.77	**6.92**	4-8 (C)	1-2 (P)
D	Vertical 5	X	3.36	**4.53**	-	-	4-8 (W)	2-4 (S)
E	Vertical 5	X	3.40	2.91	**5.44**	4.05	4-8 (C)	2-4 (C)
F	Vertical 5	X	-	10.45	**14.71**	9.91	4-8 (C)	0 (C)
G	Vertical 5	X	3.17	2.65	**8.47**	3.13	4-8 (C)	<1.0 (C)
I	Vertical 5	X	7.84	7.28	**8.31**	6.74	4-8 (C)	<1.0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 5	Y	5.36	4.67	5.47	**6.34**	2-4 (C)	1-2 (P)
C	Vertical 5	Y	4.22	5.01	**11.79**	4.78	0.5-1 (C)	<1.0 (C)
J	Vertical 5	Y	**16.11**	9.09	7.47	9.97	0.5-1 (W)	0 (W)
B	Vertical 5	Y	9.27	11.41	**17.62**	9.67	1-2 (S)	<1.0 (S)
H	Vertical 5	Y	**8.95**	5.29	5.76	7.49	2-4 (W)	<1.0 (W)
D	Vertical 5	Y	5.93	6.21	-	**6.85**	1-2 (P)	1-2 (P)
E	Vertical 5	Y	9.59	-	**9.84**	8.81	1-2 (W)	<1.0 (C)
F	Vertical 5	Y	12.42	13.75	13.91	**14.18**	1-2 (C)	0 (P)
G	Vertical 5	Y	**7.53**	3.70	4.66	4.93	1-2 (W)	1-2 (W)
I	Vertical 5	Y	**10.95**	9.96	10.53	9.68	2-4 (S)	<1.0 (C)

DRILL	TRIAL TYPE	AXIS	MATERIAL TESTED				MAX. RECOMMENDED EXPOSURE	
			WOOD WT. ACC. (M/S^2)	STEEL WT. ACC. (M/S^2)	CONCR WT. ACC. (M/S^2)	PLAST WT. ACC. (M/S^2)	ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	Vertical 5	Z	4.66	**10.13**	5.84	2.37	0.5-1 (S)	<1.0 (S)
C	Vertical 5	Z	4.83	6.28	**14.52**	4.14	0.5-1 (C)	0 (C)
J	Vertical 5	Z	3.56	2.49	**3.83**	2.10	4-8 (C)	4-8 (C)
B	Vertical 5	Z	6.07	4.53	**7.80**	7.13	4-8 (C)	1-2 (C)
H	Vertical 5	Z	3.44	4.72	**5.62**	3.53	4-8 (C)	2-4 (C)
D	Vertical 5	Z	2.58	1.69	**4.72**	1.81	4-8 (C)	2-4 (C)
E	Vertical 5	Z	10.83	7.80	**14.93**	14.21	1-2 (C)	0 (C)
F	Vertical 5	Z	-	5.20	**6.14**	5.71	4-8 (C)	1-2 (C)
G	Vertical 5	Z	2.60	1.41	**5.49**	1.54	4-8 (W)	2-4 (C)
I	Vertical 5	Z	10.96	10.98	**12.55**	6.82	1-2 (C)	0 (C)

Appendix F

This appendix summarizes the results from appendices D and E. It also shows mean drilling acceleration amplitudes and the standard deviations of these means for each drill.

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	WOOD	X	1.93	2.15	**2.31**	0.13	4-8	4-8
C	WOOD	X	0.68	2.04	**2.41**	0.08	4-8	4-8
J	WOOD	X	1.04	**5.60**	5.50	1.94	2-4	2-4
B	WOOD	X	3.83	5.40	**6.14**	0.88	4-8	1-2
H	WOOD	X	3.62	5.46	**5.88**	0.34	4-8	2-4
D	WOOD	X	2.51	**4.57**	3.73	0.31	4-8	2-4
E	WOOD	X	2.91	3.06	**3.52**	0.27	4-8	4-8
F	WOOD	X	1.55	**11.39**	10.08	1.51	4-8	<1.0
G	WOOD	X	1.62	**4.79**	3.33	0.61	4-8	2-4
I	WOOD	X	7.18	**7.87**	7.03	1.04	4-8	1-2

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	WOOD	Y	2.93	5.06	**5.26**	0.80	2-4	2-4
C	WOOD	Y	1.09	3.63	**4.06**	0.17	4-8	2-4
J	WOOD	Y	1.45	8.88	**10.26**	3.44	0.5-1	<1.0
B	WOOD	Y	3.75	6.84	**8.27**	0.78	1-2	<1.0
H	WOOD	Y	3.48	5.44	**8.11**	1.14	1-2	<1.0
D	WOOD	Y	1.66	**8.71**	8.28	1.84	0.5-1	<1.0
E	WOOD	Y	5.37	6.53	**8.80**	0.85	1-2	<1.0
F	WOOD	Y	1.82	**16.34**	13.19	1.59	1-2	-
G	WOOD	Y	2.26	4.49	**6.59**	0.67	1-2	1-2
I	WOOD	Y	10.02	10.39	**11.03**	1.35	1-2	<1.0

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	WOOD	Z	0.98	2.89	**4.11**	0.33	2-4	2-4
C	WOOD	Z	1.21	3.59	**5.13**	0.31	2-4	2-4
J	WOOD	Z	1.10	2.74	**3.57**	0.72	4-8	4-8
B	WOOD	Z	2.45	4.19	**5.01**	0.73	4-8	2-4
H	WOOD	Z	2.15	**3.83**	3.70	0.50	4-8	4-8
D	WOOD	Z	0.88	2.96	**3.00**	0.38	4-8	4-8
E	WOOD	Z	10.38	9.16	**11.35**	1.79	1-2	<1.0
F	WOOD	Z	0.69	-	-	-	-	-
G	WOOD	Z	0.90	2.23	**2.33**	0.26	4-8	4-8
I	WOOD	Z	11.39	**11.96**	9.99	1.48	1-2	<1.0

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	STEEL	X	2.36	**5.00**	3.89	1.20	2-4	2-4
C	STEEL	X	0.79	2.10	**3.15**	0.17	4-8	4-8
J	STEEL	X	1.01	3.55	**4.55**	0.67	4-8	2-4
B	STEEL	X	2.51	4.77	**7.09**	0.58	4-8	1-2
H	STEEL	X	3.19	5.09	**5.56**	0.42	4-8	2-4
D	STEEL	X	2.24	5.15	**5.75**	0.71	4-8	2-4
E	STEEL	X	2.31	2.92	**2.94**	0.27	4-8	4-8
F	STEEL	X	2.04	10.27	**11.28**	1.57	4-8	<1.0
G	STEEL	X	1.64	3.78	**5.63**	3.21	4-8	2-4
I	STEEL	X	12.14	**11.65**	9.33	1.41	1-2	-

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	STEEL	Y	3.46	**4.45**	4.38	0.60	2-4	2-4
C	STEEL	Y	1.29	3.65	**5.59**	0.68	1-2	2-4
J	STEEL	Y	1.17	6.00	**7.38**	1.26	2-4	1-2
B	STEEL	Y	3.13	4.96	**10.40**	1.65	1-2	<1.0
H	STEEL	Y	3.37	5.11	**5.65**	0.68	4-8	2-4
D	STEEL	Y	1.19	3.08	**6.33**	2.90	1-2	1-2
E	STEEL	Y	4.87	5.60	**6.31**	0.79	4-8	1-2
F	STEEL	Y	1.69	10.99	**14.67**	1.41	2-4	-
G	STEEL	Y	1.53	2.70	**3.96**	0.49	4-8	4-8
I	STEEL	Y	14.77	**14.63**	12.23	1.45	1-2	-

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	**STEEL**	**Z**	1.39	6.66	**9.31**	2.64	<0.5	<1.0
C	**STEEL**	**Z**	1.19	2.53	**5.81**	1.77	0.5-1	2-4
J	**STEEL**	**Z**	0.84	**2.44**	2.27	0.17	4-8	4-8
B	**STEEL**	**Z**	1.66	3.69	**4.73**	0.56	4-8	2-4
H	**STEEL**	**Z**	4.49	**4.35**	4.32	0.45	2-4	2-4
D	**STEEL**	**Z**	0.74	**2.21**	1.87	0.33	4-8	4-8
E	**STEEL**	**Z**	6.30	**10.27**	8.09	1.55	2-4	<1.0
F	**STEEL**	**Z**	-	-	**5.09**	0.28	-	-
G	**STEEL**	**Z**	1.13	2.17	**3.05**	1.76	4-8	4-8
I	**STEEL**	**Z**	18.05	**17.94**	12.55	1.60	0.5-1	-

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	CONCR	X	1.85	**5.05**	4.81	0.53	2-4	2-4
C	CONCR	X	0.84	4.33	**4.91**	0.99	2-4	2-4
J	CONCR	X	2.49	3.72	**4.74**	0.89	4-8	2-4
B	CONCR	X	2.88	7.06	**7.80**	1.60	4-8	1-2
H	CONCR	X	5.80	**7.11**	6.61	0.49	2-4	1-2
D	CONCR	X	2.12	**4.60**	-	-	-	-
E	CONCR	X	3.90	5.05	**5.76**	0.40	4-8	2-4
F	CONCR	X	1.90	9.61	**12.72**	1.33	4-8	<1.0
G	CONCR	X	2.55	4.42	**4.96**	2.01	4-8	2-4
I	CONCR	X	12.63	9.26	**9.80**	0.86	1-2	<1.0

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	CONCR	Y	3.49	**6.30**	6.13	0.58	1-2	1-2
C	CONCR	Y	1.59	7.85	**7.96**	2.15	0.5-1	1-2
J	CONCR	Y	1.83	5.65	**6.94**	0.59	1-2	1-2
B	CONCR	Y	2.89	-	-	-	-	-
H	CONCR	Y	7.19	6.41	**6.91**	0.87	2-4	1-2
D	CONCR	Y	1.35	4.15	**7.37**	1.61	<0.5	1-2
E	CONCR	Y	8.31	8.51	**10.19**	1.15	1-2	<1.0
F	CONCR	Y	2.12	14.13	**14.17**	1.39	<0.5	-
G	CONCR	Y	2.52	4.21	**4.92**	0.59	1-2	2-4
I	CONCR	Y	13.19	11.39	**12.63**	1.38	0.5-1	<1.0

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	CONCR	Z	1.91	**9.93**	8.00	1.79	0.5-1	<1.0
C	CONCR	Z	1.46	8.88	**10.87**	2.35	0.5-1	<1.0
J	CONCR	Z	0.93	**4.20**	3.69	0.34	4-8	2-4
B	CONCR	Z	1.84	**8.24**	7.76	1.40	2-4	<1.0
H	CONCR	Z	12.43	7.98	**8.32**	2.33	1-2	<1.0
D	CONCR	Z	0.69	**5.31**	3.94	0.51	4-8	2-4
E	CONCR	Z	15.13	14.79	**15.58**	1.22	0.5-1	-
F	CONCR	Z	1.76	6.26	**6.37**	1.12	2-4	1-2
G	CONCR	Z	2.92	**6.73**	4.39	0.76	4-8	1-2
I	CONCR	Z	18.77	**14.78**	14.69	1.20	0.5-1	-

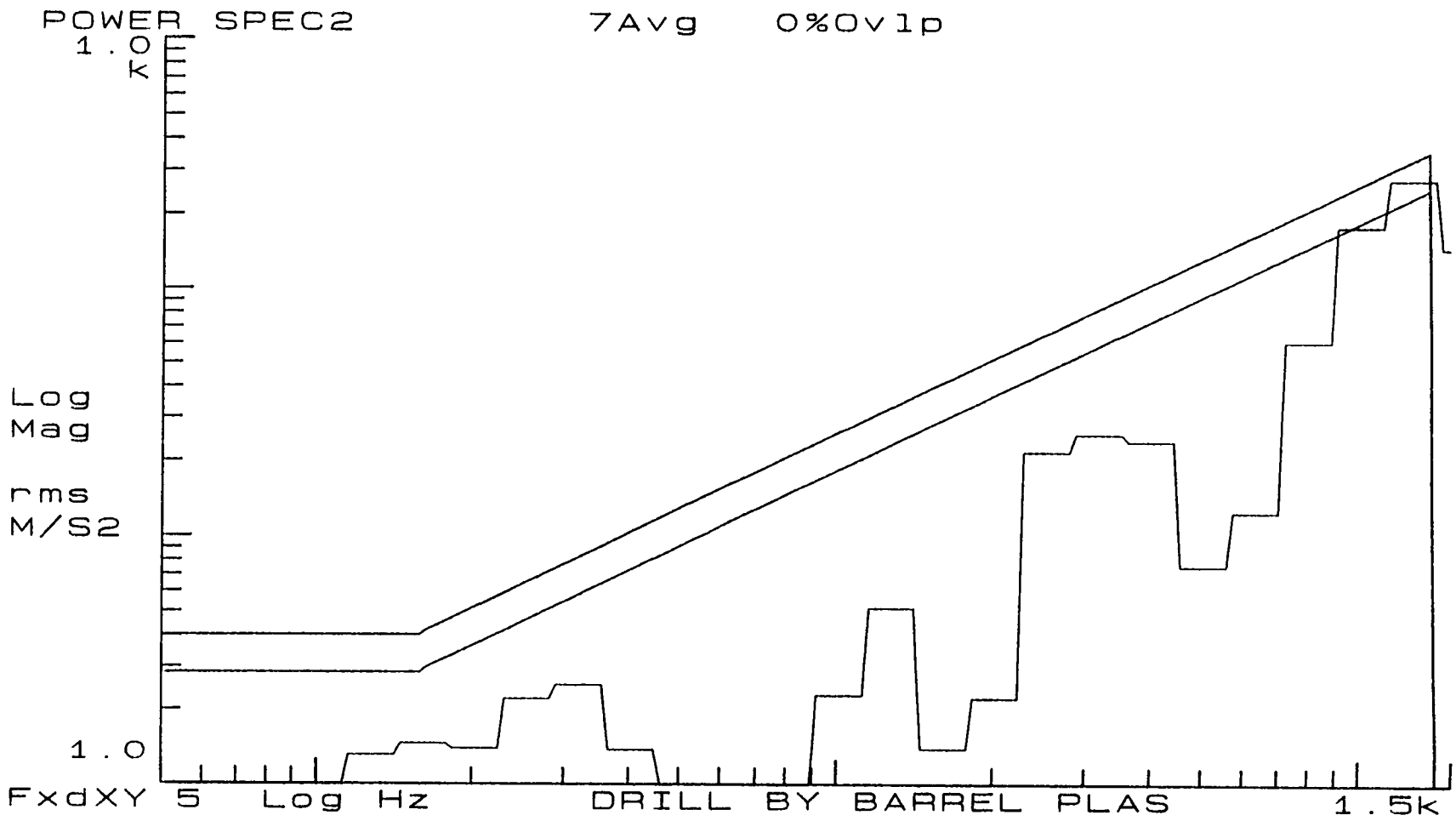
DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	PLAST	X	2.97	**3.87**	2.43	0.34	4-8	4-8
C	PLAST	X	1.33	4.73	**4.92**	0.47	4-8	2-4
J	PLAST	X	1.34	5.76	**7.45**	0.73	4-8	1-2
B	PLAST	X	3.59	**9.63**	9.54	1.36	4-8	<1.0
H	PLAST	X	4.36	**8.67**	7.09	1.66	4-8	<1.0
D	PLAST	X	-	-	-	-	-	-
E	PLAST	X	0.84	2.97	**3.16**	0.54	4-8	4-8
F	PLAST	X	1.77	**12.48**	7.76	1.46	4-8	-
G	PLAST	X	1.79	2.87	**4.16**	1.51	4-8	2-4
I	PLAST	X	5.87	6.03	**6.38**	0.69	4-8	1-2

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	PLAST	Y	4.18	5.44	**6.30**	0.53	2-4	1-2
C	PLAST	Y	1.68	**4.86**	4.67	0.51	4-8	2-4
J	PLAST	Y	1.43	7.69	**10.58**	1.78	1-2	<1.0
B	PLAST	Y	3.23	8.18	**9.40**	0.97	2-4	<1.0
H	PLAST	Y	4.13	5.93	**6.02**	1.19	4-8	1-2
D	PLAST	Y	1.34	**9.25**	6.44	1.01	0.5-1	<1.0
E	PLAST	Y	4.42	6.70	**6.84**	1.22	2-4	1-2
F	PLAST	Y	1.49	**18.00**	12.33	2.49	1-2	-
G	PLAST	Y	2.22	4.83	**5.26**	1.15	1-2	2-4
I	PLAST	Y	8.77	8.73	**8.88**	0.77	4-8	<1.0

DRILL	MATERIAL TESTED	AXIS	FREE RUN ACC. (M/S^2)	HORIZ. ACC. (M/S^2)	MEAN VERT. ACC. (M/S^2)	VERT. STANDARD DEVIATION	MAX. RECOMMENDED EXPOSURE	
							ANSI S3.34 SPECTRA (HOURS/DAY)	ACGIH-TLV CRITERIA (HOURS/DAY)
A	PLAST	Z	1.18	**4.22**	2.32	0.15	2-4	2-4
C	PLAST	Z	1.08	**4.77**	3.81	0.25	4-8	2-4
J	PLAST	Z	1.10	1.87	**2.13**	0.19	4-8	4-8
B	PLAST	Z	3.66	5.28	**7.06**	1.94	4-8	1-2
H	PLAST	Z	2.37	**3.64**	3.24	0.22	4-8	4-8
D	PLAST	Z	0.65	1.57	**2.85**	2.31	2-4	4-8
E	PLAST	Z	6.50	9.01	**10.28**	2.68	1-2	<1.0
F	PLAST	Z	0.71	**5.35**	4.83	0.77	4-8	2-4
G	PLAST	Z	0.86	1.33	**1.89**	0.30	4-8	4-8
I	PLAST	Z	9.28	**7.32**	6.86	0.86	2-4	1-2

Appendix G

This appendix contains examples of third-octave spectra obtained from recorded acceleration data for handle versus barrel amplitude comparisons. The ANSI standard exposure zones are superimposed on the plots to determine if, and by how much, the standard may have been exceeded.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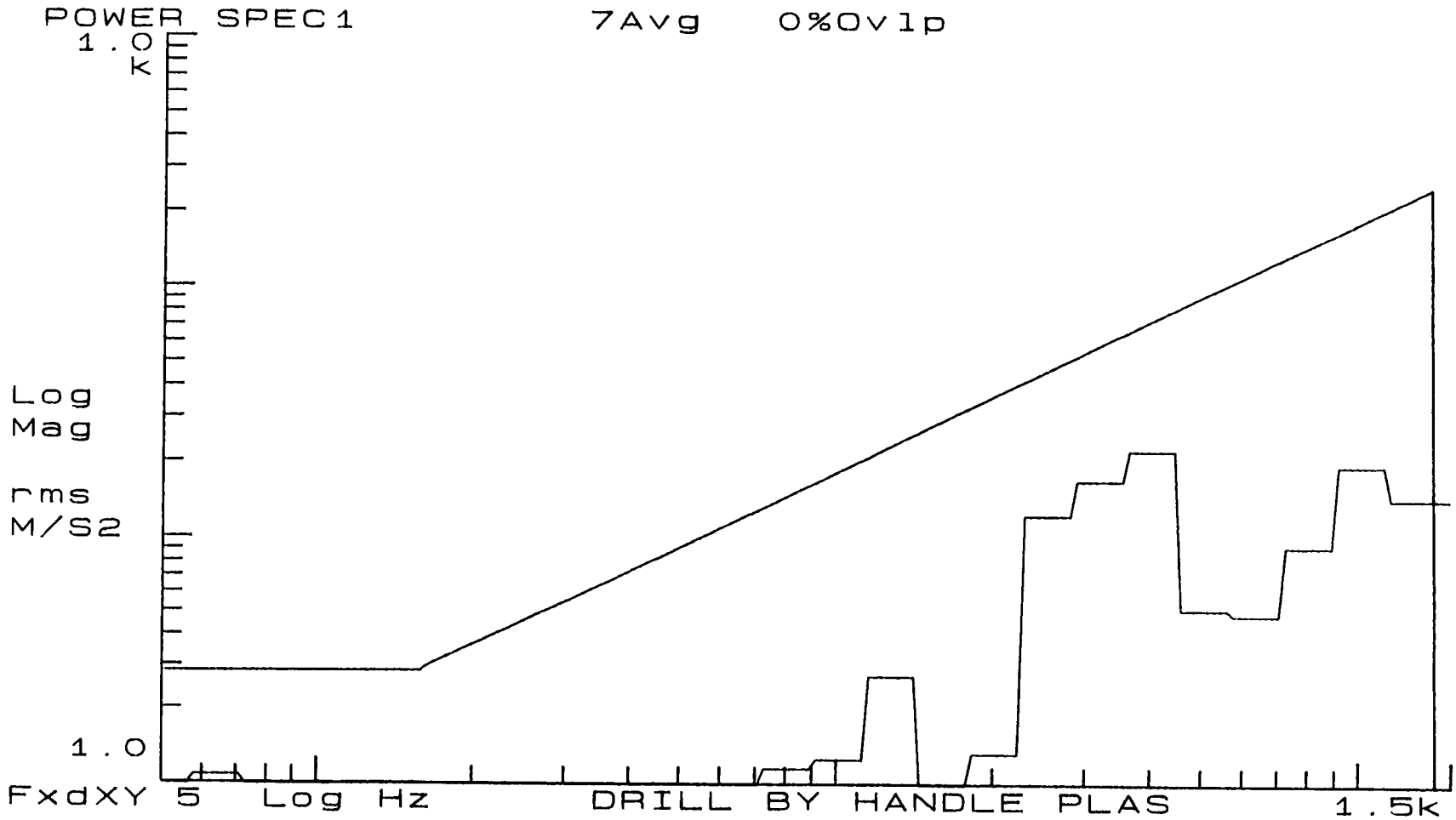
0%Ovlp
1.0
K
Log
Mag
rms
M/S2
1.0
FxdXY
5
Log Hz
DRILL BY BARREL PLAS
1.5k


POWER SPEC1
7Avg
0%Ovlp
1.0
k
Log
Mag
rms
M/S2
1.0
FxdXY
5
Log Hz
DRILL BY HANDLE PLAS
1.5k

Appendix H

This appendix summarizes the results from handle to barrel comparisons for drills A and B.

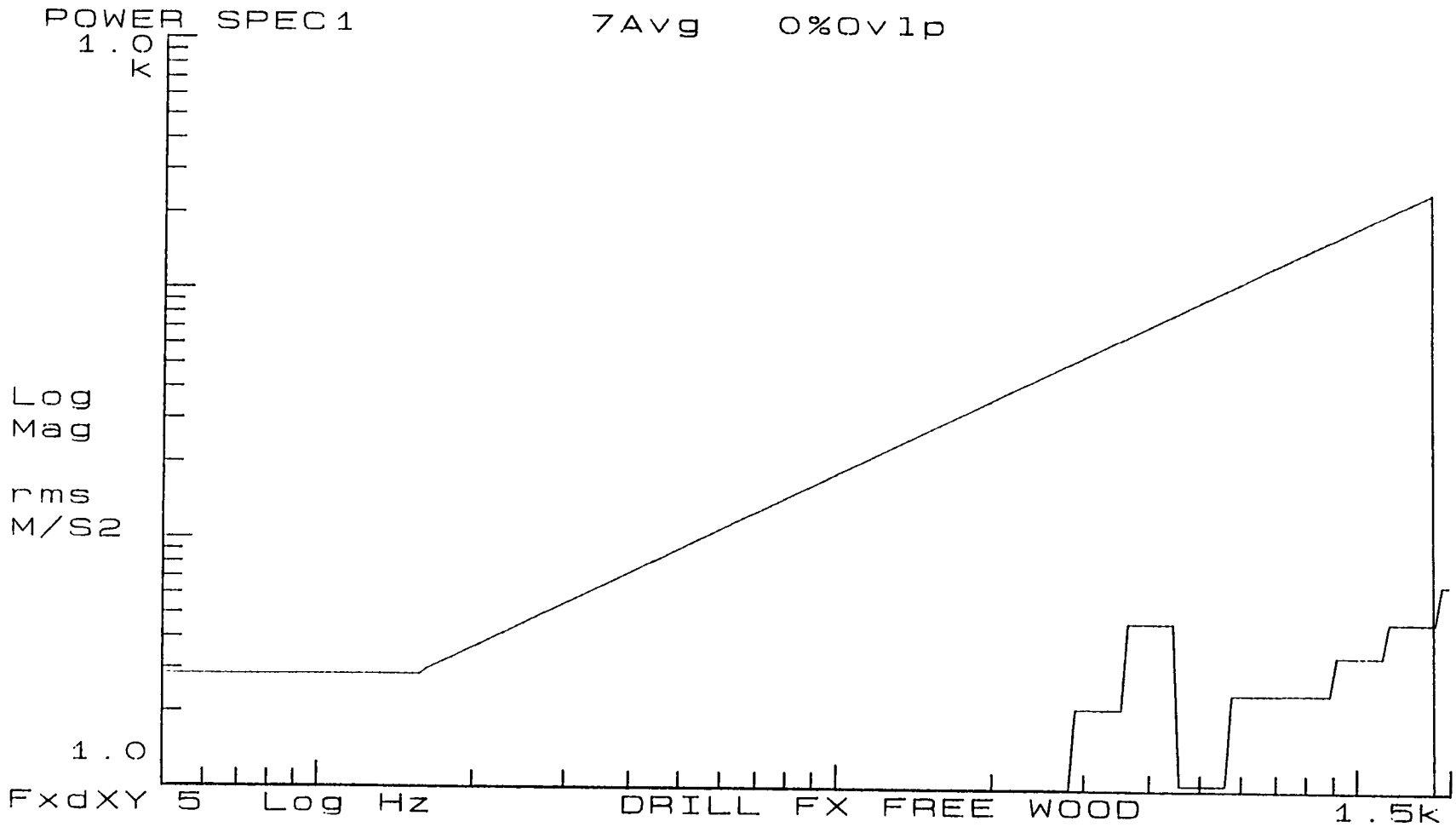
DRILL	MATERIAL	AXIS	ACCELEROMETER MOUNTING LOCATION				MAX. RECOMMENDED EXPOSURE			
			HANDLE WT. VERT. ACCEL. (M/S^2)		BARREL WT. VERT. ACCEL. (M/S^2)		ANSI S3.34 SPECTRA (HOURS/DAY)		ACGIH-TLV CRITERIA (HOURS/DAY)	
			MEAN	ST. DEV	MEAN	ST. DEV	HANDLE	BARREL	HANDLE	BARREL
A	WOOD	X	**4.58**	0.344	3.70	0.104	2-4	4-8	2-4	4-8
B	WOOD	X	6.74	0.468	**15.62**	3.16	2-4	4-8	1-2	-
A	STEEL	X	**4.10**	0.263	3.53	0.251	2-4	4-8	2-4	4-8
B	STEEL	X	6.91	0.239	**19.48**	3.59	1-2	4-8	1-2	-
A	CONCR	X	**7.74**	0.971	5.43	0.289	1-2	2-4	1-2	2-4
B	CONCR	X	7.49	1.20	**16.28**	1.24	1-2	4-8	1-2	-
A	PLAST	X	**3.27**	0.421	2.80	0.081	4-8	4-8	4-8	4-8
B	PLAST	X	4.92	0.578	**21.28**	10.13	2-4	4-8	2-4	-

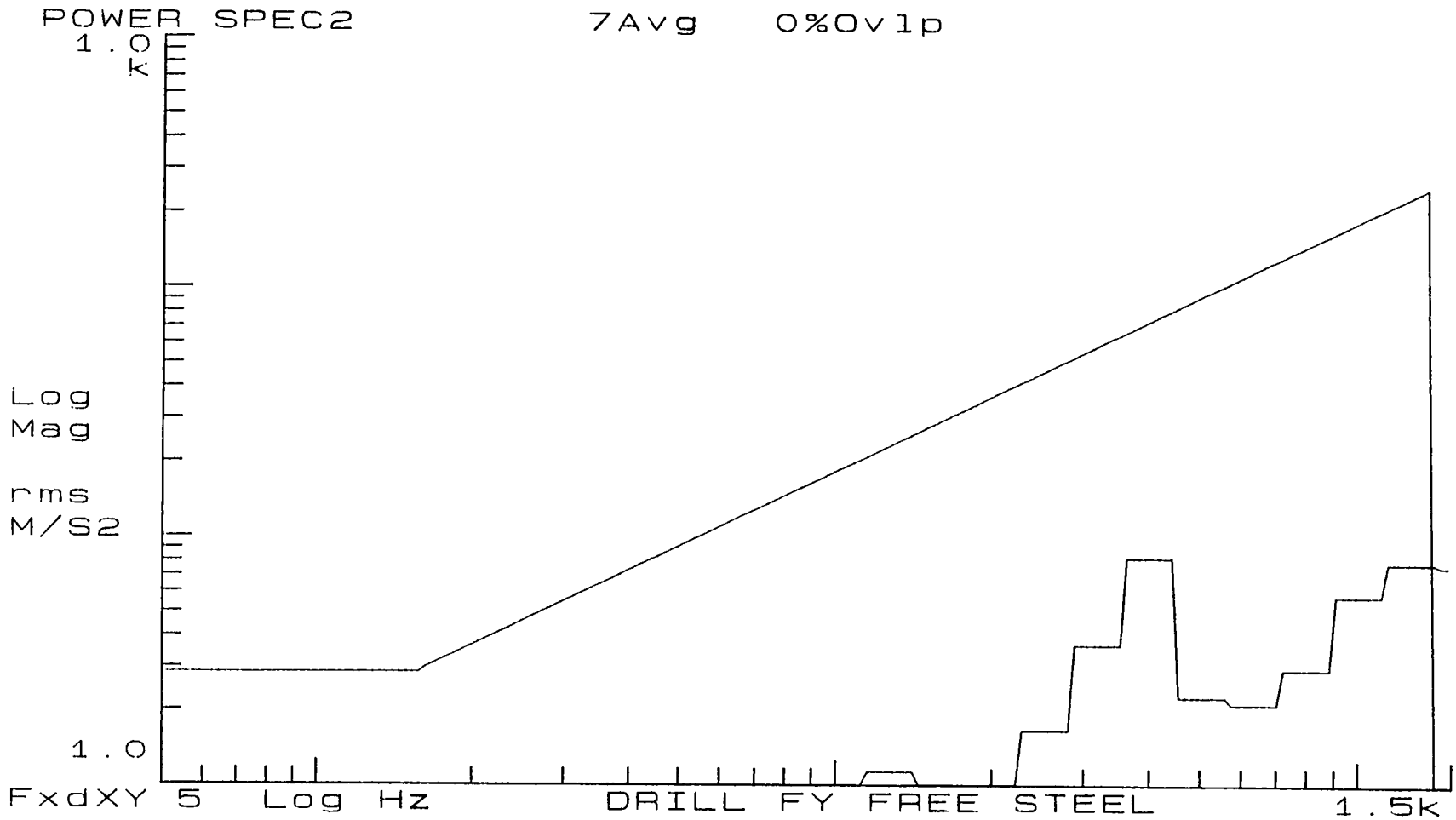
DRILL	MATERIAL	AXIS	ACCELEROMETER MOUNTING LOCATION				MAX. RECOMMENDED EXPOSURE			
			HANDLE WT. VERT. ACCEL. (M/S^2)		BARREL WT. VERT. ACCEL. (M/S^2)		ANSI S3.34 SPECTRA (HOURS/DAY)		ACGIH-TLV CRITERIA (HOURS/DAY)	
			MEAN	ST. DEV	MEAN	ST. DEV	HANDLE	BARREL	HANDLE	BARREL
A	WOOD	Y	4.71	0.301	**8.77**	0.883	2-4	0.5-1	2-4	<1.0
B	WOOD	Y	4.15	0.479	**11.77**	1.06	4-8	1-2	2-4	<1.0
A	STEEL	Y	3.41	0.305	**8.07**	0.204	4-8	0.5-1	4-8	<1.0
B	STEEL	Y	6.08	1.79	**11.56**	1.20	4-8	1-2	1-2	<1.0
A	CONCR	Y	4.46	0.125	**9.23**	0.696	2-4	0.5-1	2-4	<1.0
B	CONCR	Y	5.54	1.68	**13.07**	0.872	4-8	1-2	2-4	-
A	PLAST	Y	3.55	0.362	**5.84**	0.182	4-8	4-8	4-8	2-4
B	PLAST	Y	4.32	0.990	**10.24**	2.58	4-8	1-2	2-4	<1.0

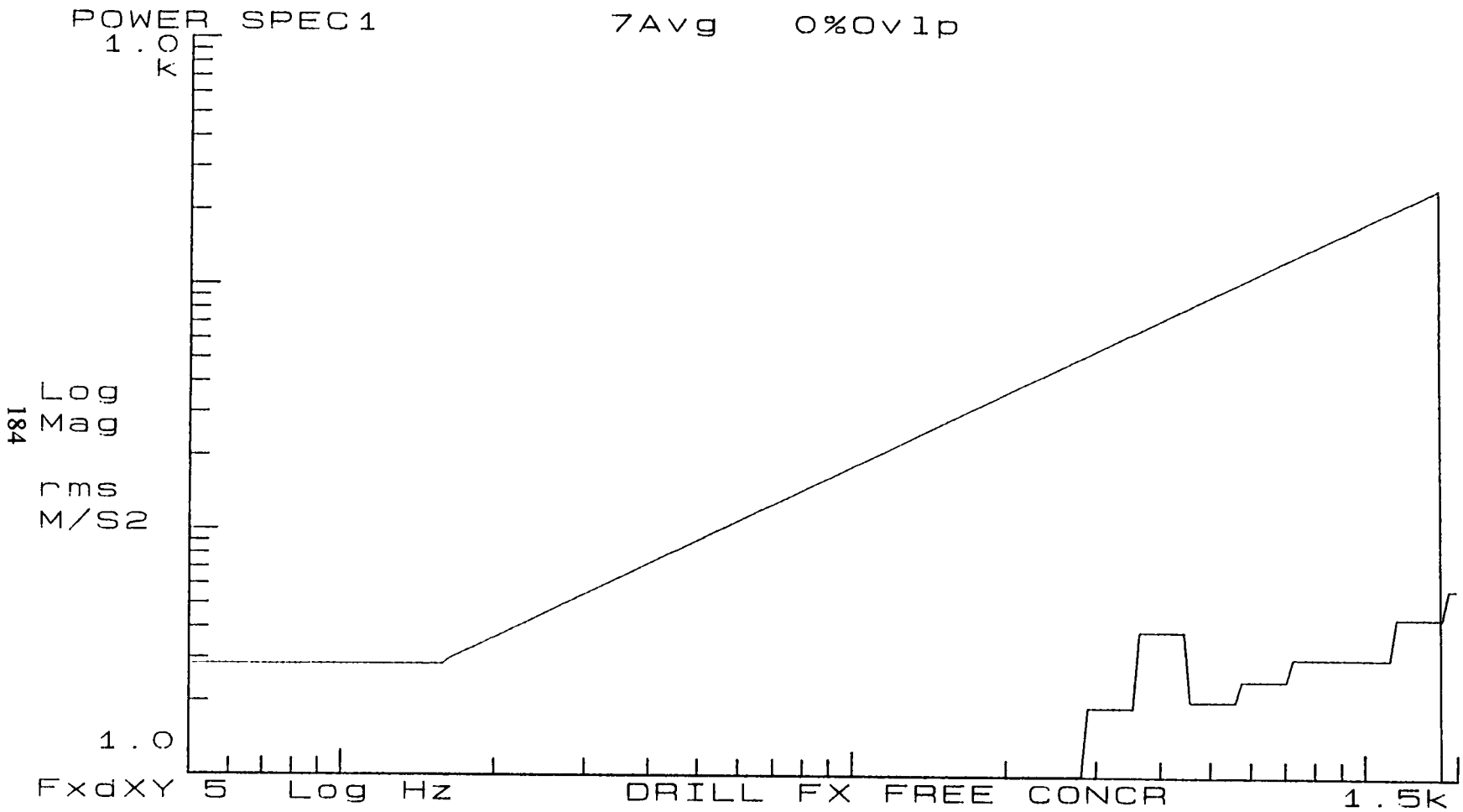
DRILL	MATERIAL	AXIS	ACCELEROMETER MOUNTING LOCATION				MAX. RECOMMENDED EXPOSURE			
			HANDLE WT. VERT. ACCEL. (M/S^2)		BARREL WT. VERT. ACCEL. (M/S^2)		ANSI S3.34 SPECTRA (HOURS/DAY)		ACGIH-TLV CRITERIA (HOURS/DAY)	
			MEAN	ST. DEV	MEAN	ST. DEV	HANDLE	BARREL	HANDLE	BARREL
A	WOOD	Z	**6.60**	0.385	5.27	0.395	2-4	4-8	1-2	2-4
B	WOOD	Z	4.57	0.295	**4.86**	0.083	4-8	4-8	2-4	2-4
A	STEEL	Z	**5.85**	1.05	4.44	1.59	1-2	2-4	2-4	2-4
B	STEEL	Z	**4.88**	0.520	4.21	0.274	4-8	4-8	2-4	2-4
A	CONCR	Z	9.64	0.477	**11.69**	0.167	0.5-1	0.5-1	<1.0	<1.0
B	CONCR	Z	6.17	1.65	**6.94**	0.912	2-4	4-8	1-2	1-2
A	PLAST	Z	**4.36**	0.120	2.44	0.222	4-8	4-8	2-4	4-8
B	PLAST	Z	3.27	0.320	**5.11**	0.516	4-8	2-4	4-8	4-8

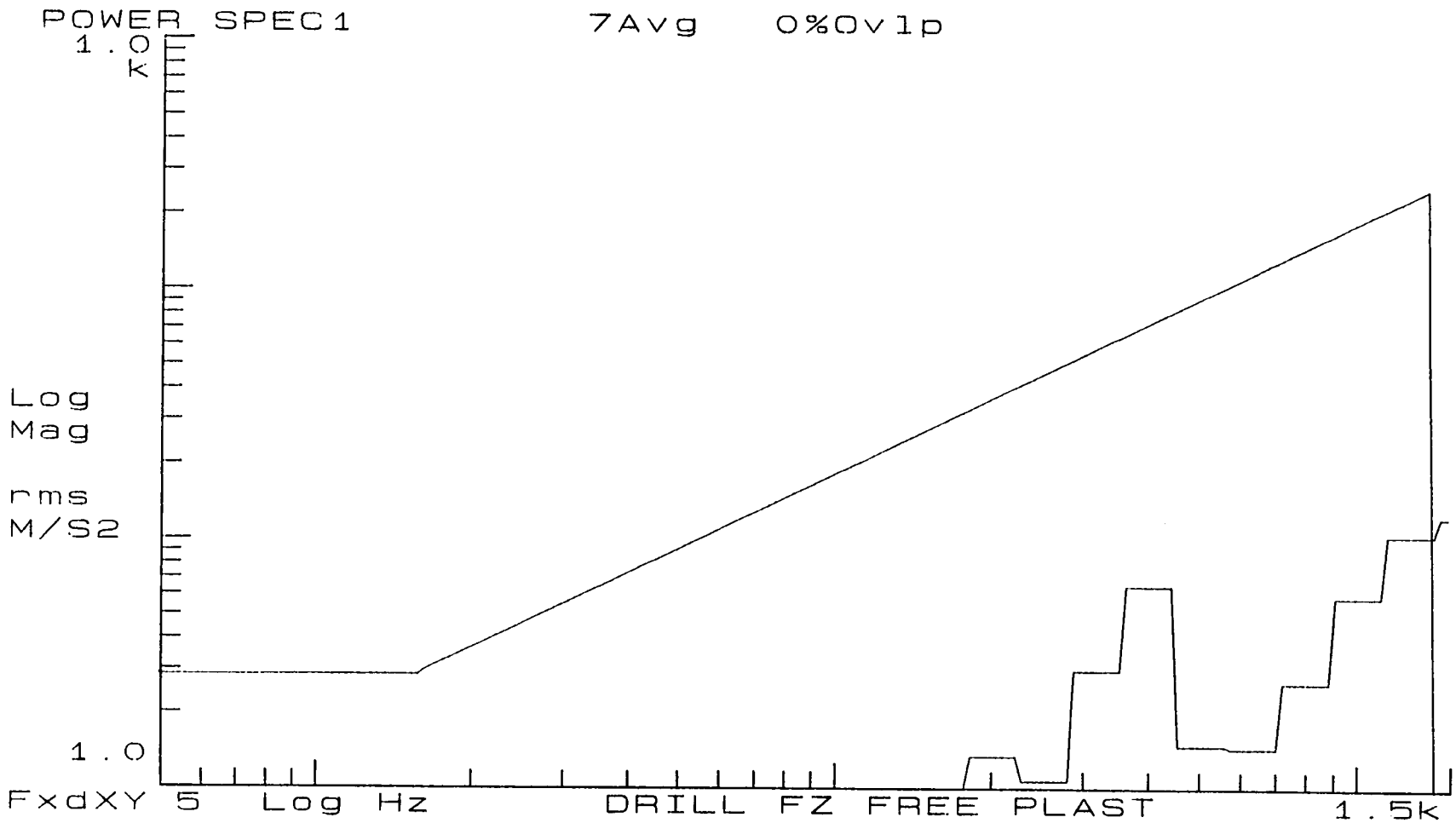
Appendix I

This appendix contains samples of third-octave spectra obtained from various free run data. They are only used to determine a bandwidth of applicable frequencies for a particular tool. Since the tool does no work against a resistance, they **cannot** be used to determine acceptable exposure times.


POWER SPEC 1
7Avg
0%Ovlp
1.0
k
Log
Mag
rms
M/S2
1.0
FxdXY 5
Log Hz
DRILL FX FREE WOOD
1.5k


POWER SPEC2
7Avg
0%Ovlp
1.0
k
Log
Mag
rms
M/S2
1.0
FxdXY
5
Log Hz
DRILL FY FREE STEEL
1.5k


POWER SPEC1
7Avg
0%Ovlp
1.0
k
Log
Mag
rms
M/S2
1.0
FxdXY 5
Log Hz
DRILL FX FREE CONCR
1.5k


POWER SPEC1
7Avg
0%Ovlp
1.0
k
Log
Mag
rms
M/S2
1.0
FxdXY
5
Log Hz
DRILL FZ FREE PLAST
1.5k

VITA

Howard Thomas Joseph Duffey IV (Tom) was born in Wilmington, Delaware on August 13, 1965. He attended Avon Grove High School in West Grove, Pennsylvania and received his diploma in June, 1983. During high school he was involved with the DuPont future engineers explorer program and the Boy Scouts of America. He received his Eagle Scout award in 1983. In August, 1983 he entered the Pennsylvania State University in State College, Pennsylvania, where he studied health education and sports medicine, until taking a leave of absence in the Fall of 1984. In August, 1985 he enrolled at Bowling Green State University in Bowling Green, Ohio, where he studied mechanical design and took pre-engineering courses. He was featured in the 1986-1987 edition of the National Dean's List. In August, 1989 he entered West Virginia University in Morgantown, West Virginia, to study Mechanical Engineering. In 1990 he was inducted into the Pi Tau Sigma (ΠΤΣ) national mechanical engineering honorary, and served as Vice President of that organization during his senior year. He was also a member of the American Society of Mechanical Engineers (ASME) and the Society for Automotive Engineering (SAE). In addition to his engineering studies, he completed all required courses for the pre-medicine curriculum. He received his Bachelor of Science degree in Mechanical Engineering from West Virginia University in August, 1993. During his senior year he gained increasing interest in the field of Biomedical Engineering, which he credits to Dr. Timothy Norman of West Virginia University. In August, 1993 he entered the graduate program at the University of Tennessee in Knoxville,

Tennessee, to pursue a Masters degree from the department of Engineering Science and Mechanics. He was an instructor for Basic Engineering Graphics and a member of the Biomedical Engineering Society (BES). While enrolled at the University of Tennessee he passed the Fundamentals of Engineering exam. He concentrated his efforts in the field of biomedical engineering. His thesis research project was conducted under the guidance of Dr. Jack Wasserman. In August, 1997 he received his Master of Science degree in Engineering Science from the University of Tennessee.