ABSTRACT

Because of the physical damage caused by rock drilling equipment to miners' hands, arms and shoulders since the advent of compressed air-operated machinery, this research project has considered medical literature concerning the occupational disease of miners as related to disease of the tissues and bone of the hands.

Primarily, however, the research has been concerned with the relationships that exist between vibrational frequencies and the amplitudes, velocities and accelerations associated with them. This appraisal was made by operating a particular rock drill under various conditions of attitude and air pressure so as to determine optimum operating conditions as related to vibrations and penetration rates.

A STUDY ON VIBRATION
IN ROCK DRILLS DURING DRILLING

by

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The project was supported by funds provided by the Department of National Health and Welfare, channelled through the Quebec Ministry of Health. This support is gratefully acknowledged. In view of the health interests of the sponsors, the project was directed towards the influence of machine vibrations on operators, the characteristics of those vibrations and the means of suppression.

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I. INTRODUCTION

The effects produced by high intensity vibration during rock drilling are unpleasant and can be physically harmful to workers and equipment, damaging to morale, and detrimental to attempts to attract workers to the mining industry.

Considerable study has been done on the topic of biological damage since the beginning of the century. A brief review of such evidence is included in this thesis. Very little work, however, has been done on the engineering aspects of drill vibration. Knowledge of such aspects hopefully could lead to design implementations to improve the environment without lowering penetration efficiency. In the past, increases of penetration rate have always meant corresponding increases in vibrational energy.

The purpose of this thesis is to establish practical relationships between the frequencies of vibrations and their corresponding displacements, velocities and accelerations as determined under common drilling conditions using various air pressures.

II. THEORY OF VIBRATION

1. Parameters

When an object with a mass moves back and forth in a direction, it is said to vibrate. In this thesis, vibration will be reviewed in three classifications: Periodic, Transient and Random.

Periodic vibration is the form most generally measured on rotating or reciprocating machinery and represents a periodic motion. Also known as Simple Harmonic Motion (SHM), this type of vibration repeats itself in all its particulars after a certain interval of time called the period, T. Simple Harmonic Motion (SHM) is represented in mechanics by an equation in which the acceleration is proportional to the displacement. The plot of displacement against time (Figure 1) of SHM is a sinusoidal wave for which the function is:

$$X = A \sin\omega t \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

Where X represents the displacement, A represents the amplitude, ω is the circular frequency or the angular velocity and t is the time.

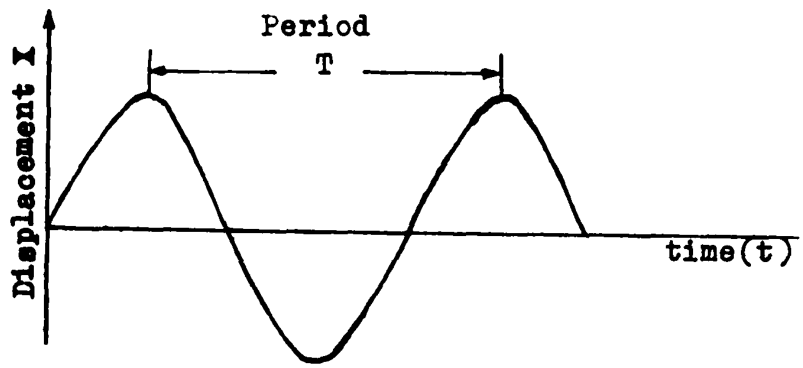

Fig. 1. Sinusoidal Wave for SHM. The frequency (Number of cycles per unit time) is given by $F = 1/T = \frac{\omega}{2\pi}$

The relationships between the three quantities defining the SHM are given in Table I

Given Quant.	Transferred to		
	s	v	a
s $s = s_o \sin(\omega t)$		$v = \frac{ds}{dt}$ $v = \omega s_o \cos(\omega t)$	$a = \frac{d^2s}{dt^2}$ $a = -\omega^2 s_o \sin(\omega t)$
v $v = v_o \sin(\omega t)$	$s = \int v\,dt$ $s = -1/\omega\, v\cos(t)$		$a = \frac{dv}{dt}$ $a = \omega v_o \cos(\omega t)$
a $a = A_o \sin(\omega t)$	$s = \iint a\,dt^2$ $s = -\frac{1}{\omega^2} A_o \sin(\omega t)$	$v = \int a\,dt$ $v = -\frac{1}{\omega} A_o \cos(\omega t)$	

Table I. Relationships between quantities of SHM

Graphically, these quantities can be represented as in Figure 2.

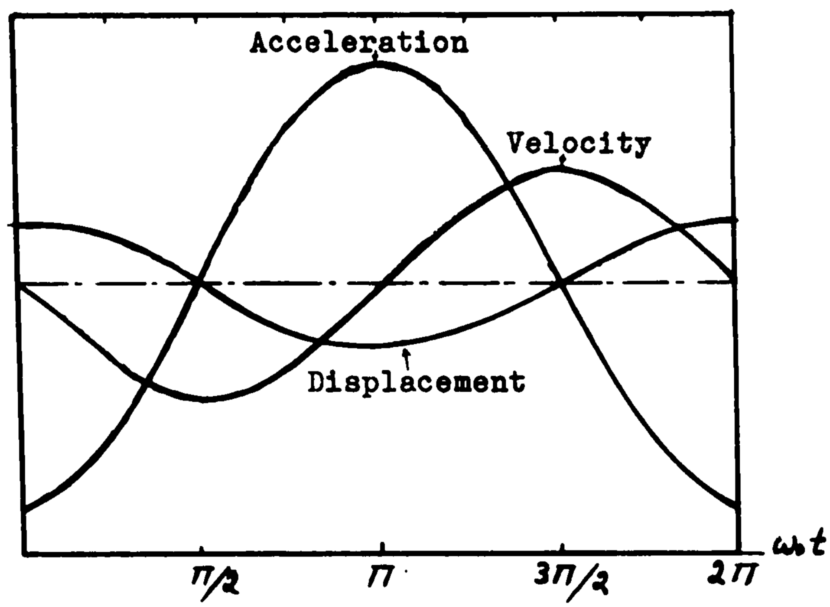

Figure 2. Relationships between quantities of SHM (From Kimsler and Frey) (1)

To further explain Table I and Figure 2, it is seen that the velocity leads the displacement by a time interval. corresponding to $\pi/2$ radians of phase—angle difference. Acceleration and displacement are always π radians out of phase with each other. The curves plotted in Figure 2 correspond to phase angle difference $\phi=0$ and circular frequency $\omega_0 = 2$.

Taking the first derivative of equation 1, the velocity term is obtained:

$$V = \dot{X} = \omega A \cos\omega t = \omega A \sin\ (\omega t + \pi/2) \qquad (2)$$

which indicates the $\pi/2$ difference in phase with the displacement term.

Further, differentiation yields the acceleration term

$$a = \ddot{x} = -\omega^2 A \sin\omega t \qquad (3)$$

Since $x = A \sin\omega t$, then

$$a = \ddot{x} = -\omega^2 x \qquad (4)$$

hence the definition of SHM is proved. In passing, it can be mentioned that in most vibratory equipment, accelerations are designated as multiples of the gravitational acceleration, g.

Transient vibrations are due to forces applied to a mass for a short interval of time and then removed. The subsequent motion of the mass is free vibration which gradually decreases in amplitude due to damping present in the system. Mechanical shocks and percussive sounds can be represented by functions which create the transient vibrations.

The vibrations which are unpredictable and are not limited by defined time intervals are called random vibrations; aircraft, traffic noise, air-cushion vehicles and mass conversations are examples of random vibration.

Thus far, some basic definitions of vibration theory have been reviewed. Since disturbances are irregular, some methods have evolved in order to compare the quantities defining a particular vibration. Mainly, a) Peak-to-peak values and b) Root mean square (r.m.s.). The root mean square of, say, acceleration, is defined as the root of the mean square of the instantaneous values. In case of sinusoidal vibration, rms is equal to 0.707 of the peak acceleration. For complex waves of random vibration, rms of acceleration is given by

$$a_{rms} = \sqrt{\frac{1}{T} \int_0^T \left| a^2 t \right| dt} \qquad (5)$$

Another important quantity is the average value of the acceleration

$$a_{average} = \frac{1}{T} \int_0^T \left| a \right| dt \qquad (6)$$

For sinusoidal waves, these quantities are given in figure 3, where $a_{peak} = \frac{\pi}{2} \; a_{average}$

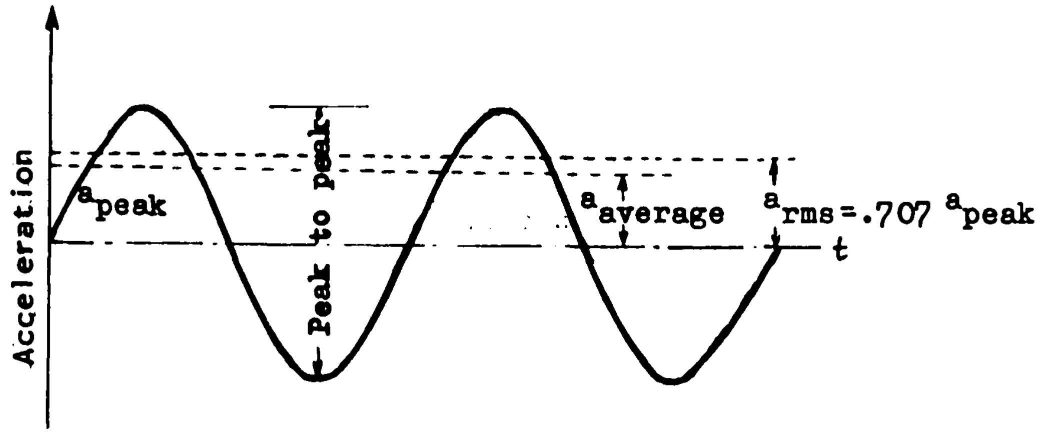

Figure 3. Relevant Terms for Sinusoidal Wave.

The tendency in studying vibration is to refer to sinusoidal waves most of the time because they are simple to deal with. However, in practice, wave shapes are more complex. Fortunately, all these complex waves can be handled by using the Fourier Series which makes it possible to represent any shape by a combination of a number of sinusoidal waves.

2. <u>Effects of Vibration</u>

Controlled vibration can be used effectively to aid mankind in such instances as conveyor systems and hopper discharge points. However, vibration has usually an adverse effect, such as human discomfort and fatigue from excessive vibration of a tool, fatigue and rupture of structural members and increased breakdown of machines, appliances and other devices.

Vibration, then, is of concern not only due to noise, annoyance and discomfort, but also due to safety aspects as well. The present refinements of high speed planes, ships, automobiles and pneumatic tools could never have been achieved without thorough measurement and study of mechanical vibration.

Vibration-related problems can be classified as:

i) Effects on man:

This is the most important one. The published works on the effects of vibration on man has recently been reviewed comprehensively in chapter 44, Shock and Vibration Handbook (2), in chapter II, Handbook of Noise Control (3) and by J.C. Guignard (4) in 1966. It can briefly be said that because of vibration fatigue, annoyance and interference with performance of the man take place.

If rock drills are considered, improvements in design to achieve greater drilling speeds have been paralleled by an increase in the intensity of the vibrations. Many people who use pneumatic tools suffer from vascular disturbances which produce a local anemia or pallor of the fingers, making them stiff and awkward. It is rather surprising that very little attention has been paid to a reduction of the high levels of vibrations in all pneumatic machines. As White says, "the total environment of the mining industry is seldom examined as a whole". (5)

ii) Mechanical failure:

Excessive vibration leads to excessive stress, as well as fatigue, destructive impacts and other effects that cause excessive wear resulting in high costs for machinery maintenance. Periodic measurement of machinery vibration has become an important preventative maintenance procedure in many factories. Limits on vibration on many machines have been set for a variety of reasons, generally on the basis of experience. Thus, knowledge of vibration should help to insure high quality of work and low maintenance.

Rathbone (6) in 1963 recommends that, for hand tools the velocity should be less than 0.1 in./sec. peak. The manufacturer of a compressor may select a velocity of 0.5 in./sec. peak, but the user may prefer to have the velocity kept to 0.1 in./sec. peak.

Here the manufacturer and the user have different criteria.. The former is interested in producing machinery which will have a reasonable life and at the same time be able to compete with other manufacturers. The latter is interested in machinery that will fit into his operation and at the same time be economical.

3. Relationship of Vibration and Noise

Vibration problems occur in so many devices and operations that the number of types increase year by year; hence during the past decade more and more people have become concerned with the problems of vibration. Noise is even more important. In fact, it can be said that noise and vibration are twins. The study of sound is closely related to that of mechanical vibration, because sound is produced by the transfer of mechanical vibration to air.

The vibration disturbs the air particles near the object and sets them into motion, producing a vibration in normal atmospheric pressure. The disturbance spreads and when the pressure vibrations reach the human ear drums, they too are set vibrating. This vibration of eardrums is translated by complicated hearing mechanism into the sensation called sound. Sound is produced by the transfer of mechanical vibration to air. Hence the process of "quieting" a machine or device often includes a study of the vibrations.

Acoustic noise is sound which in the physical sense, is a mechanical vibration of particles either in a gas, a liquid or a solid. Such vibrations are characterized by their frequency, amplitude and phase.

Noise and vibration have become matters of some consequence in human affairs since the industrial revolution. The present generation has noise and vibration problems that previous generations did not have.

All mechanical vibrations cannot be perceived by the hearing mechanism of the human ear. Firstly, the vibrations have to be of a certain magnitude to be audible and secondly, the frequency has to be within certain limits. Not all vibration is necessarily harmful; some people find moderate levels of vibration exhilarating. Today it is possible to buy and the so called "weight-control" machines which are built on simple vibration principles. However, the rock drill has a very high level noise and a very intensive vibration which may cause irrepairable physiological damages.

4. Vibration Isolation

Reduction of vibration is a means of decreasing transmission of vibratory motions or forces from one structure or material to another. There are two types of vibration isolation applications: (1) those to prevent transmission of unbalanced forces from a machine to its foundation. (2) those to reduce the motion transmitted from a substructure to a sympathetic device mounted on it (7).

Four resilient materials are most commonly used in vibration isolators: (1) Metal Springs: These are by far the most commonly used to isolate delicate scientific instruments from foundation vibrations. Some resilient mountings are fabricated with a metal spring inside a rubber gland with a calibrated orifice which regulates the flow of air in and out of the gland thereby furnishing viscous damping. (2) Rubber Mountings: These are used very effectively to isolate small machinery and mechanical devices such as engines, motors, instruments electronic gear, etc. Rubber in compression is used widely for applications which require high energy-storage capacity and an ability to support heavy loads without failure. (3) Cork: This is one of the oldest materials used for vibration isolation. Cork is used in compression or in combination of compression and shear. The dynamic properties of cork are also very much dependent upon frequency. The pressure to which the cork should be subjected for optimum performance is between 7 and 20 psi. (4) Felt: By using felt as a vibration isolation material, the greatest isolation efficiency is obtained when using the smallest possible area of the softest felt. It has a high damping factor and thus is particularly useful in reducing amplitude of vibration at resonance. Felt is particularly useful in reducing vibration transmission in the audio-frequency range since it offers a large impedance mismatch to most engineering materials.

Principles and general practical methods for effecting vibration isolation have been considered. To decide what method to use for a specific problem one must consider cost, space, degree of isolation required, availability, reliability and other factors.

As far as rock drills are concerned, there is a great tendency at present to change from machines held by hand to machines on stands. However, it is estimated that at least 25 percent of those held by hand will still be used in the future (8).

All of the experiments produced vibrations which were of a similar nature. This was observed throughout the experiments carried out under widely varied conditions: i) operating the drill at no-load, ii) drilling horizontally and iii) drilling down vertically. Immediately this suggests that since the vibrations in the drill are all similar, they can be effectively isolated from the handle by using suitable vibration isolators. There is one major difficulty associated with the practical use of this system; the attachments must not interfere with the operator's control over the operation of the drill. Meanwhile attempts are made to protect the hands by using different materials in the handles. Much has been achieved at Malmberget by furnishing drillers with chamois gloves to be worn inside rubber gloves (8). In this way the hands are kept warmer and it should be possible to protect them from chilling with soft inner gloves.

5. Summary

With experience, the measurement of vibration can be used as an indicator of machinery or structural condition. The measurement of vibration level over a period of time can show a trend in the condition of the unit under investigation. Corrective measures can be applied then to prevent break down.

A mechanical machine usually possesses many sources of vibration, originating from different moving systems. The vibrations produced will be characteristic of their individual sources, with respect to their frequency, amplitude and phase. Particular frequency components are often traceable to some moving element's frequency of repetition whereas the absolute amplitude of the vibration is consistantly unpredictable. This quantity is determined by a variety of factors, one of which, for example, is the mechanical stability of the moving system. The mechanical failure increases with time as a consequence of unbalance caused by wear, insufficient lubrication and inadequate maintenance. Since vibration is the essential etiologic agent, a brief interpretation of some commonly used terms is indicated. Vibration can be adequately defined by stating its frequency and amplitude. Each of these terms can be expressed by using different terminology i.e., frequency is sometimes described by beats, revolutions, strokes or cycles per second. These different expressions for frequency cause some confusion. It would help, of course, if all future studies were standardized.

Noise is the product of transfer of mechanical vibration to air which in turn reaches the hearing mechanism -- the ear. As a result the study of noise is also important since the characteristics of such vibrations may vary to be harmful for the physiology of the human body.

As explained, reduction of vibration in rock drills is an important but at the same time very complex problem. This involves a sequence of studies to understand and to analyse the nature of vibration inherent in a particular drill.

III. PHYSIOLOGICAL EFFECTS OF VIBRATION

1) Early Investigations

Since the last 60 years, reports have appeared, both in the American and European literature, relating hand and forearm disability due to vibration from pneumatic work tools. Close agreement on the physiological and physical findings described by investigators from both continents have been noted (9). The disorders resulting from the use of these tools involve:

i) alteration of vasomotor responses;

ii) injury to nerves (neurological physic disturbances);

iii) effects on the muscles and soft tissues;

iv) injuries to bones and joints (forearm, shoulder and especially the elbow);

Pneumatic tools were first used in French mines in 1839. These tools began to be manufactured commercially in the United States in 1883 and subsequently, injuries from vibration became widespread (10).

The vibration disease was described first by Loriga (11) in Rome in 1911. Since then there have been many reports of unusual maladies of the hands and arms of workers, caused by vibrations which are transmitted to the hands and arms.

There were many complaints concerning intermittent attacks of blanching and numbness of fingers among the Indiana Limestone quarry workers who used pneumatic hammers. Hence, the first report of the disease was made by Dr. C.E. Cottingham (12) in the United States in 1917. The U.S. Department of Labor and later, the U.S. Public Health Service also made investigations of the complaints. Valuable pioneer work was done by Leake (13), Edsal (14), Rothstein (15) and others. A. Hamilton (16) made a detailed study of miners using vibratory tools in the Indiana limestone quarries. A certain number of workers who operated these tools have always complained that their use caused what was described as "dead hands" or "white fingers", attacks of blanching and numbness in the fingers with loss of power. It is, however, most widely known as "pneumatic hammer disease". Thus, reports prior to 1945 placed most of the blame on pneumatic hammers.

The attacks occur in the hands of workers after a variable period (months to years) of exposure to vibration, and they last from a few mimutes to several hours. This disturbance reoccurs at irregular intervals but most frequently when the hands are exposed to cold.

Subjective complaints of most cases are one or more of the following: intermittent numbness and clumsiness of the fingers; intermittent blanching of the hands either totally or in part; tingling, burning, weakness, stiffness, aching, pain, loss of grip, cramps, or color changes. These occur most frequently at the beginning or the end of an attack, and occasional temporary loss of muscle control in the effected extremity (16), (17), (18), (19),(20), (21).

The duration of exposure before the development of Raynaud's phenomenon was different case by case, but it was usually less than 3 years of handleing a jack-leg hammer (22). Frequency and severity of the vasomotor disturbance are variable but in most cases reach a maximum within a few years of their appearance, after which further exposure does not aggravate the disease (23). The disease progresses to a stage where productive capacity is so impaired that stricken workers must find another type of work. All evidence indicates that the attacks persist even though the workers are removed from exposure of vibration, but the severity of the symptoms usually decreases. Complete remission or cure is rare. Hardgrove and Barker (24) reported in 1933 that the fingers of men who have not used the tool for as many as ten years still may turn white in cold weather and this may make it impossible for them to take up a skilled trade where their hands are exposed to the cold. There are many cases of attacks occuring on a hot summer day, especially in those who have had the disturbance for a long period. Agate (25) found two men who had experienced Raynaud's phenomenon after hot baths as well as after washing in cold water. Marshal (26) found that 15 of the 37 workers he examined had nocturnal attacks of Raynaud's phenomenon which disturbed their sleep. An attack passes off when normal circulation is established in the affected part. All the fingers do not recover at the same rate, some being bright red while others still remain deep blue (17).

Hamilton (16) reported on the stonecutters who used pneumatic hammers. Raynaud's phenomenon occurred in the hand that gripped the tool, the hand which absorbed the most vibration.

In most cases the first symptoms are a slight blanching and numbness of the fingertips. The sensitiveness of the vasomotor nerves to mechanical stimuli was most marked in those parts of the body which were in closest contact with the vibrating tool. Investigations since then have substantiated the fact that the hand receiving the most intense vibration is, in most cases, affected sooner and to a greater extent than the other parts.

Hamilton (27) noted in her second report in 1930, that the men who used pneumatic tools for approximately two years, experienced numb and clumsy fingers while the vascular spasm lasts, and as this passes into hyperemia there may be decided discomfort and even pain. In addition, she noted "I saw men who were obliged to bend back the fingers of the left hand with the help of right hand after the tool was laid down so stiff had the muscles grown". Other patients complained of a good deal of pain in the fingers, especially on a cold morning or after working. One said his whole left side felt different from the right side. If he held up his hands for a few minutes as in reading a newspaper, they grew numb and he had to lower them. He had lost sensitiveness in his fingers so he could not put his left hand in his pocket and pick out a coin by touch; he must look to see if it was a dime or nickel. He was uncertain in distinguishing between sharp and dull on fingers. He was very clumsy and usually was having restless nights.

If the hand is pricked or cut during an attack it does not bleed or, as one patient remarked, "only a little dark blood oozes out". Heavy pneumatic tools weighing 40 to 80 pounds, i.e., rock drills, jack hammers and roadrippers, with frequencies up to 2000 cycles per minute, predominantly affected the hands, arms and shoulders, and manifested this as muscular soreness and joint damage that may became permanent after years of using the tools. Mills (28) described the case of 37-year-old Jack-hammer operator with far advanced vascular disease of the left leg who used it to exert additional force on the Jack-hammer, but after about two years of such use it became gangrenous and was amputated.

Actual injuries of joints were first described by Holzmann (29) in 1929. They have generally occurred in miners. The changes of joints in the hands, elbows and shoulders that some investigators claim they observed are caused by tools such as chisels used for the breaking up of paving-stones and the like which exhibit very large amplitudes. As far as rock-drills are concerned it has been impossible to show convincingly that joint injuries have occurred (8).

Reports have stated that in Europe, Raynaud's Disease has been observed in several places. On the other hand, as late as 1960 ("U.S. Public Health Service", Mallvin-Christman), it was stated that this disease practically does not exist in the U.S.A. It has been mentioned by way of explanation (Williams-Roegert, 1961) that the temperature of the workrooms in the U.S.A. is generally several degrees above the corresponding temperature in Europe. Copeman (30) in England found in one operator, a calcified subacremial bursa in conjunction with early degenerative changes around the shoulder joint which were regarded as result of using the pneumatic hammer. Areas of decalcification on the bones of the hands and forearms were described by McLaren (31) in 1937. He reported a relationship between the vacuoles in the carpal bones and the length of exposure to vibration.

Hunter, McLaughlin and Perry (32) found seven cases of arthritis of the wrist and 30 cases involving the elbow in their survey of 286 pneumatic tool workers. The type of joint injury produced depends upon the reaction of the particular joint to vibration.

Peters (33) described cases of approximately 11 per cent of 2000 employees using high speed grinders. The predominant complaints were pain, swelling, numbness and stiffness. The pain was throbbing and burning. Many complained more of pain in the wrist and shoulder than in the hand or fingers. According to Dart (18), the exposure time necessary to cause trouble ranged from one week to 30 months, the median time being 8 months. However, Peters (33) noted the onset to range from one week to 18 months with a median of five months.

Hamilton (16) noted that exposure time prior to onset in the limestone workers ranged from 18 months to 16 years, but this is not an uncommon period for symptoms. If frequencies are greater than 10,000 cycles per minute, symptoms can appear after one week's exposure (26). The delay in onset does not seem to be affected by age. Telford, et al. (20) noted the delay in the age group 20-30 years to be no different from that in the age group 45-55 years. There have been many cases where the onset occurred after the subject had stopped working with vibrating tools, this silent period being even longer than a year in some instances. Agate (25) noted that when age is to be compared with severity of lesions or other damage the effect of length of exposure can reasonably be ignored.

In 1930 Seyring (34) found the percentage of cases among 92 pneumatic tool operators, compared with exposure as follows:

Years of Exposure	Per cent of Positive cases
Less than 2	4
2 to 3	48
3 to 10	55
Over 10	61

Table 2 is a more recent report given by Dr. Clair Renard (8) of Sweden, published in 1962. He sent 2000 copies of a questionaire to underground and surface labourers. A detailed description of the symptoms of the attack was given in the questionnaire, and the labourers were asked to state occurence of such attacks. Frequency of vasospasm in different age groups and different drilling period groups is shown in table 2.

Table 2

Category Age	Drilling period >1 <3 years		Drilling period >3 <5		Drilling period >5		All		Total	Frequency
	+	-	+	-	+	-	+	-		
20-34 years	18	48	24	33	29	15	71	96	167	42.5 %
35-60 years	10	5	11	13	53	19	74	36	110	67.3 %
Total 20-60	28	53	35	46	82	34	145	132	277	
Class total	81		81		116		277			
Frequency	34.7 %		43.2%		70.6%		52.3%			

Table 2 shows that in the two age groups taken together (20-60 years of age) the number of people effected increases with the duration of drilling. It also indicated that in the age group 20-34 years, the frequency of the disease was 42.5 % , whereas in the older group, 35-60 years, the frequency was 67.3 %.

It has been found that the left hand is generally attacked before the right one and the middle finger is attacked most frequently, the thumb most rarely (8). But the reason was not given in the literature cited. Whether the right or left hand is attacked more frequently, seems to depend upon type of work and working posture. Renard (8) obtained from the questionnaire of 1956 the following distribution in the fingers involved. See table 3.

Table 3. Frequencies of hands and fingers involved

Fingers	Thumb	Index	Middle	Ring	Little	Total
Right hand	9	36	45	37	25	152
Left hand	9	39	50	42	27	167
	18	75	95	79	52	319

Seyring (34) noted two cases of gangrene of the finger tips necessitating amputation. Teleky (35) mentioned one case of gangrene of the terminal phalanx of the first finger in the left hand of a man who had used an air hammer for five years. Junghanns (36) reported gangrene of the finger tips of the left hand in pneumatic tool workers who later developed nodules in both forearms. Bennett, Waine and Bauer (37) in 1942 had also observed gangrene of the finger tips in pneumatic hammer workers.

There is agreement among most investigators that local skin lesion such a ulcers, gangrene or changes in texture or thickness are not characteristic of Raynaud's phenomenon of occupational origin. Injuries to the soft tissues other than the nerves and blood vessels are comparatively rare (38).

Dart (18) and Peters (33) have done a great deal of work on vibration in this country, and detailed information is available as a result of the work by Agate and Druet (39). Sporadic reports have appeared in the literature since 1918 without adding significantly to the finding by Cottingham (12), Leake (13), Edsal (14), Rothstein (15), and Hamilton (16) until findings of Dart (18) and Peters (33) were described by Pecora et.al (9).

Hunter et al (32) did significant work in England. In North America, Dart (18) and Peters (33) reported their findings on workers using hand-held rotary tools with speeds up to 60,000 rpm. The symptoms patients complained about included pain, numbness, tingling, clumsiness, sensation of cold, cramps and weakness. The relative frequency of occurrence is summarized in the table 4 by Dart (18):

Table 4

Symptom	Patients	
	Number	Per Cent
Pain	76	68
Numbness	45	41
Stiffness	31	28
Paresthesia	10	9
Tendency to drop objects	9	8
Sensation of cold	8	7
Cramps	8	7
Weakness	8	7

Table 4

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Pain	76	68
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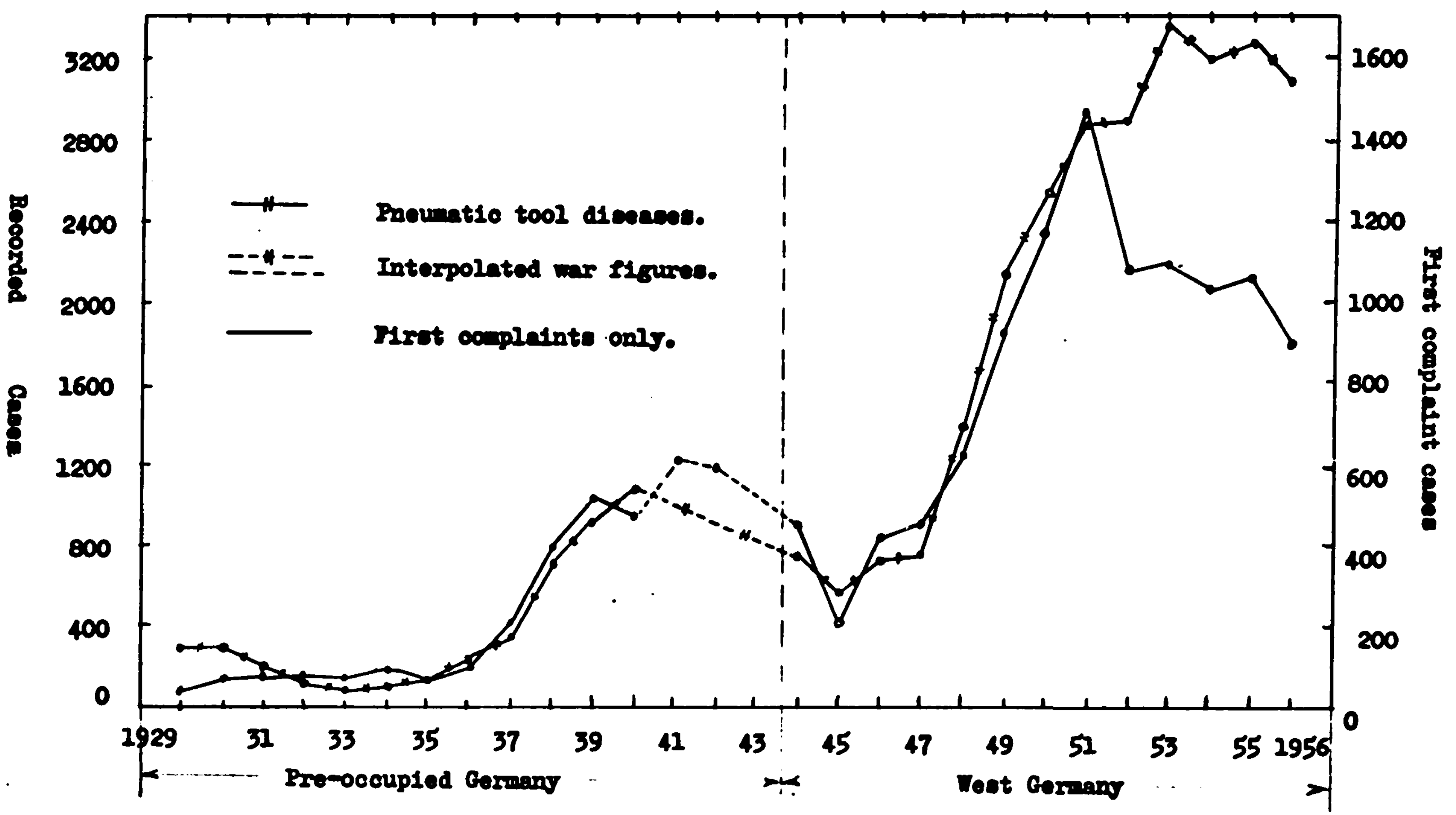
Sensation of cold	8	7
Cramps	8	7
Weakness	8	7

Table 5

The location in which the various symptoms appeared are shown in the table 5 by Dart (18).

Location	Pain	Numb-ness	Pares-thesia	Stiff-ness	Cold	Cramps	Weak-ness
Thumb	13	15	3	10	1	3	1
Index finger	11	20	3	14	1	2	1
Middle finger	19	19	3	18	2	2	-
Ring finger	17	21	3	20	1	2	-
Little finger	14	18	3	18	1	2	-
Hand	26	15	2	8	1	2	1
Wrist	37	9	-	-	-	-	2
Forearm	29	5	-	-	-	-	1
Elbow	17	-	-	-	-	-	1
Arm	18	-	-	-	-	-	1
Shoulder	24	-	-	-	-	-	-

Gurdjian and Walker (21) in 1945 checked a number of operators using pneumatic tools for any evidence of vibration syndrome. Pneumatic tools were operating at a rate of 3,400 strokes per minute. They reported that 84 % of the workers had injuries in the carpus, 60 % had poor circulation in the hands and some had experienced hearing difficulties.



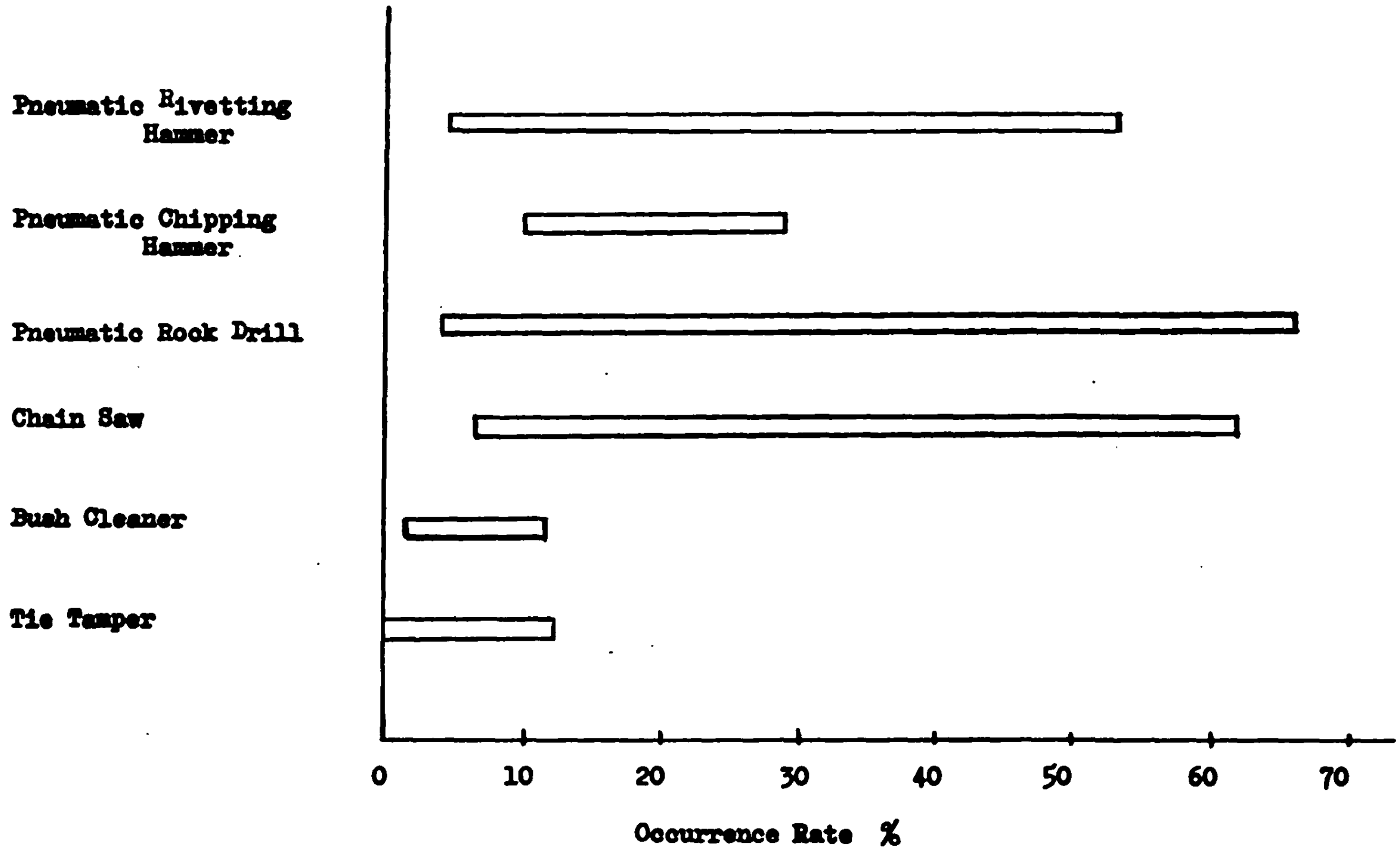
Graph I : Recorded and first complaint cases of pneumatic vibration sickness among miners in Germany from 1929 to 1956 (from Coermann and Lange 40).

The reports of investigation were few during the interval between the two World Wars. The advent of World War II brought with it the need for a rapid expansion of industry. This expansion caused more people to be exposed for greater lengths of time to the hazardous effects of pneumatic tools (40). Coermann and Lange (40) show their findings in Germany on Graph I. It can be easily seen that there was a rapid increase in the number of cases after the second World War commencing in 1947.

Miura et al. (22) made a detailed study of workers using vibratory tools in Japan in 1965. Graph 2 shows their findings for the occurrence rate of Raynaud's phenomenon due to vibrating tools. As Graph 2 indicates, the pneumatic rock-drill, according to Miura (22), caused the maximum vibration sickness.

2) Relationship Between Vibration Injuries and Temperature:

Workers in the tropics do not develop any appearent signs of vascular disturbances even after prolonged use of vibrating pneumatic tools. This was determined as a result of tests carried out amongst



Graph 2. Occurrence Rate Raynaud's Phenomenon due to Vibrating Tools in Japan (1965 - 1966) (From Miura et. al. 22).

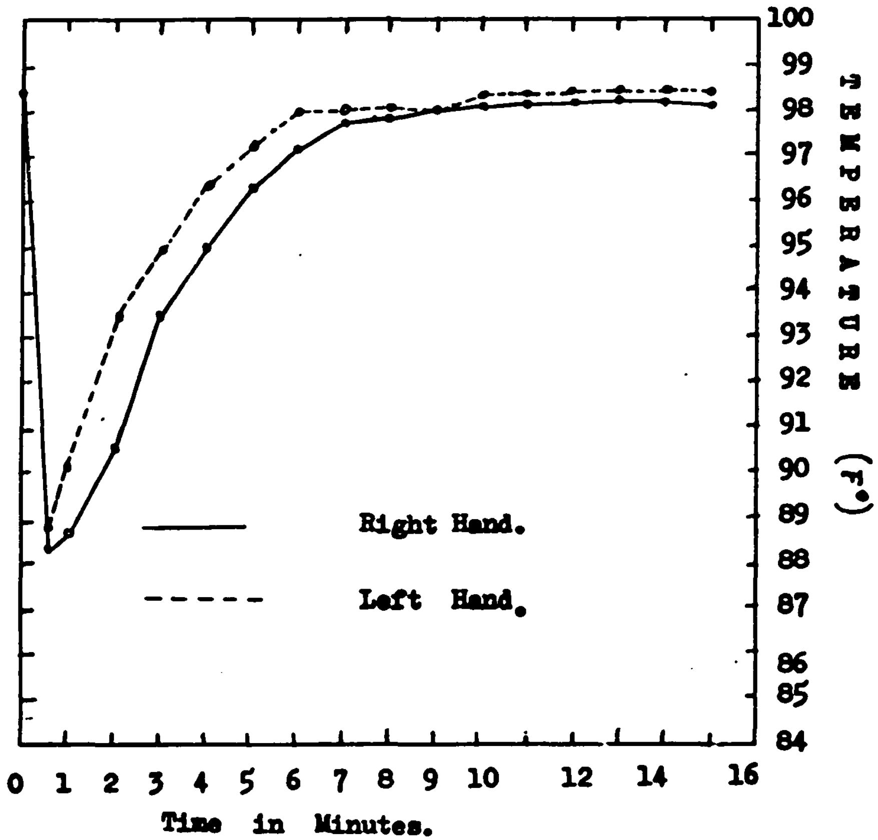
dockyard workers in Malaya, who were exposed to vibrations of high intensity (41). It was interesting to note that none of the workers complained of poor blood circulation. Thus, it is clear that the warm climate eliminates this occupational hazard. Although it is unlikely that cold is the most important factor in the cause of "white fingers", vibration injuries do occur in cold climates. All investigations have shown that attacks are precipitated, for the most part, by a cooling effect caused by cold air, washing of hands in cold water, handling cold objects or simply a chilly feeling even though the subjects hands are not cold. During work in well heated rooms, attacks are uncommon. Conversely, Hunt (17) found that when operators bodies are warm it is impossible to produce an attack. However, there are reports of some cases of vasospasms evoked by rainy weather in summer, warming oneself at a fire or a hot bath in winter. The effect of warmth in shortening or relieving an attack is well known. An attack passes when normal circulation is established in the affected part. Various ways of expediting the resumption of blood circulation are used by the workers, most frequently massaging the hands, fanning their arms or swinging them in a vertical circle, immersing the effected part in hot water or simply moving themselves to a warm environment. Telford et al. (20) stated that the chief trouble was the "loss of sensation and usefulness of the hand" during an attack. Marshall (26) reports that the attack usually occurs on cold days, and only 13 out of 37 affected men experienced attacks on warm days as well as cold days.

As a response to cold air or cold water (especially in the morning), attacks of vasospasm start in the fingers. During the spell, the involved fingers become white. If the patient enters a warm room or warms himself at a fire, the finger becomes bluish yellow or cyanotic and then pinkish and the vasospasms are soon followed by vasodilation.

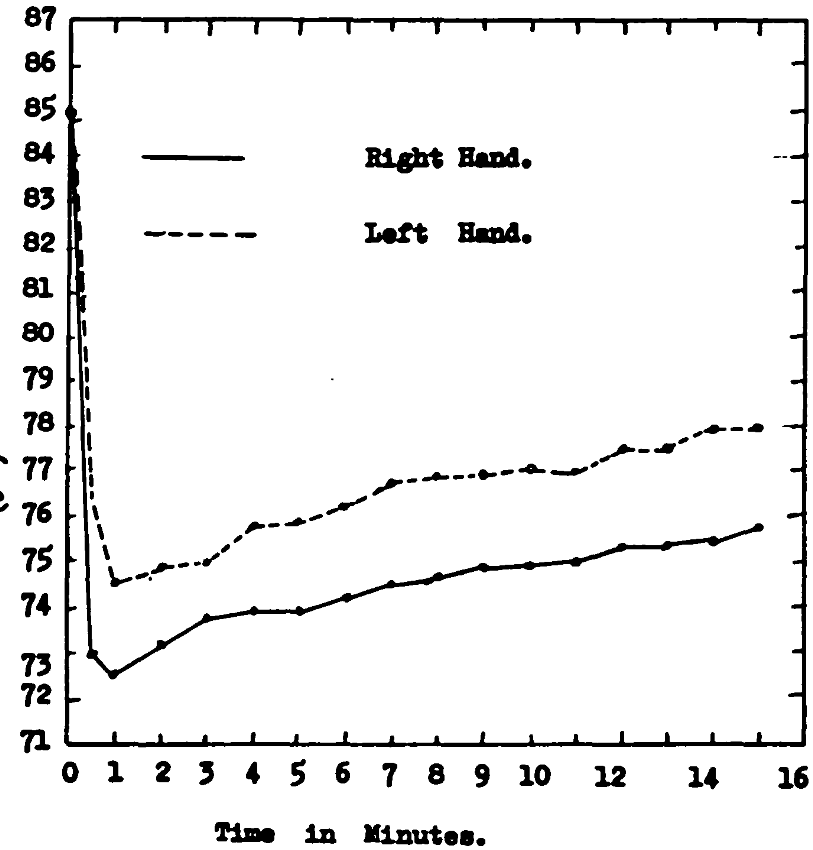
Hamilton (16) reported alcoholism might increase the trouble; however, Agate (25) and Telford et al. (20) noted that there is no correlation between the incidence of cases and use of alcohol or tobacco nor is sex a determining factor. In addition, Dart (18) described that women were much more susceptible than men to the effects of vibration. Clinical observation-by Miura et al (22) - noted that Raynaud's phenomenon could be produced by body cooling in a cool atmosphere, hand cooling in a cool box of 4° C or immersion of the hand into water of 4°C to 10° C. The authors repeatedly noted that cooling of the entire body in addition to local cooling of the effected hand helped to cause the vasospasm.

An experimental study by Kimura et al. (42) in 1962 carried out for the purpose of investigating the effect of mechanical vibration on the skin temperature of the hand demonstrated that the skin temperature of the back of the hand showed a decline during the application of vibration and rise after the cessation of application.

All vibrating tools tightly gripped will, by their very nature, cause an alteration of normal blood flow in the hand. This alteration may vary from intermittent peripheral flow to complete temporary cessation of flow. Vasospasm together with the mechanical interruption of flow adds to the hypoxia. This tissue hypoxia then in various ways, injures the vascular and nervous system so that from then on they are unusually sensitive to certain stimuli and particularly to cold (38). Allen et al. (43) in 1955 described almost invariably the precipitating cause of the vasospastic disturbance associated with the organic



Graph 3. Temperature of normal persons hands after exposure to cold.



Temperature of hands of patient after exposure to cold.

From Dart (18).

vascular disease in lowering of the external temperature.

Graph 3 test result from Dart (18), indicates the temperature of hands of a normal person and of a tested operator after exposure to cold. The drastic difference in temperature regain may be mainly because the constriction in a healthy person is slight while in the effected person the blood is almost entirely shut off (8).

3. <u>Relationship of Vibration Injuries and Vibration Frequencies</u>

Vibration can be adequately defined by stating its frequency and amplitude. It was obvious to the early investigators that some types of vibration were more harmful than others. They neglected the amplitudes of the vibrations and attempted to correlate the types of injuries with the vibration frequencies. Data on frequencies of vibration responsible for "dead fingers" were at best fragmentary until Hunter, McLaughlin and Perry (32) presented evidence indicating that "white fingers" occur most frequently as a result of exposure to vibration rates ranging from 2000 to 3000 cycles per minute. Leak (13) studied the effects of vibration on stonecutters and found by means of a tuning fork, that the principal vibrations were in the vicinity of 3000 to 3500 per minute, and that secondary vibrations up to 10000 per minute were present.

The weight of pneumatic vibrating tools varies from approximately 95 lbs (Rock Drills, Jack-Hammers and Road Rippers) down to approximately a pound in the small types (Pencil Grinders and Hammers). These tools often operate at 1200 to 3500 cpm and have an amplitude as high as 16.5 mm, so it is very hard to keep them in contact with the work surface and an inexperienced worker can not handle them at all. The fastest tools are used for the most part on the lightest jobs so that the grip and exertion of the operator are correspondingly light and less vibration is absorbed as a result. Gurdjian and Walker (21) noted that the vibrating tools struck between 3000 and 3400 times per minute, the most efficient rate according to the engineers.

Telford et al. (20) reported that with vibration frequencies less than 2000 per minute and working with soft metals, the risk of developing symptoms is probably insignificant. Hunt (17) thought hardness of the material was important. However, in the 112 patients examined by Dart (18) there was no relation between the hardness of the rock and the incidence of complaints.

Hamilton (16) described the possibility that holding the tool too tightly along with continued muscular contraction might aggravate conditions. Marshall (26), Agate and Druett (38) also felt that work necessitating a strong grip or the excessive grip used by some inexperienced workers should be considered as agents in the development of the disease. The strength of grip is determined by the weight, design, amplitude and frequency and the usual operating position of the tool, the experience of the operator, the type of work being done and the speed at which the operator is working.

Seyring (34) noted that work on soft metals was less conducive to trouble than on hard metal, but the soft metal workers were also exposed to vibrations of lower frequencies. Most reports have dealt with occupations in which the encountered vibration rates ranged from 800 to 3,500 per minute. Investigators on the other hand, found the "white finger" syndrome in the shoe manufacturing industry to result from exposure to vibration frequencies ranging from 17,000 to 36,000 cycles per minute.

The higher frequencies are less likely to be transmitted through the tissues, being more localised near the source. Agate and Druet (39) studied the transmission of vibration up the arm while a worker used a flexible drive, rotary tool at 2,900 c.p.m. There was a reduction in the greatest amplitude from 700 microns, and no vibration was detected at the shoulder. The transmission of the harmomic frequencies and amplitudes was checked and showed that the damping action of the tissues had more effect on the higher frequencies than on the lower.

Frequency, like the other factors involved in the production of vibration symptoms, cannot be isolated completely and examined as such. It is also necessary to consider the amplitude and the form of the vibration realizing that few would be in the form of a pure sine wave if depicted graphically. Agate and Druett (39) nearly all have complex wave forms which can be expressed conveniently in terms of a fundamental frequencies of large amplitude upon which are imposed various harmonics or progressively higher frequencies and smaller amplitudes. A tool may be said to have a speed of so many revolutions or strokes per minute which will in most cases, determine the fundamental frequency. It is at the fundamental frequency that the largest amplitude usually occurs. The vibration of the tool while idling differs from that while it is operating and constantly changing vibration-spectra are developed when the tool speed varies in response to being pressed against the job with varying pressure. It is obvious that the reason why some men develop the phenomenon and others do not, lies in differences of mechanical trauma and energy transmitted to the hand in different uses of the same tool on the same job. This indicates a need for more experience to improve the operator's technique.

It was not known until 1937 when Hunt (17) and McLaren (31) suggested that 2,300 c.p.m. was a critical frequency. Cummins (44) in 1940 quoted the same figure and stated that rates greater than this were also hazardous. Mills (28) in 1942 thought that tools at 3,000 strokes per minute were more likely to produce lesions than speeds of lower rates. Hunter, McLaughlin and Perry (32) in 1945 studied groups of men using tools of different speeds and published their observations in England. They believed that 2500 c.p.m. should be avoided. Even though the majority of pneumatic tools in use operate at speeds above 2000 c.p.m. Schweisheimer (45) in 1949 noted that of 300 operators, 75 had dead hand after using high speed tools. The Jack-hammer has an intense fundamental vibration but does not require the continuous grip required by the smaller tools. Thus, the most strenuous work which requires a persistantly strong grip and which is associated with the most intense vibration, may necessitate using tools operating at this most dangerious range. Hunter et al. (32) found that 53.5 per cent of riveters working at less than 2000 c.p.m. had white fingers compared with 74 per cent of a group working at 2,000 to 3,000 c.p.m. When the influence of exposure is considered, the significance of the frequency range is less marked.

Frequencies, less than 1000 c.p.m., associated with a large amplitude are more likely to produce bone and joint injury (30). Hunter et al. (32) also described the highest incidence of bone cysts, 64 per cent, in those using a light-weight, low frequency tool. Dart (18) and Peters (33) indicated that low frequency rather than light weight is more often associated with bone cysts. Agate and Druet (39) noted that high acceleration at a low frequency is more dangerous than an indentical acceleration and amplitude at a higher frequency.

Jepson (23) studied a group of operators who used a pneumatic tool that operates in the 2000 to 3000 cycles per minute range. He noted that frequency and severity of the vasomotor disturbance are variable and usually reach a maximum within a few years of their appearance. Almost all of them had attacks of Raynaud's phenomenon and in addition, joint pains, cramps and weakness of the hands. McKinnon and Kemp (46) examined a group of workers who used pneumatic tools operating at 1300 cycles per minute and reported that the operators complained of burning in the palm of the hand, and a grip so weak that they could not grasp the tool.

Agate and Druet (39) studied 10 operators of light-weight rotary pneumatic tools which operated at approximately 30,000 c.p.m.; their duration of exposure was about three years; however, none of them complained of symptoms.

Agate and Druet (39) carried out complete harmonic analysis of the vibrations present during operation of a number of different pneumatic tools. They thought the amplitude was as important as the frequency of the vibration, and the energy involved in a vibration depends on the product of the amplitude squared and the frequency squared; thus, a vibration of one micron at 5,000 c.p.s. is more damaging than one micron at 500 c.p.s. In order to simplify the comparison of the vibration spectra derived from different tools, they chose 1 mm, 100 microns, 10 microns, 1 micron and 0.1 micron as standard amplitudes and listed the highest frequency at which they were present. Their results are especially important since the spectra of amplitudes is at regular sequences rather than being random.

The extent of the vibration frequency spectrum which is of physiological significance can be divided into five fairly distinct bands (4).

1) 0.1 to 1 c/s. Oscillations in this band can provide motion sickness if intense and sustained.
2) 1 to 30 c/s. This range (and especially the band 1 to 15 c/s.) is of the greatest importance because it is the band in which the

major resonances occur in the human body. It is also a band in which vibration isolation is technically difficult.

3) 30 to 100 c/s. This is above the band in which major body resonances occur, and blurring of vision can be an important symptom of whole body vibration in this range. Intense local vibration at frequencies in the same region creates the special industrial hazard of disease associated with handheld mechine tools.

4) 100 to 20,000 c/s. Broadly speaking, the audio-frequency range, in which vibration is strongly attenuated at the surface of the human body.

5) Above 20,000 c/s. By definition, ultrosonic regime. Although ultrasonic vibrations transmitted by fluid or solid media can be biologically destructive, they are poorly propagated in air and are unlikely to be a serious hazard to man in most practical situations.

4) Discussion

Most of the studies reported in the literature missed coverage of what the writer feelsto be important information. A survey of the literature concerning injury from vibration shows there is no doubt cast now on the causal role of the vibration. But the exact mechanism of injury and the physiopathology involved are still undecided and further study will be needed before the question is definitely resolved.

The results of previous studies of vibration do not represent the complete answer to the determination of the danger of the vibration present in any machine. There are many other factors such as type of tool, kind of work being done, time of operation, strengh of grip required, method of holding, etc., to be considered before one tool can be claimed to be more dangerous than any other. It was hoped the results of the experiments of previous vibration studies would indicate the following information:

i) The amplitude and frequency of the vibrations;

ii) The effect of different factors in the design of tools;

iii) The number of workers exposedto vibration from hand-held tools;

iv) The number exposed and showing changes attributable to vibration;

v) The duration of the exposure;

vi) The relative merits of different methods of carrying out the same piece of engineering work,

vii) The manner in which the neurovascular and musculotendinous changes are produced.

It is interesting to compare the vibrations of piston-operated pneumatic tool table 6-7 which were obtained by Miura's group (22) in Japan, and by Agate and Druett (39) in England. It is not easy to find any similarity when their results of tests are compared. For example in amplitudes, although different makes of tools were used, there should not be so much difference between two amplitudes i.e., Agate and Druett found 14.2 mm. for 13.75 lbs. chipping hammer and the Miuras group obtained 0.46-1.18 mm. amplitude for 13.3 lbs. chipping hammer. They did not mention the experimental conditions by which their figures were recorded, nor how a 93 lb rock drill can be so operated or constructed as to have an amplitude of only 0.264 mm.

Table 6. The vibration of piston-operated pneumatic tools

Tools	ASD 25 Jack-Ham	stopper	Jumbo Ty 145	Chipping Ham large	Chipping Ham small	Mech. Peak	Scaling Hammer
Weight	43	93	?	13.3	11	?	4.4
Nominal freq. of beat p.m.	2,100	?	2,050	1,750	?	?	1,750?
Recorder freq. of beat p.m.	2,040	1,860	2,220 2,140	1,320 1,500	1,740	1,080	4,200
Amplitude mm.	0.752	0,264	0.46 1.46	0.46 1.18	0.40	0.42	0.172

from Miura et al. (22)

A great number of rotary tools were examined by Agate and Druett and none of them had an amplitude greater than 1 mm; however, huge amplitudes (over 57 mm) were measured with the piston operated tools. However Agate and Druett used a crystal pick-up and an acoustic spectrometer which were high-speed wave-form anlyzers. These instruments enabled them to calculate the frequency and amplitude of the various harmonics in addition to the fundamental frequency and amplitude.

Table. 7 Vibration From Piston-Operated Pneumatic Tools

Tools	Road Ripper	Chipping Hammers Large	Chipping Hammers Medium	Chipping Hammers Small	Rock Drill	Coal Peak	Scaling Hammer
Weight	75	13.75	12.75	7.25	30	29.5	4.5
Nominal tool speed cpm	1,050	1,700	3,500	6,000	2,300	1,350	4,500
Fundamental Freq. cps	15.5	Appr. 28	Appr. 40	Appr. 64	Appr. 40	?	Appr. 64
Fundamental Amplitude mm	57.15	?	16.6	17.4	0.88	?	0.46
1st Harmonic freq.cps	31	50	80	125	80	40	125
1st Harmonic Amplitude mm	3.55	14.2	4.15	2.95	0.11	3.0	0.11

Highest frequency (cps) at which the respective standard amplitudes are present

1.0mm	40	125	100	160	-	40	-
100 microns	80	360	320	400	80	80	80
10 microns	200	800	640	1250	400	200	360
1.0 microns	500	6400	2500	5700	2500	500	800
0.1 micron	1250	12500	10000	16000	4000	1250	2500

from Agate and Druett (39)

IV. EXPERIMENTAL SET-UP

1. Purpose

The aims of this experimental programme were the measurement and calculation of displacement, velocity and acceleration through all frequencies at one-third-octave band intervals. The measurements of vibrations present in a rock drill were taken under different operating conditions.

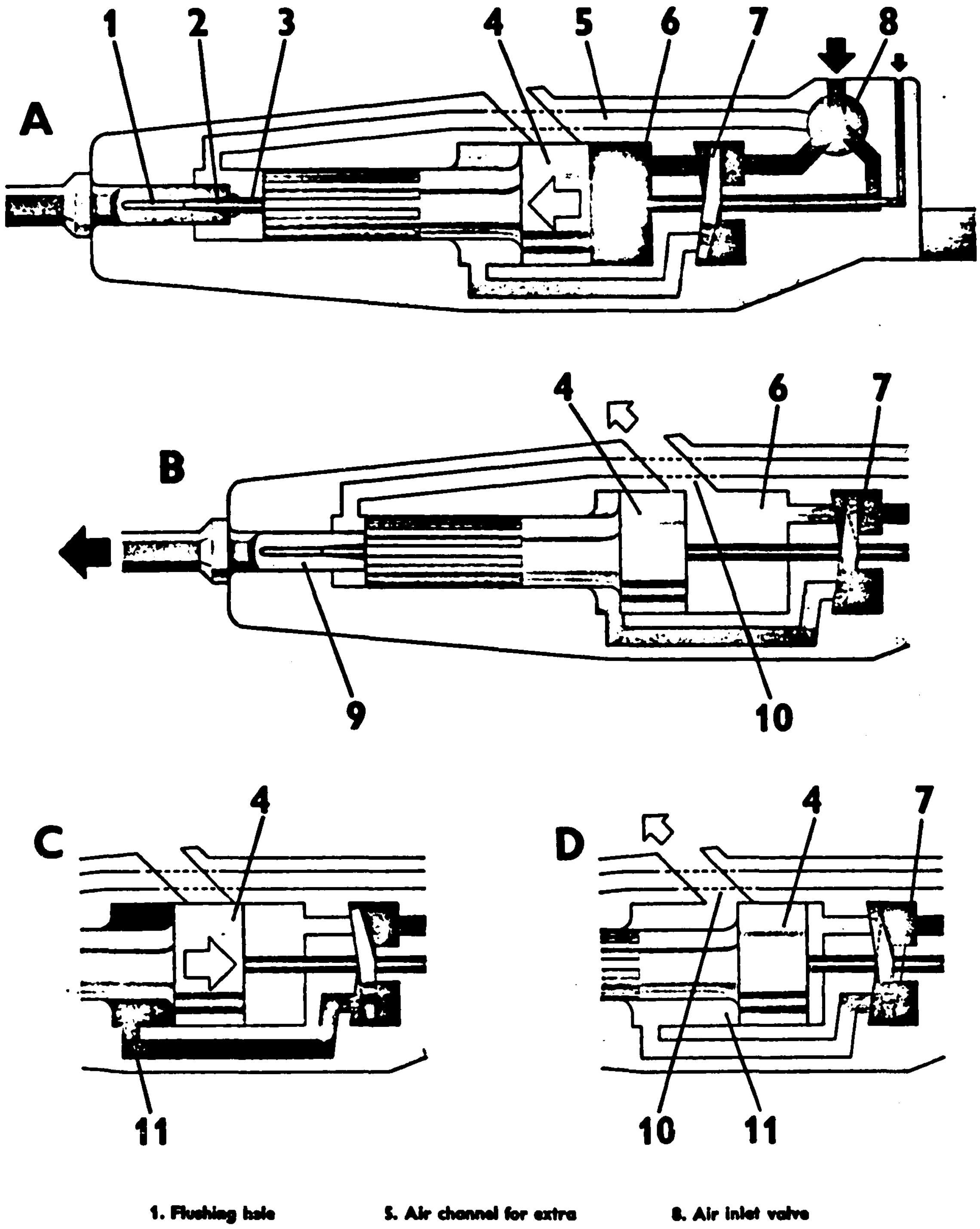
2. Pneumatic Rock Drills

The compressed air rock drill in common use is of the hammer type, a piston strikes the end of the drill steel either directly or indirectly. The basic impact mechanism is shown in figure 4 (A,B,C and D)

The piston is moved forward to strike the end of the drill steel by the introduction of compressed air into the near cylinder chamber 6 in figure 4. After a certain distance is travelled by the piston the compressed air supply is re-routed to the front cylinder chamber 11 in figure 4. and the piston is forced

ROCK DRILL

with rocker valve; water flushing or air blowing; extra blowing



1. Flushing hole
2. Water or air tube
3. Air tube
4. Piston
5. Air channel for extra blowing
6. Cylinder chamber, rear
7. Rocker valve
8. Air inlet valve
9. Drill steel
10. Air outlet
11. Cylinder chamber, front

Fig. 4. Details of Rock Drill(from Ref. Atlas-Copco; Chart No. APS 401)

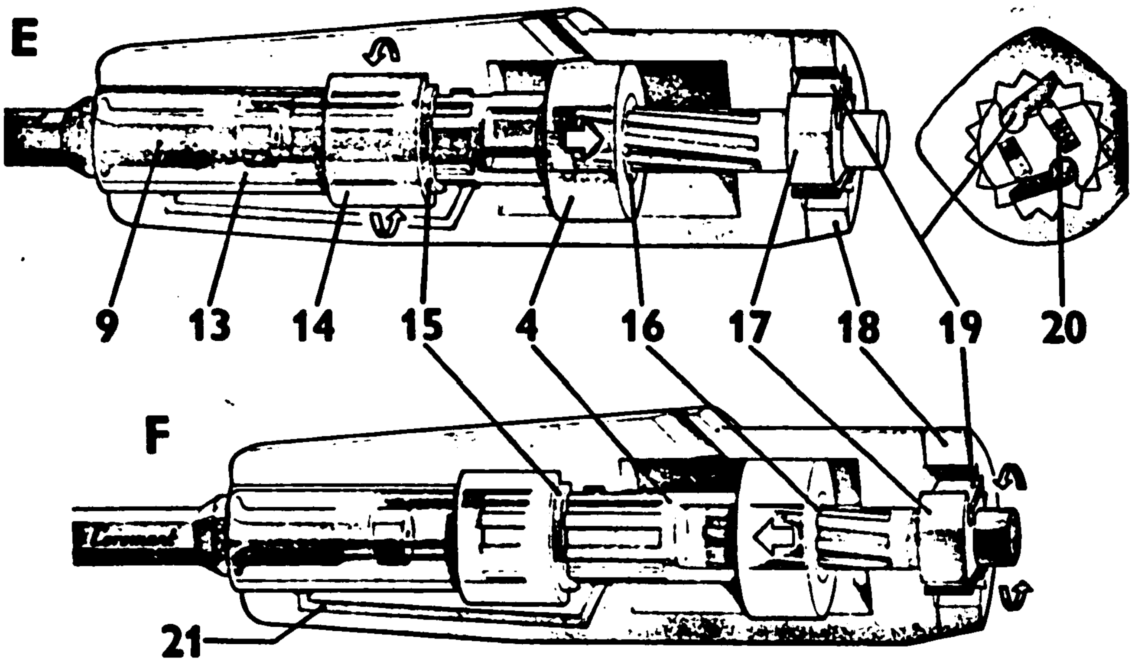
backwards away from the drill steel. When the piston has travelled backwards a certain distance the compressed air supply is again re-routed to the near cylinder chamber and the process is repeated. The number of blows delivered to the drill steel varies with the type and size of drill.

For better penetration the rotation of the drill steel is necessary. This rotation has been introduced into the drill itself by use of a rifle bar (figure 5 E and F) or rather wheel (figure 5 G and H).

The principle of the rotation of rifle bar depends on spiral grooves. The piston with the rifle bar can be rotated by its own cycle movement and this rotation in turn is transmitted to the drill steel. Thus as the piston moves backwards it is turned anti-clockwise by its running in the spiral grooves of the rifle bar, the rifle bar being unable to rotate in the clockwise direction since its spring loaded pawls engage the teeth of a ratchet box to prevent rotation in that direction. As the piston moves forward the rifle bar is rotated in an anticlockwise direction, since it is free to move in this direction and it is easier for it to turn than the piston. Thus with every cycle of the

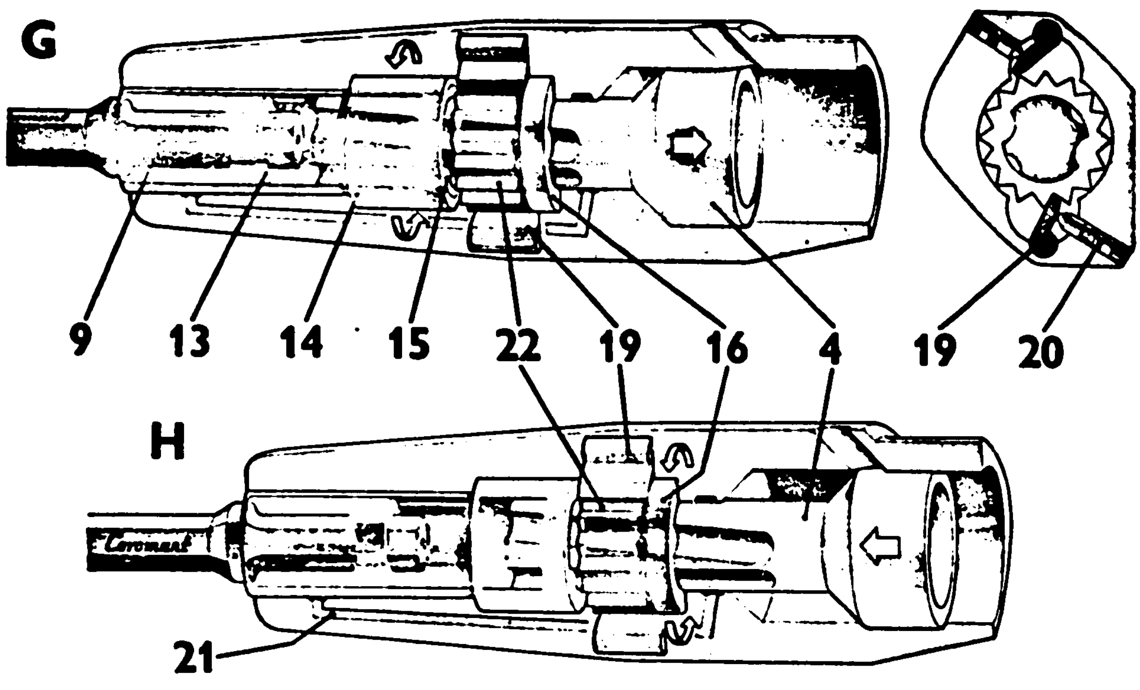
ROCK DRILL

RIFLE BAR ROTATION



4. Piston
9. Drill steel
13. Chuck bushing
14. Rotation chuck
15. Chuck nut
16. Rifle nut
17. Rifle bar
18. Ratchet box
19. Pawl
20. Pawl spring
21. Lubrication channel

RATCHET WHEEL ROTATION



4. Piston
9. Drill steel
13. Chuck bushing
14. Rotation chuck
15. Chuck nut
16. Rifle nut
19. Pawl
20. Pawl spring
21. Lubrication channel
22. Ratchet wheel

Fig. 5. Details of Rock Drill (from Ref. Atlas-Copco; Chart No. APS 403)

piston the drill steel is rotated.

The principle of the ratchet wheel rotation is that spiral grooves are made in the piston and a ratchet wheel is placed between the piston and the end of the drill steel. As the piston moves backwards it, and thus the drill steel, is rotated in an anti-clockwise direction. As the piston moves forward the ratchet wheel turns in an anti-clockwise direction. Thus with every cycle of the piston the drill steel is rotated.

In most rock drills a system for flushing the drill hole is incorporated, using either water, air or a combination of both. The drill steel used has a hole down its centre for this purpose.

The drill is usually lubricated by the introducion of the oil in the compressed air supply. In this way the oil is distributed in the form of a mist to all parts of the machine.

3. Type of Drill Used

A widely used compressed-air rock drill was chosen for these experiments.

Rock Drill Data:

Piston diameter: 2 3/4 in. (70 mm.)

Length of strock: 2 3/4 in. (70 mm.).

Impacts per minute: 2,050 (85 psig "6 kg/cm^2")

Weight : 65.5 lbs. (29.7 Kg.)

Total length : 30 1/4 in. (770 mm.)

Air Consumption : 159 cfm. (4.5 m^3/min.)

Hose diameters : Air 1 in., Water 1/2 in.

Drillsteel diameter : 1 5/8 in.

Type of drillsteel : chisel

4. Determination of Most Significant Vibration Direction

To achieve the desired objectives the most significant vibration direction was important. Considering the ranges of pressure and frequency at which measurements were to be made, the author wished to determine whether one mode of vibration would be sufficient to describe drill motion, in order to reduce the total number of readings. Consequently, measurements were made (with the drill suspended) in three directions, in six different places, using the Askania Hand vibrograph. The figure 6 shows measurement of direction. Measurements made parallel to the long axis of the machine and at right angles to the long axis, in the horizontal and

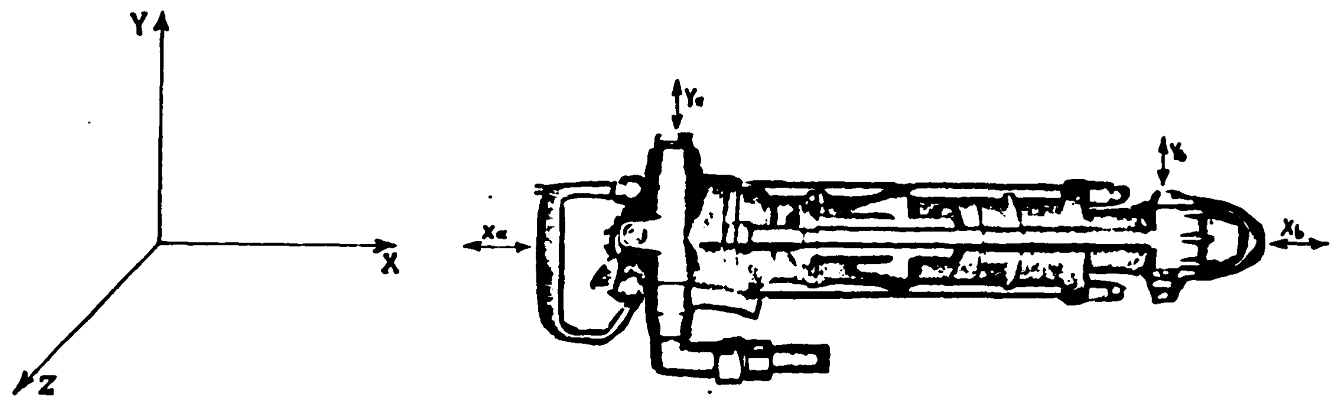


Fig. 6. Points on the rock drill where vibration measurements were taken to determine the most significant vibration direction.

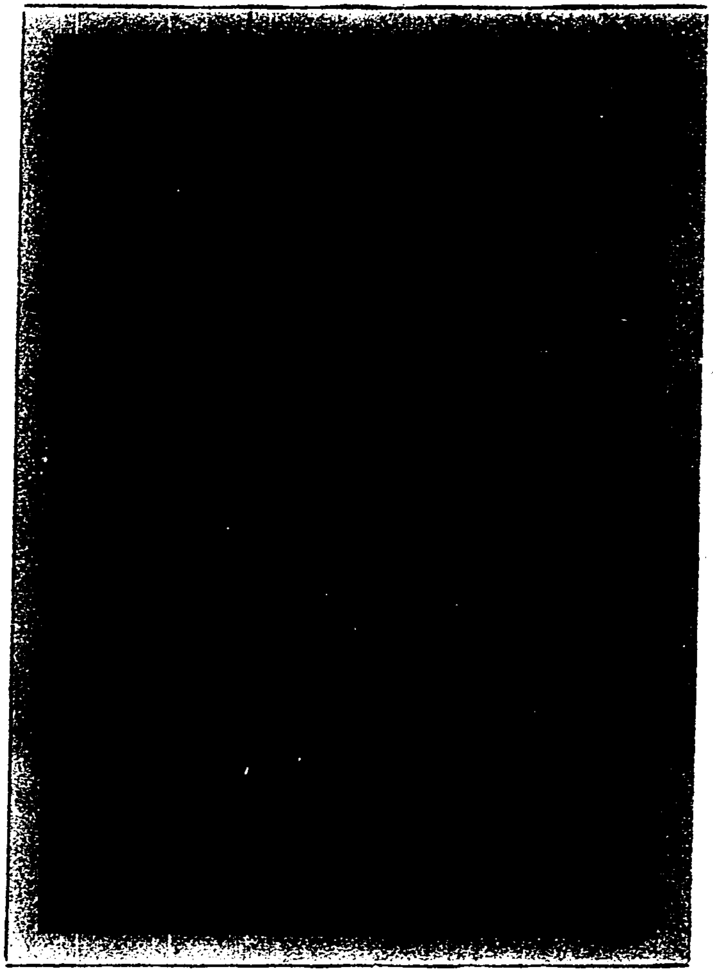
vertical directions, showed that the vibrations parallel to the long axis were of the greatest magnitude by far. Results are shown in Appendix A. Since these larger vibrations are the most likely to cause tissue damage to operators, the longitudinal mode was considered for all further measurements.

5. Tests and Operating Conditions of Rock Drill

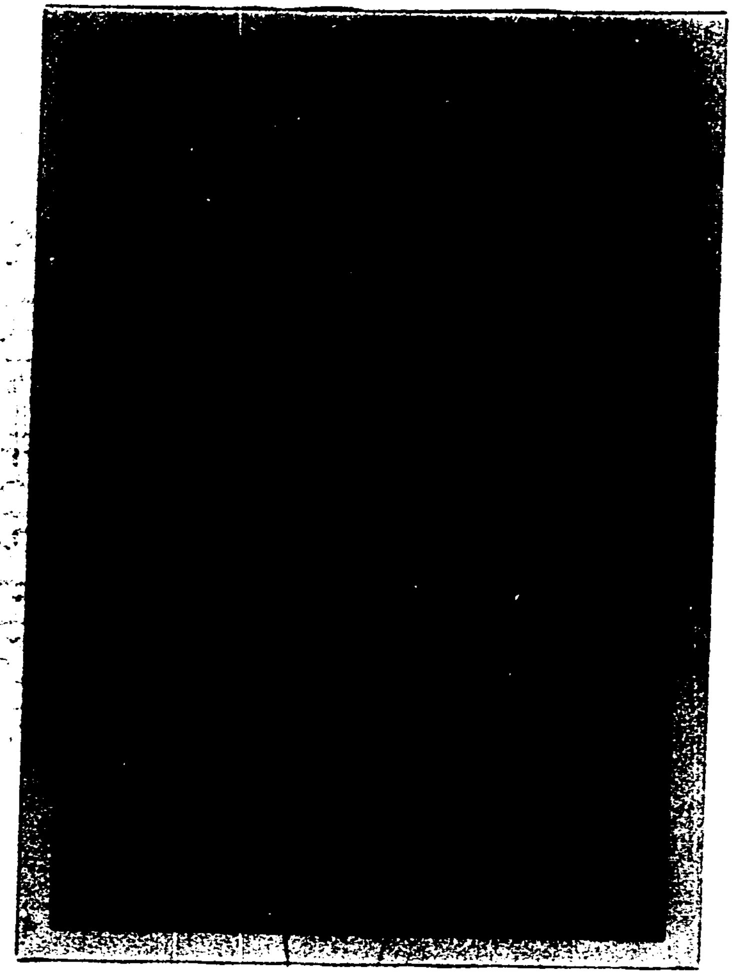
To get the best result of vibration measurement in a rock drill, three different operating conditions were chosen: i) Operating at No-load ii) Drilling Horizontally and iii) Drilling down Vertically.

i) Operating at No-load

The drill was freely suspended from two chains (as shown in the attached photograph 1a and 1b) and the measurements of vibration characteristics were taken with a mechanical instrument (Askania hand vibrograph) and electrical instruments, which are described later in this chapter. Measurements were taken at least twice. The average of the results was taken as the correct value for compressed air pressures of 60,70,80,90, 100 and 110 psig. Actual figures recorded for amplitudes velocities and accelerations are listed in Appendix A.



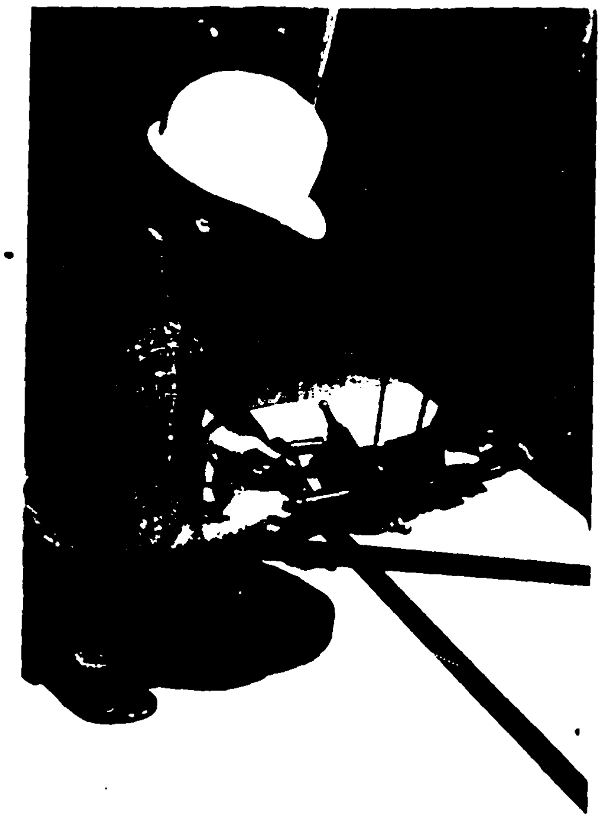
Photograph 1a :



Photograph 1b :

Measuring Vibrations with the Askania Hand Vibrograph under Operating at no-load Conditions.

Photograph 1a :



Photograph 1b :

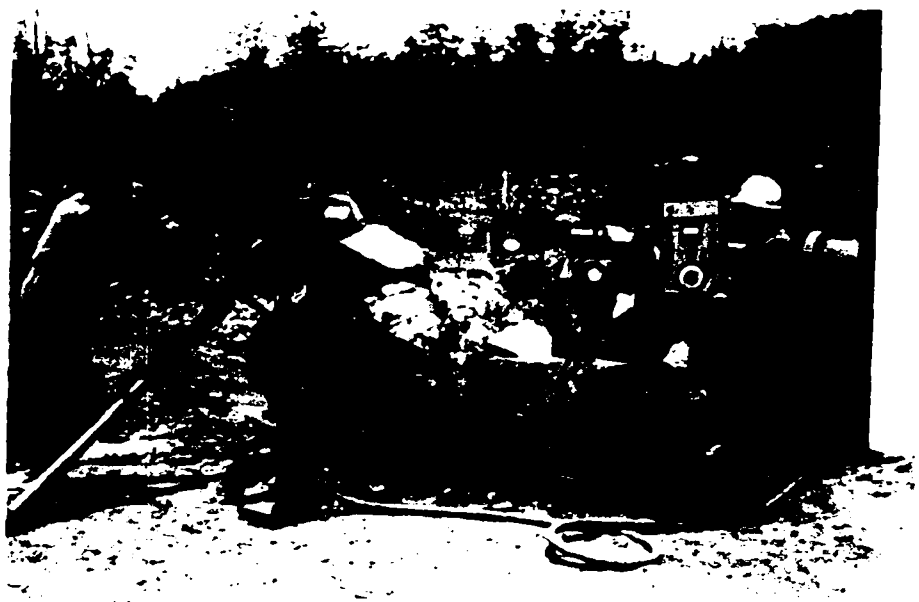
Measuring Vibrations with the Askania Hand Vibrograph under Operating at no-load Conditions.

ii) Drilling Horizontally

The drill was operated under normal conditions in a horizontal drilling with a pneumatic air-leg. The rock specimen was of igneous origin. The penetration rate was also determined. Graph 5 shows the relationship between penetration rate and air pressures for horizontal drilling conditions, and graph 6 shows the relationship between penetration rate and air pressures for vertical down drilling conditions. The measurements of vibration characteristics were carried out at 50, 60, 70,80,90 and 100 psig air pressures with electrical instruments. Each measurement was taken twice; the average of the two results was taken as the correct value measuring the vibration under horizontal drilling conditions.

iii) Drilling down Vertically

The drill was hand-held and operated under normal conditions while drilling position vertically downward into rock. This is the most common method with hand-held rock drills in mining operations. Photograph 3 shows the arrangement of instruments for measuring the vibration under vertical down drilling conditions. The



Photograph 2:

Drilling and Recording under Horizontal Drilling Conditions.

Photograph 3:

Drilling and Recording under Vertical Down drilling Conditions.

assistant operating the drill was a student who did not have any drilling experience. (He could not help the second day, because he had pain in his wrists, shoulders and sore muscles). All measurements were carried out twice at 50,60,70,80,90 and 100 psig air pressures, using electrical instruments only, because of the danger of damaging the mechanical recording instrument. The fundamental amplitude was too high, especially with high pressures. It was not possible to measure the amplitude with mechanical instrument at 50 psig air pressure or higher.

In order to carry out measurements under these conditions each measurement was taken twice and then the average was taken to get the figures recorded in Appendix A.

6. Type of Rock Used

The rocks used for drilling were all huge igneous rock boulders. They were selected from glacial gravel around the Institute for Mineral Industry Research, at Mont St. Hilaire.

7. Instrumentation

In order to carry out reliable measurements the

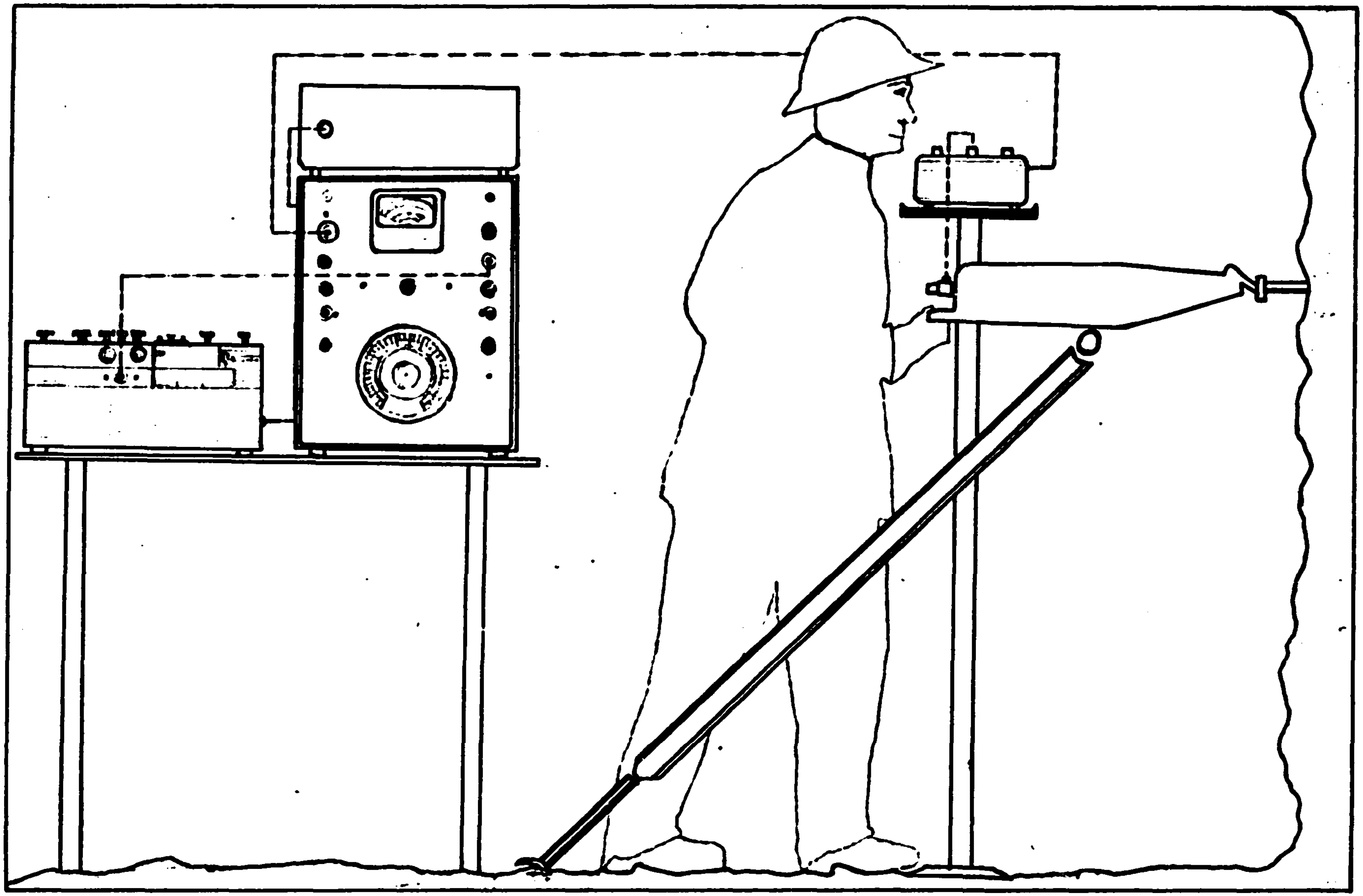


Fig. 7. The Sketch of Vibration Testing Apparatus set-up.

best equipment available was used.

i) Electrical Devices

These instruments are designed to measure vibration and noise parameters.

It was not easy to carry out accurate measurements under the difficult conditions created by the drilling operations. For this reason measurements were taken at least twice and the averages determined. Figure 7 shows the electrical apparatus as set-up for testing. The instruments are all BRUEL & KJAER except the oscillascope which is a Hewlett Packard model.

The basic electrical measuring system consisted of the following :

(a) Accelerometer, type 4333.

This is a transducer which converts the mechanical vibration into a voltage proportional to the acceleration of the test object. This voltage is fed to a preamplifier.

b) Preamplifier, type 1606.

It amplifies the input voltage and integrates the signal to velocity or displacement as required.

c) Audio Frequency Spectrometer, type 2112.

It incorporates 33 one third and 11 full octave filters and allows manual or automatic frequency

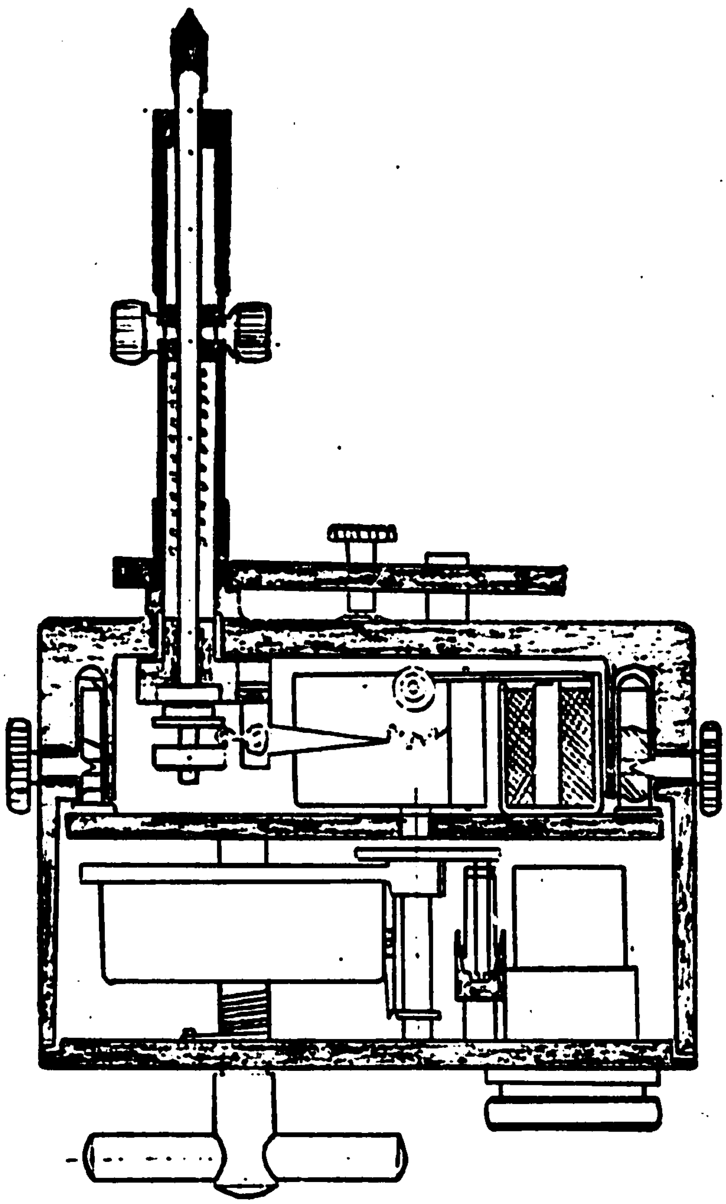


Fig. 8. Sectional Diagram of the Askania Hand Vibrograph.

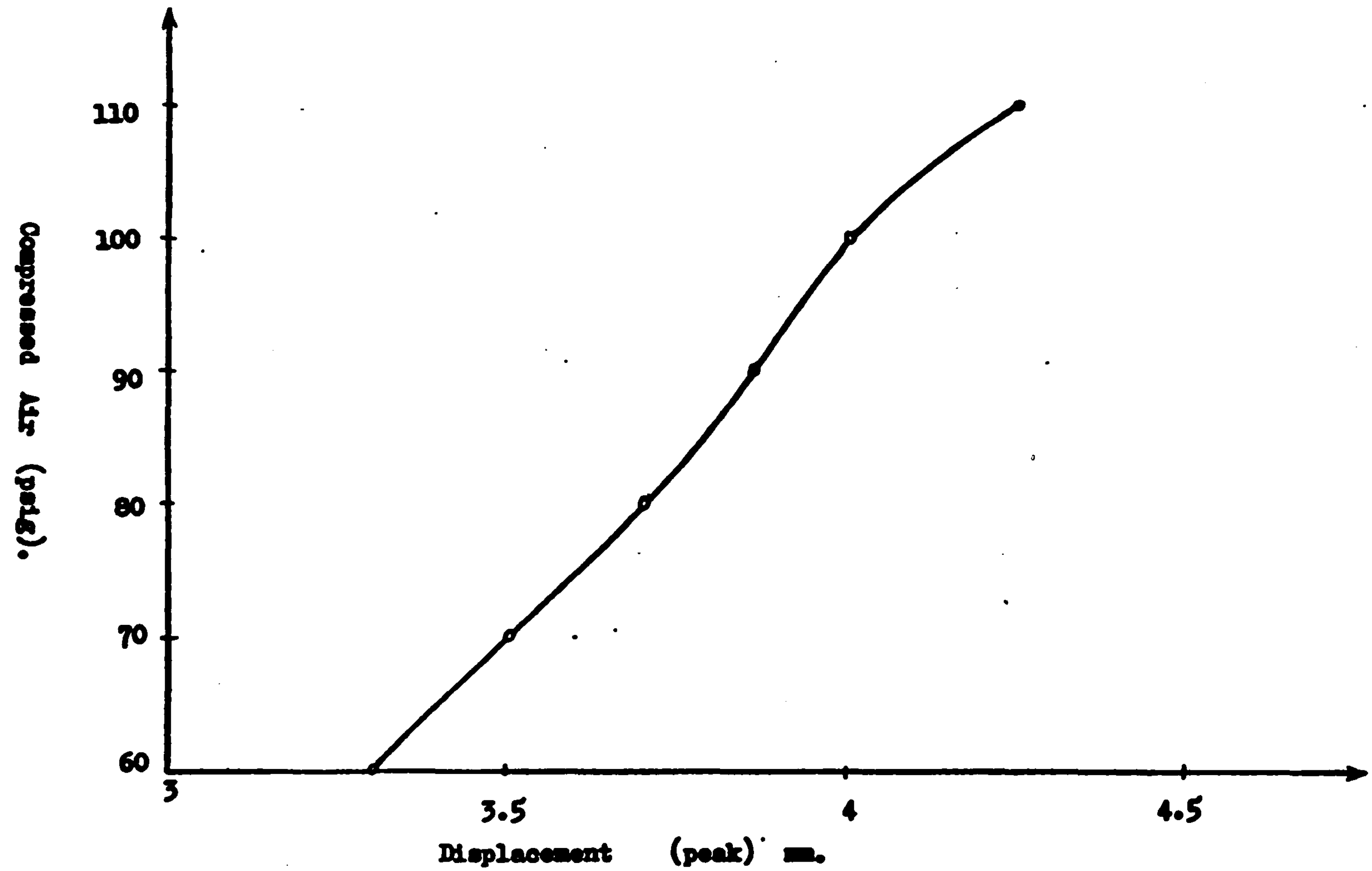
analysis to be performed.

d) 132 Dual Beam Oscilloscope

This was used to verify the calibration of the measurement system and as an aid to ensure that no distortion of the input signal existed.

i) Mechanical Device, (Askania Hand Vibrograph).

This instrument depicted in figure 8 is designed for low frequency vibration measurements and is suitable for use from 5 cps upto 250 cps. It is very compact, light weight and easy to operate. Measurement of displacements and frequencies are possible without special calibration. In carrying out the measurement, the stylus position on the graph is proportional to the mechanical amplitude of vibration throughout the whole frequency range. Consequently, we can measure resonant and critical frequencies of mechanical systems, which are difficult to calculate. A limitation of this type of recorder is that the natural frequency of the holding device (operator or clamp) must be below 5 cps. Graph 4 shows the relationship between displacement and air pressures, using the Askania Hand Vibrograph.



Graph 4. Graph of First Harmonic Displacement vs. Air Pressure at no Load Vibration in Rock Drill.
(Determined using the Askania Hand Vibrograph).

V. RESULTS

Compressed air pressures of 50 to 110 psig with intervals of 10 psi were used in the experiments. Graphs (7-15) show the results for air pressures of 60, 80 and 100 psig only. This was done for reasons of simplicity and clarity. However, the pressures of 50,70,90 and 110 psig were considered in analyzing the final results.

The experimental results were of such magnitudes it was not possible to find log-log graph papers with sufficient cycles to plot the various graphs. In preparing this thesis, home-made graphs were patched together to assist in making evaluations, but these augmented graphs are not included in this final write-up.

1. Frequency vs. Displacement

From the graphs (7,8,9) it is evident that for each drilling situation (i. Operating at no-load, ii. Drilling horizontally and iii. Drilling vertically) the amplitude or displacement varies inversely as the frequency. Hence, as the frequency of vibration increases, the amplitude of displacement decreases. It is also evident from these graphs that for each of the air pressures used, the higher air pressures gave lower amplitudes for the same frequency. This phenomenon is most evident in the case of horizontal, air-leg drilling. The least variations occur for the suspended, at no-load situation.

In all three methods of drill operation it can be said that a linear relationship exists between the logarithm of the frequency and the logarithm of the amplitude. Variations from these features will be discussed later.

2. <u>Frequency vs. Velocity</u>

From the graphs (10,11,12) it is clear that for the three operating conditions of the rock drill, the velocity changes are contrary to the increase in the frequency of vibration. These graphs indicate that for each operating condition of the rock drill (keeping the frequency constant) the velocities decrease with the increasing compressed air pressures. This is most clear in the case of vertical and horizontal drilling.

For the three operating conditions of the drill there are linear relationships between the logarthm of the frequency and the logarithm of the velocity.

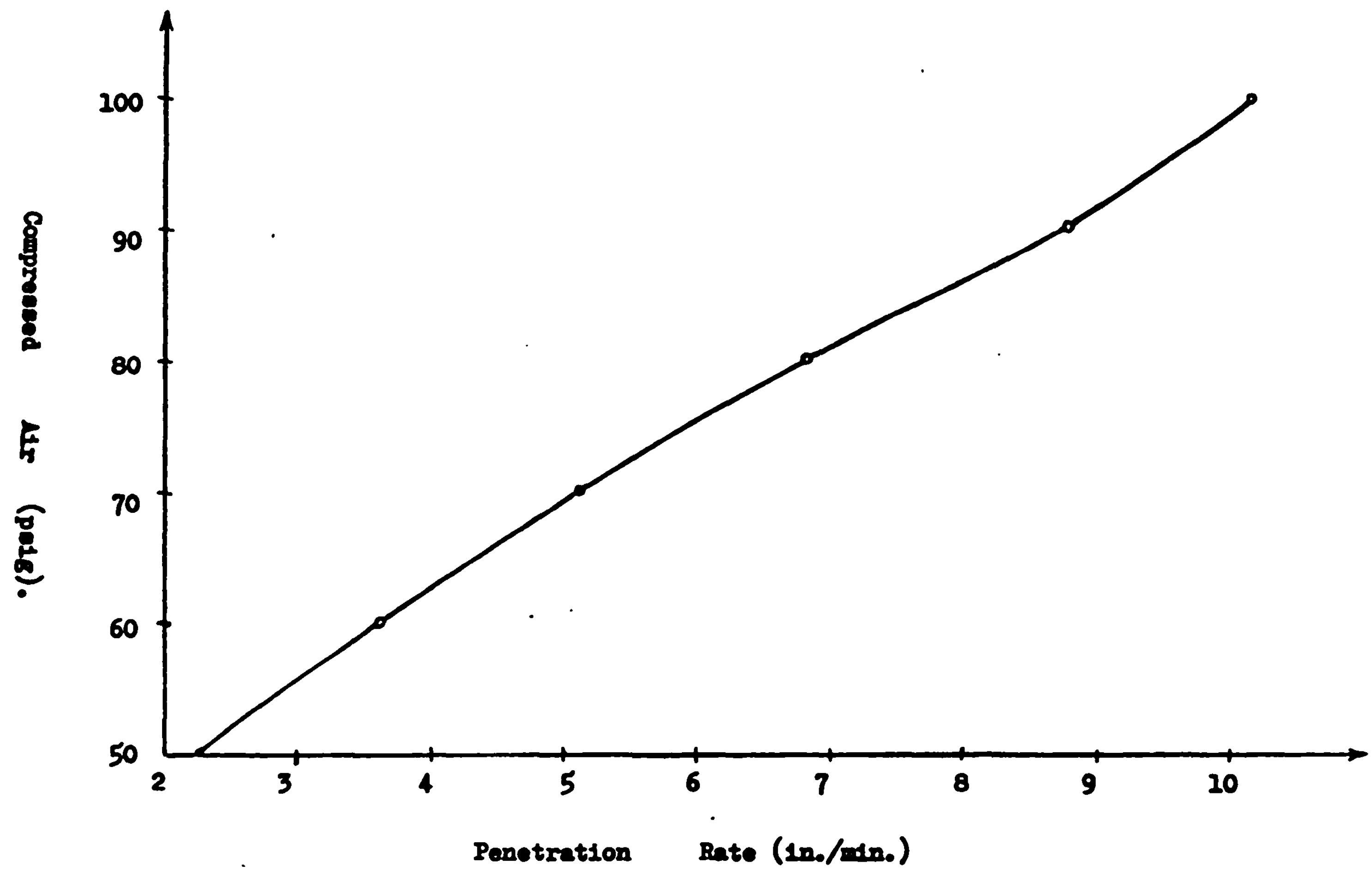
3. Frequency vs. Acceleration

The interpretation of the graphs (13,14,15) for each of the operating conditions is more difficult in this case. In considering the case of the rock drill being suspended, the relationship between acceleration and frequency is roughly a direct ratio, with some variations that will be discussed later. It can be noted from these graphs that no definite relationship exists between the accelerations incurred under the different air pressures. However, the trend indicates that for frequencies larger than 10,000, higher pressures result in decreases in acceleration were for frequencies lower than 10,000, there are increases in acceleration as the frequencies are increased. The lowest pressure used 50 psig gave the least accelerations, while the 80 psig pressure resulted in the highest accelerations, except at frequencies higher than 2000 cps.

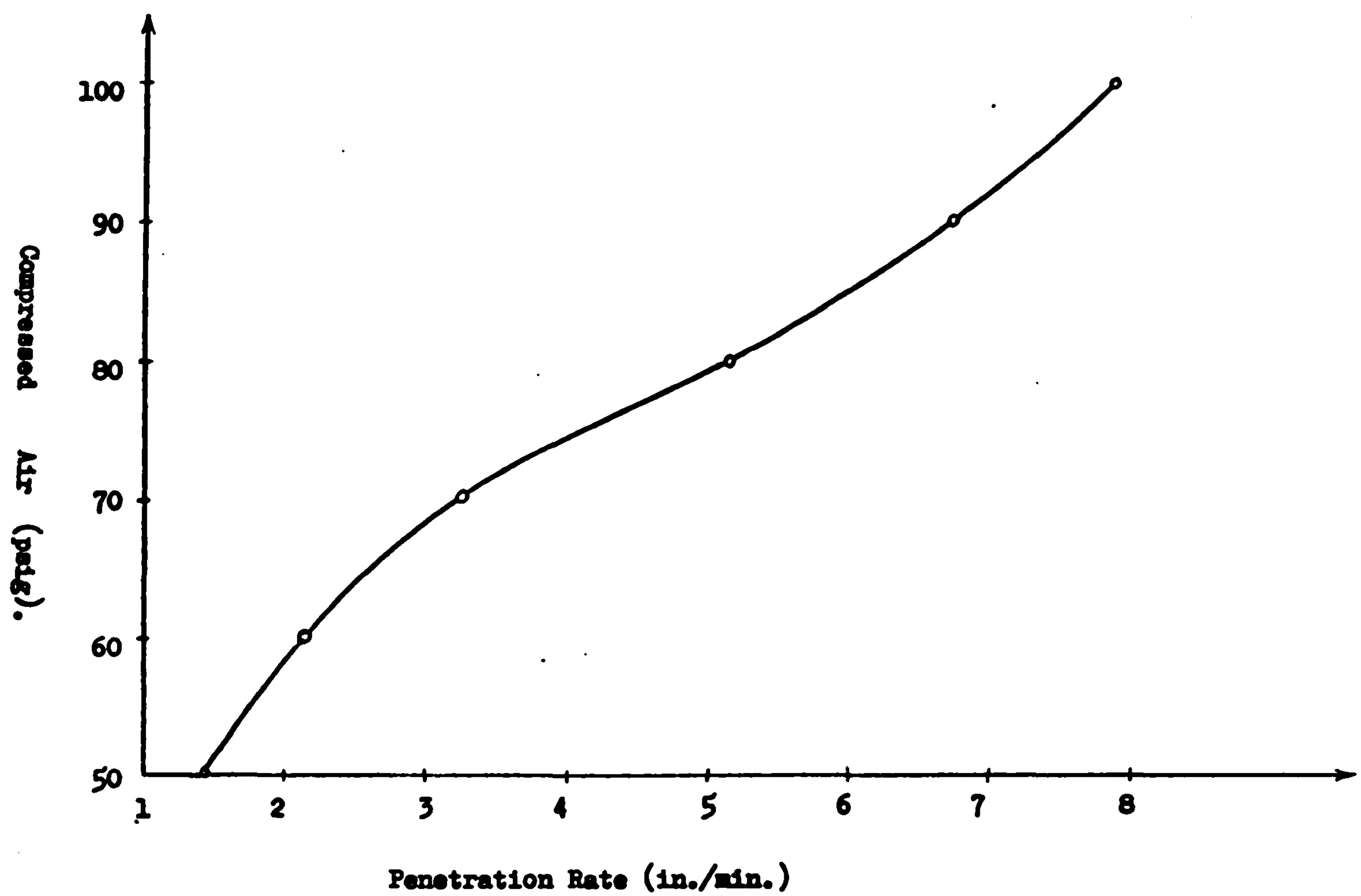
Finally, in considering the horizontal operating case, shown in graph number 14 there appears to be a maxima and a minima in accelerations, with no linearity evident. For frequencies between 100 and 1000 cps, the minimum values for acceleration occur, whereas the maximum values occur around the 800 cps frequency. It was noted in all cases that at frequencies, greater than 8,000 cps, acceleration values declined. It is interesting to note that a pressure of 70 psig gives the minimum values at the minimal node, closely followed by the 60 psig pressure, whereas the maximum values are given at the maximum node by the 60 psig pressure, with the 70 psig pressure giving values slightly less.

Penetration results

From Graphs (5 and 6) it can be seen that the higher the air pressure, the greater the rate of penetration. In conjunction with graph (4), it is logical that when the air pressure is high, it produces a higher amplitude of oscillation for which the rate of penetration would likewise be high.



Graph 5. Graph of Penetration Rate vs. Air Pressure.
(Horizontally Drilling).



Graph 6. Graph of Penetration Rate vs. Air Pressure.
(Vertically down Drilling).

VI. DISCUSSION OF RESULTS

Attempts to operate the drill under conditions simulating these found in mines lead to non-systematic errors in the readings taken. These errors could be eliminated by taking large numbers of readings. The true arithmetic mean of these results could be accepted with sufficient reliability. However, due to adverse weather conditions and a lack of suitable rock specimens, it was not possible to carry out the desirable number of experiments. Therefore, this environmental error was not eliminated completely. However, as indicated in Appendix B for the no-load situation, an extensive statistical analysis was made of the data for the vibrational displacements, velocities and accelerations for each of the air pressures used for drilling. The conclusions of the statistical analysis indicate that the errors are small, so that the mean values are reasonable and valid. Statistical analysis were not made for the vertical and horizontal drilling situations because adequate data could not be obtained.

Explanation of Statistical Analysis

Operating at no-load condition provided the only opportunity for taking a sufficient number of readings to derive a mean, standard deviation and standard error. However, for drilling horizontally and vertically, there was not an opportunity to take more than two readings of amplitude, velocity and acceleration, because the driller was not experienced and strong enough and the rocks being drilled was not in-situ. Generally, however, for the statistical analysis done, the standard error of the mean ranged from about 5-15 % of the mean.

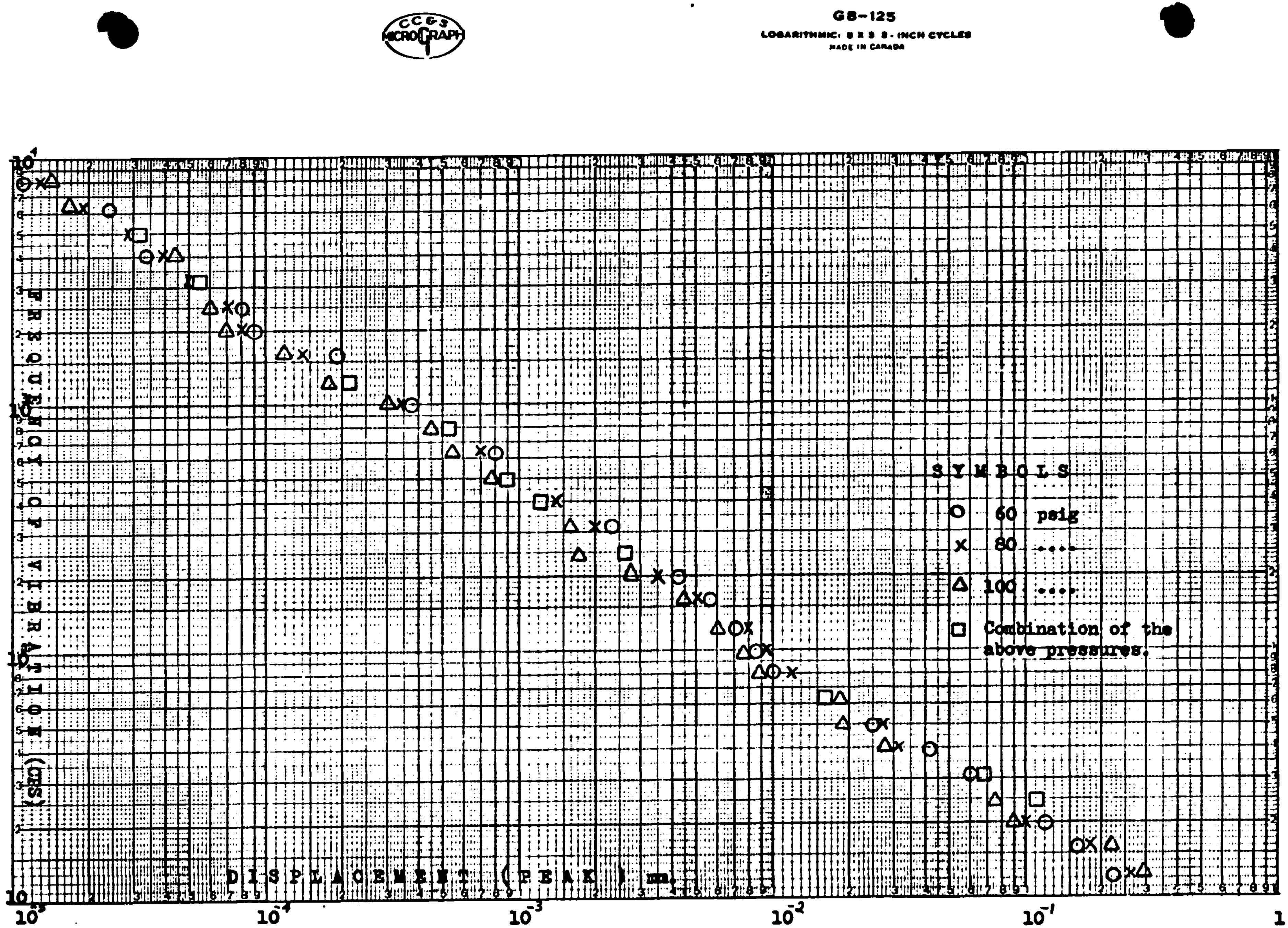
Because the statistical analysis data are too long, they are not being included in the thesis. However, one page containing some of these data is enclosed in Appendix B for the purpose of illustration.

1. Discussion of Displacement Graphs (Graphs 7,8,9)

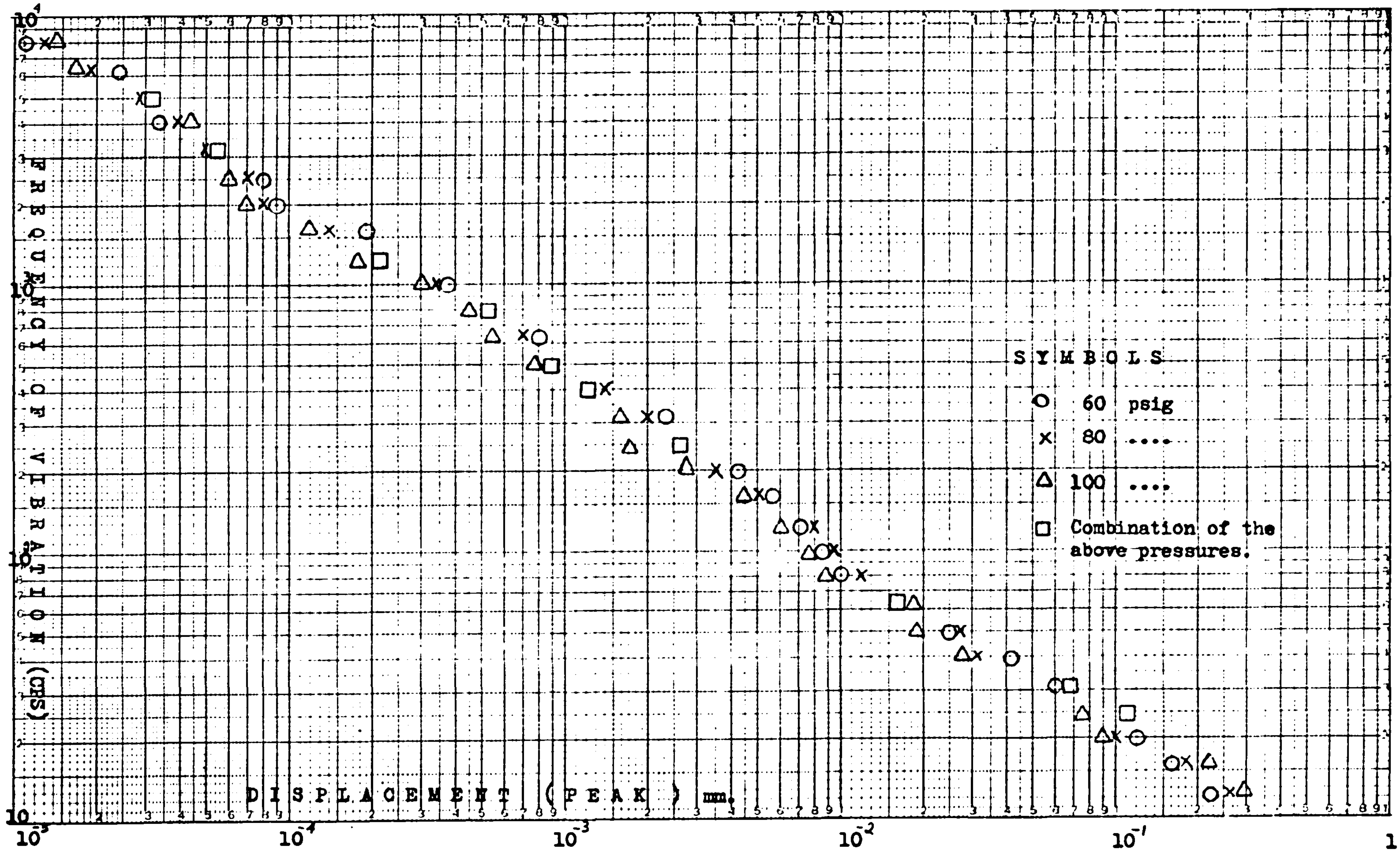
Other than the obvious relationship, log frequency $\propto$ 1/log amplitude it was noted that at high frequencies, amplitudes of the vibrations remained constant. It appears that the frequency of vibration had exceeded the response capacity of the rock drill as established by its natural frequency and related harmonics; resulting in a small, nearly zero amplitude of oscillation.

i) Operating at No-load

It was noted on Graph (4) that as compressed air pressures were increased, while operating at a resonant frequency, the highest pressure produced the greatest amplitude of vibration. Conversely, the lowest air pressure gave the lowest displacement. From Graph (7), a different technique was used to breakdown the complex frequencies comprising the fundamental frequency into the separate vibrations as indicated. In this situation, it was noted that high air pressures generally gave low displacements vs. higher displacements for low air pressures. It is interesting to learn that the aggregation of frequencies has the net effect of reversing these displacements. From the technical literature, the most dangerous vibrations are the 34-50 cps range. On Graph (7), for this frequency range, the amplitude of vibrations varied from 0.017 mm for 110 psig to 0.060 mm for 60 psig. As would be expected for this drilling case with little pressure exerted on the drilling bit the



Graph 7: Relationship between displacement and frequency of vibration under operating at no-load conditions.



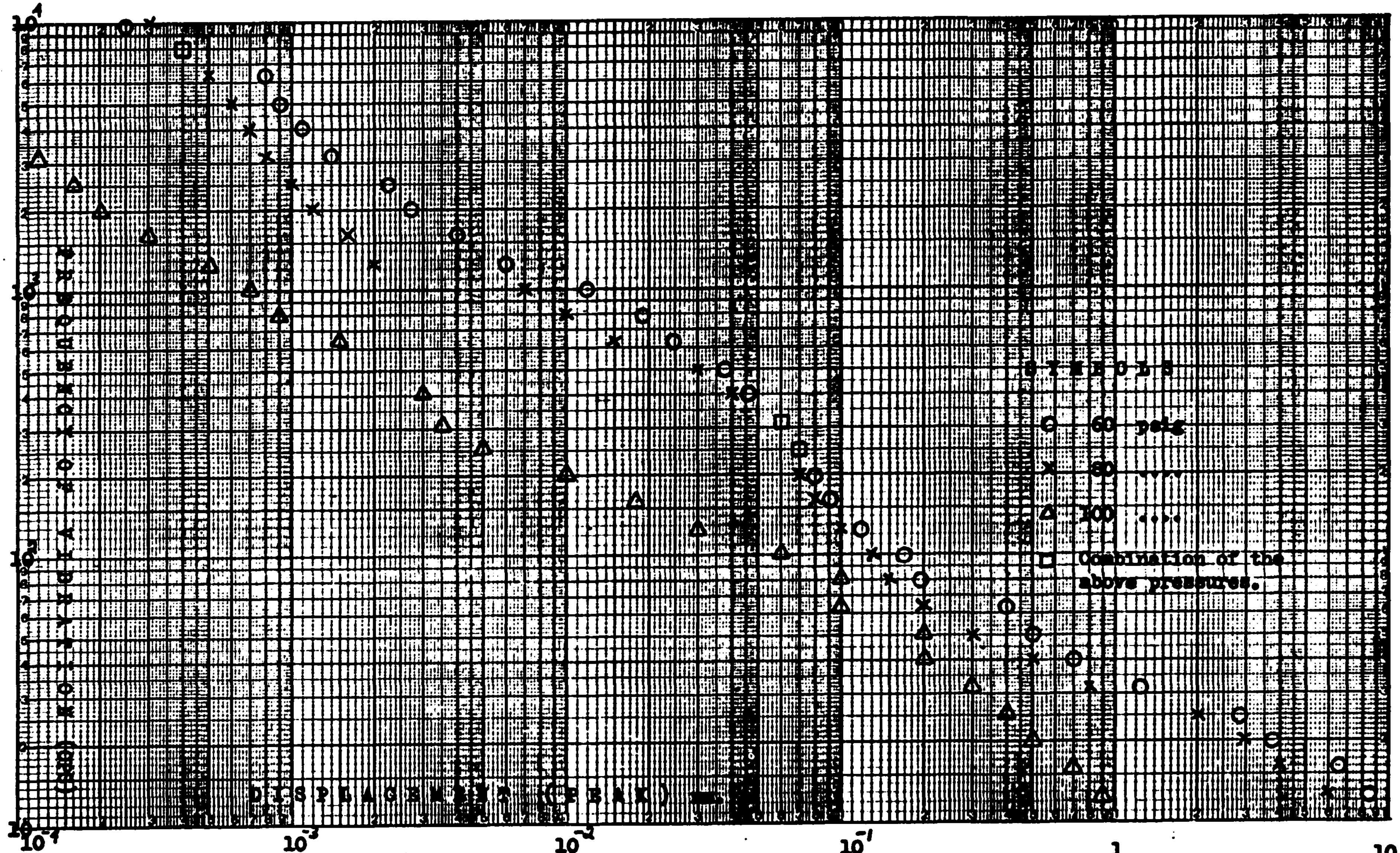
Graph 7: Relationship between displacement and frequency of vibration under operating at no-load conditions.

amplitude of the vibrations is very small.

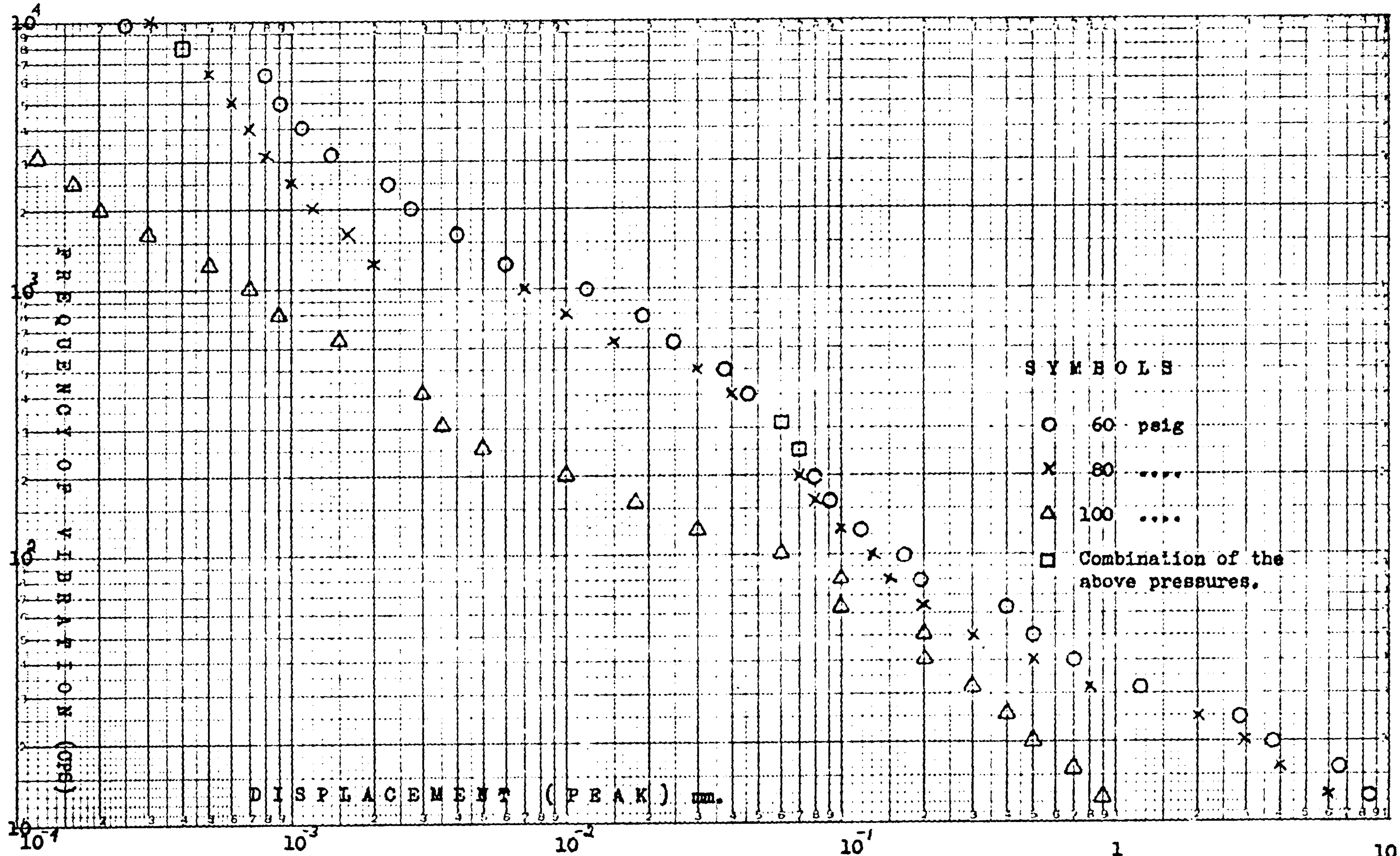
ii) Horizontal Drilling

On Graph (8) it is more evident that for any particular frequency, the divergence of amplitudes for high air pressures compared to low air pressures is much greater than indicated on Graph (7) for operating at no-lod. Also on Graph (8) in frequency range 70-100 cps the amplitude variation is not so great between different pressures. On the other hand, the greater are obtained in the higher frequency ranges. The reason for this is most likely due to the small number of readings that were taken under adverse weather conditions.

Also by comparing Graph (8) with the Graphs (7 and 9) for operating at no-load and vertical down drilling it can be seen that the slopes of the trend lines are the same, but for the horizontal drilling case the amplitudes are generally greater for the same frequency. This appeared to be the result of the diminution of amplitudes caused by the damping of the air-leg. In considering the frequency danger zone for tissue damage and disease it can be seen for the 34-50 cps range that vibrational amplitudes of 0.20 mm



Graph 8: Relationship between displacement and frequency vibration under horizontal drilling conditions.

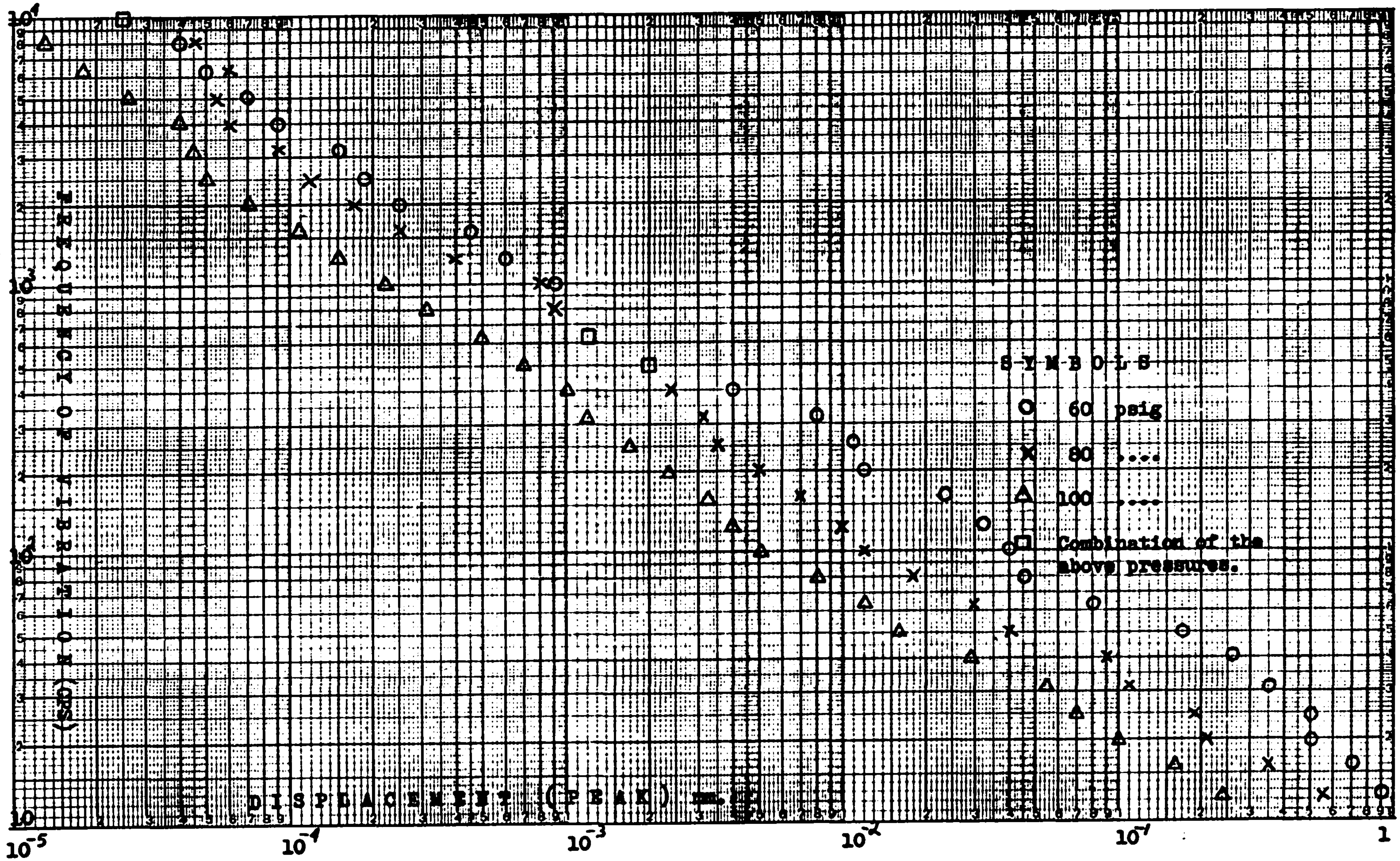


Graph 8: Relationship between displacement and frequency vibration under horizontal drilling conditions.

for 100 psig up to 2.0 mm for 50 psig are found, which in this experiment were the highest values for the three drilling cases. It is fortunate that the air-leg drill does not require the same human hand support that is required for vertical down drilling.

iii) Vertical Down Drilling

Because vertical down drilling does not use an air-leg support, the drill must be hand-held. The relationship in this case between vibrations and occupational impairment is most critical. For vibrations in the danger range of 34-50 cps, from Graph (9) it was found that the amplitude of oscillation ranged from 0.016 mm to 0.450 mm with the high air pressure of 100 psig giving the lowest amplitude of vibration. In making reference to a danger zone, it should be taken into consideration that the danger refers to Raynaud's disease of the tissues and not to bone and joint disorders that result from low frequency, high amplitude mechanical oscillations. Also, from Graph (9), although the separation of the 100 psig lines is quite large, it is relatively constant, and without the variations noted in the case of the drilling done horizontally Graph (8). The greatest



Graph 9: Relationship between displacement and frequency of vibration under vertical down drilling conditions.

discrepancies occur due to difficulties in measuring in high frequency (greater than 10,000 cps) ranges.

2. Discussion of Velocity Graphs (Graphs 10,11, 12)

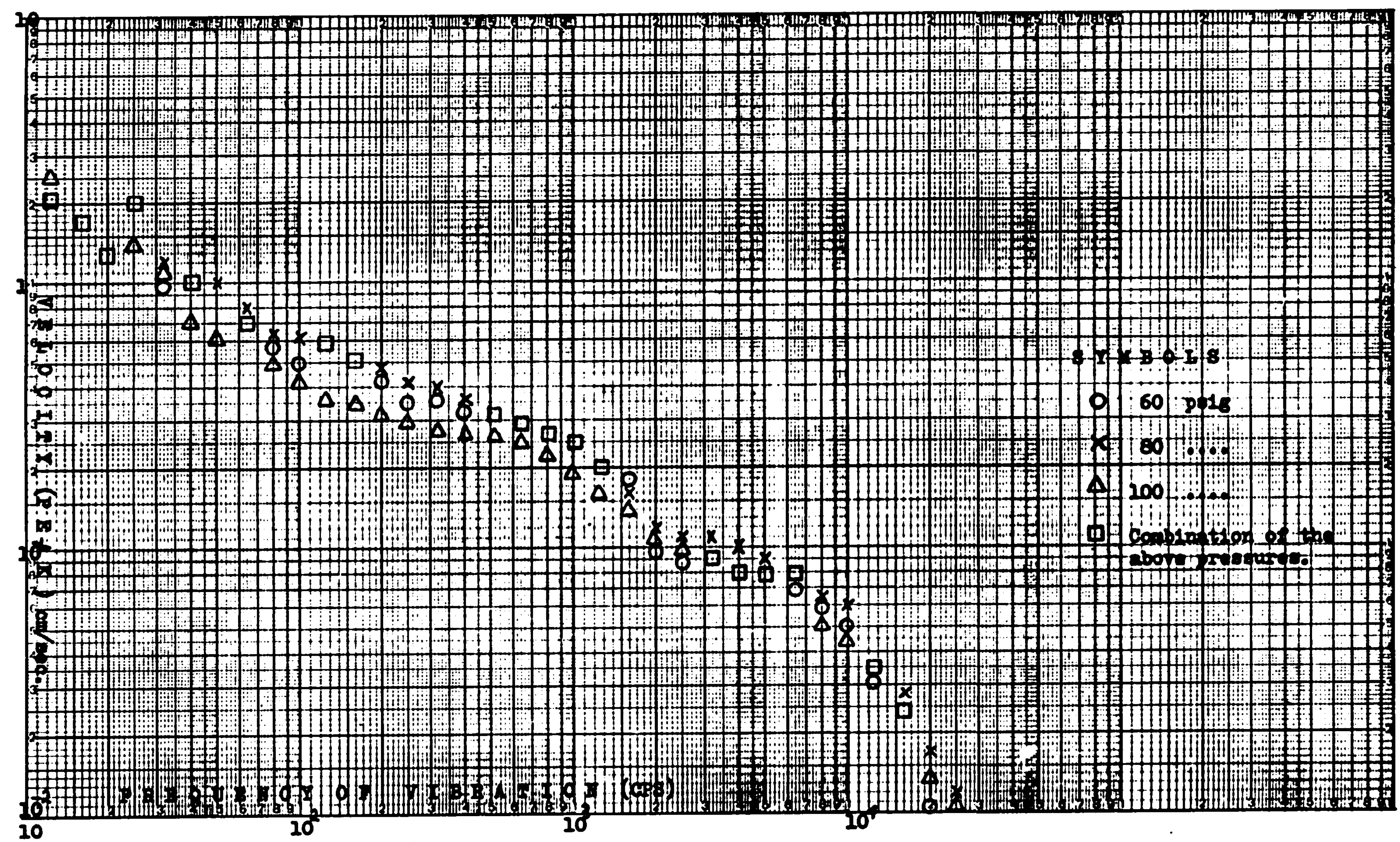
As in the discussion of the amplitude of vibrations, it can be said that the first derivative of displacement with respect to time, i.e. velocity, of the vibration has the same inverse relationship to the frequency. There appears to be less linearity in the results which is most likely attributable to the viscous damping of the system.

i) Operating at No-load

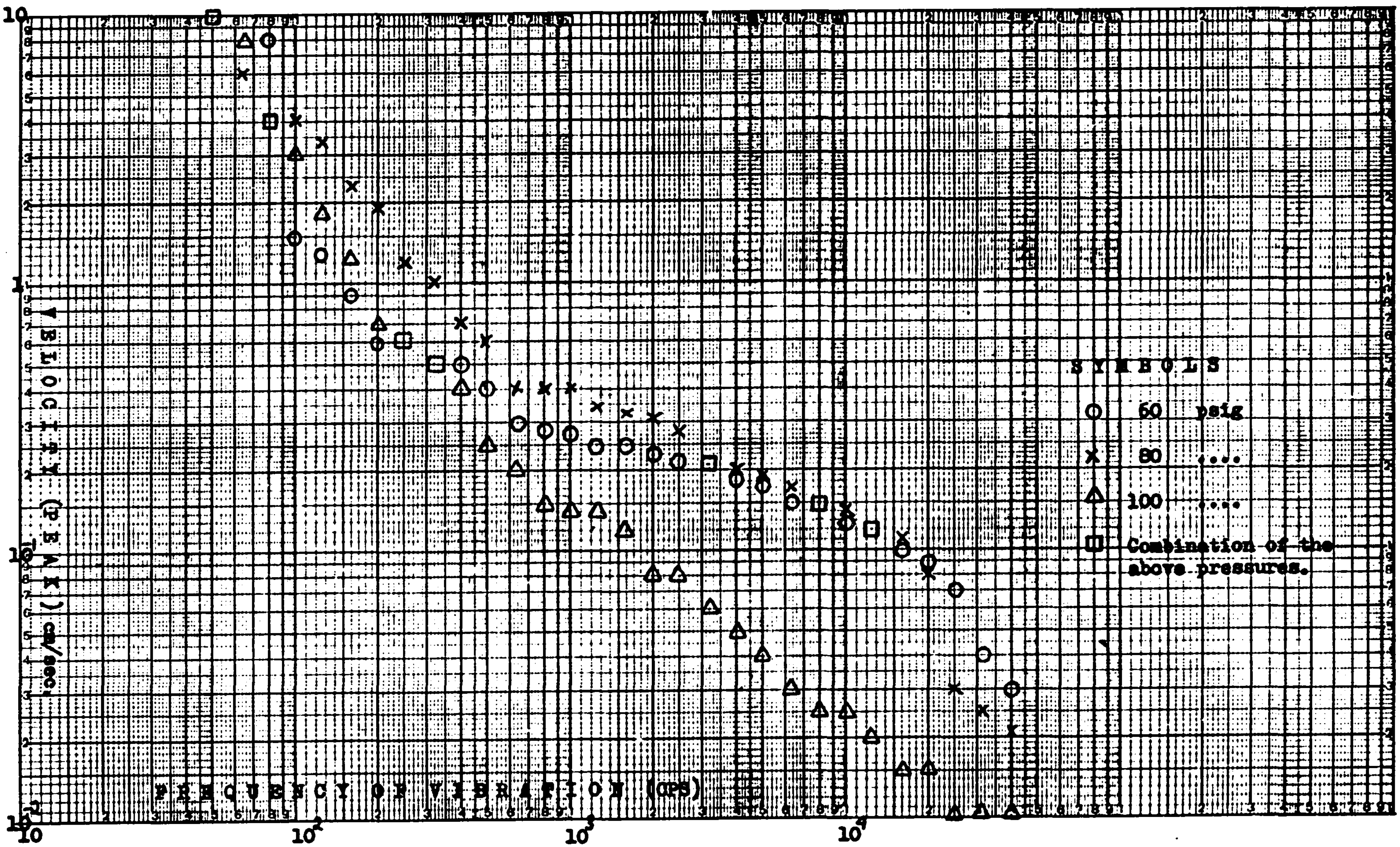
On Graph (10) the relationship of velocities at different pressures at a common frequency shows little divergence, with a slight increase in divergence occuring between frequencies 40 to 2,000 cps.

ii) Horizontal Drilling

On Graph (11) the values of the velocities at low frequencies are higher than for the free drilling case, but the spread of waves at some common frequency for the different air pressures is of the same magnitude as for the operating no-load conditions.



Graph 10: Relationship between velocity and frequency of vibration under operating at no -load conditions.

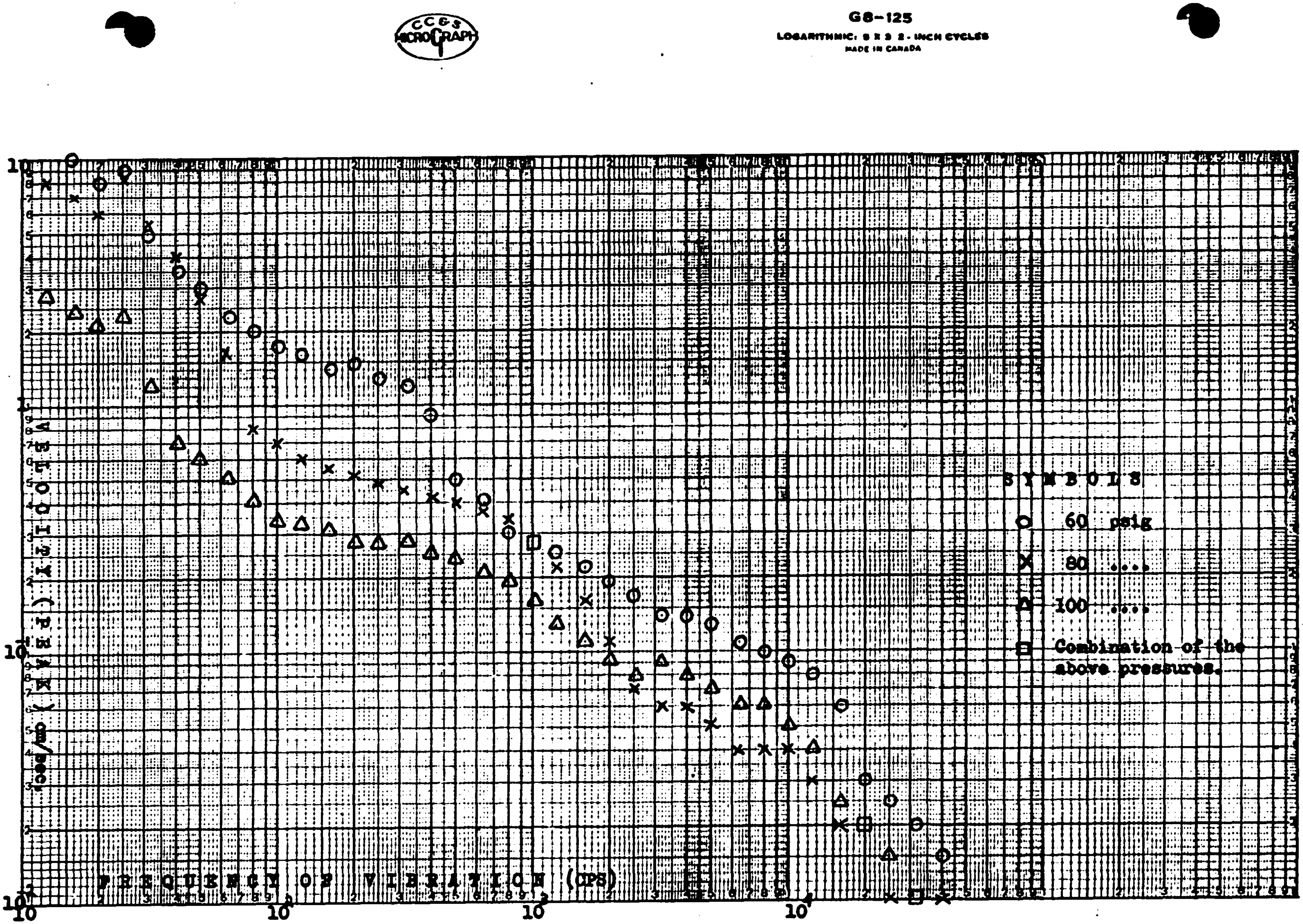


Graph 11: Relationship between velocity and frequency of vibration under horizontal drilling conditions.

This can be interpreted to mean that there is good experimental correlation between the two cases. However, at higher frequencies (greater than 1000 cps), the divergence increases considerably. This is to be expected, because the same trend is indicated on the displacement Graph (8) for horizontal drilling. This divergence can be interpreted to mean that at higher frequencies, (greater than 100 cps) a greater effect on velocity of vibrations is created by variations in air pressures than at low frequencies (lower than 100 cps). It should be borne in mind though, that in using log-log graphs the values in the low cycles for velocity (and displacement) are very small vs. very large values for frequencies, so not too much significance need be attached to the variations in amplitude and velocity for high value frequencies. In considering the critical frequency range in which tissue damages occurs, a velocity range from 1.0 cm./ sec. for 100 psig to 32.0 cm./sec. for 50 psig, the values for this case are much higher for the other two cases.

iii) Vertical Down Drilling

The trend line of Graph (12) for vertical down



Graph 12: Relationship between velocity and frequency of vibration under vertical down drilling conditions.

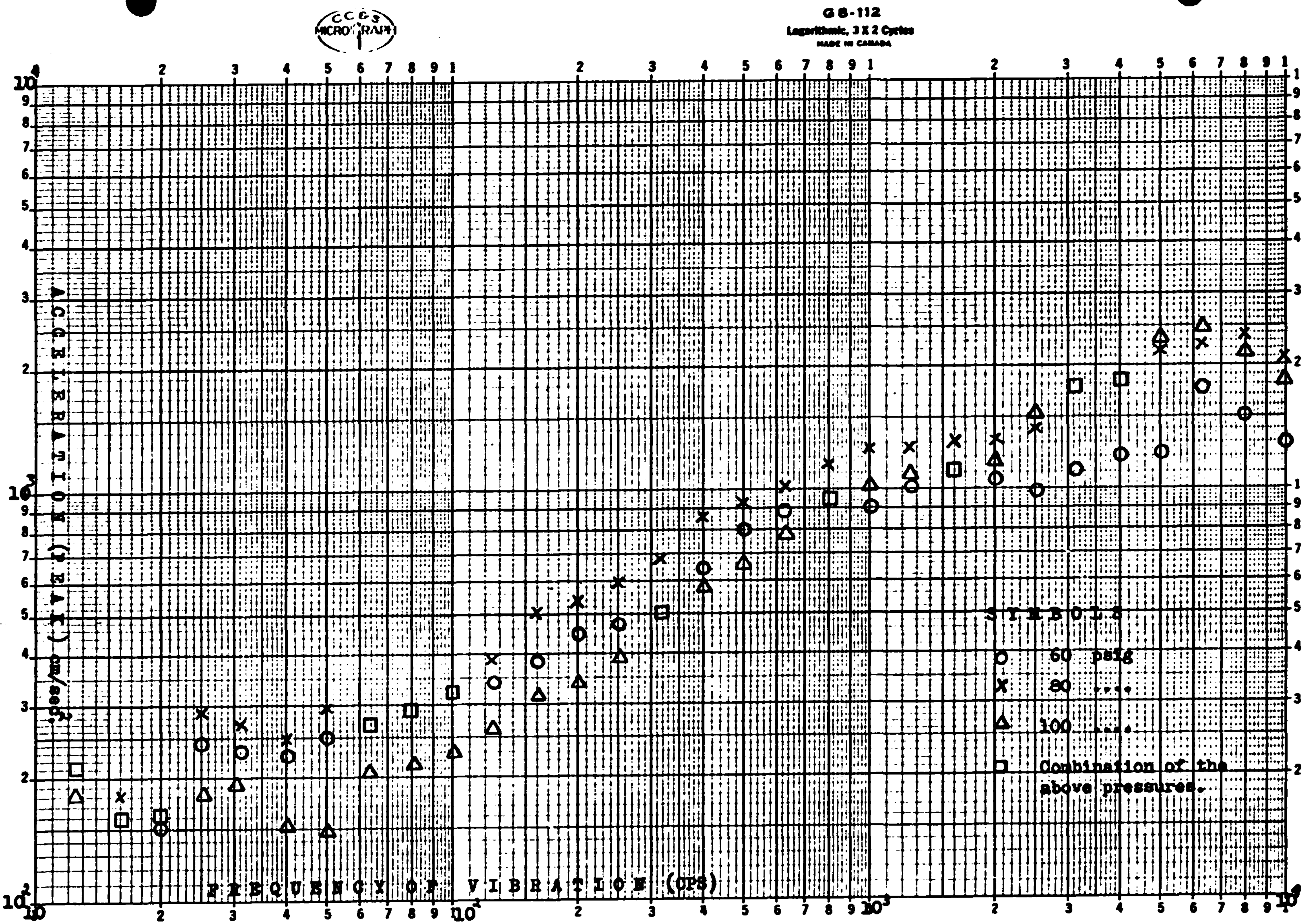
drilling most closely approximates that of the operating at no-load conditions Graph (10). However, the divergence of velocity values at lower frequencies (smaller than 1000 cps) is considerably greater, and demonstrates the concept that as air pressures vary in drilling, at low frequencies, greater variations in vibrational velocities will occur. It is important to consider physiological affects of the critical frequencies 34-50 cps, particularly in the case of vertical down drilling. From Graph (12), for an air pressure of 100 psig, a vibrational velocity of 0.60 cm/sec. occurs; and ranges up to 9.0 cm/sec. for an air pressure of 50 psig.

3. Discussion of Acceleration Graphs (Graphs 13,14,15)

In discussing these graphs it is difficult to make general statements. However, in all three drilling situations for vibrational frequencies from 10 to 100 cps, accelerations remained essentially constant. The frequency range 100 to 1000 cps produced the most dynamic results and the 1000 to 10,000 cps range essentially produced a maxima in accelerative values for the vibrations.

i) Operating at No-load

From Graph (13) the general trends mentioned

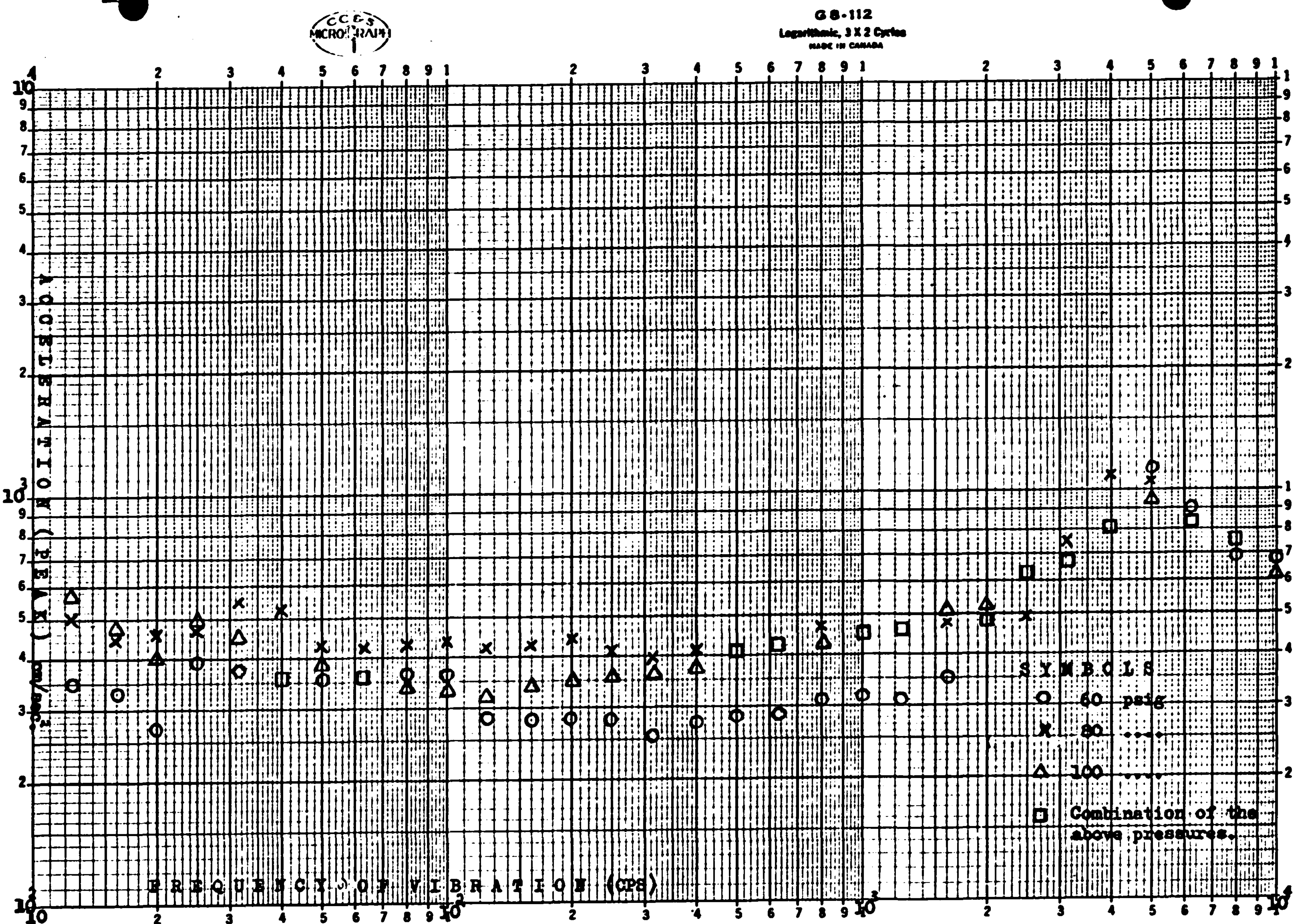


Graph 13: Relationship between acceleration and frequency of vibration under operating at no-load conditions.

above can be noted. However, for frequencies between 100 cps and 1000 cps, a linear, direct increase in acceleration occurs. For frequencies below 100 cps, acceleration values vary from about 150 to 300 cm/sec^2. The maximum acceleration values of 2600 to 1500 cm/sec^2 occur at about 8,000 cps. The acceleration values drop off as a result of the inability of the rock drill's natural frequency to respond to the forced vibrations of the system. In the critical frequency range (relating to tissue damage) of 34-50 cps, accelerations vary from 140 to 310 cm/sec^2.

ii) Horizontal Drilling

From Graph (14), for the lower frequency range of 10-100 cps, the acceleration values vary from 300 to 600 cm/sec^2, which is about double the accelerations for the operating at no-load case referred to above. For the frequency range from 100 to 1000 cps, acceleration values dip slightly to minimum value ranging from 250 to 450 cm/sec^2. In the frequency range from 1000 to 10,000 cps, the maximum values of acceleration vary from 1100 to 900 cm/sec^2. at a frequency 5000 cps. For frequencies above 5000 acceleration values fall off for the same reasons referred to above in the



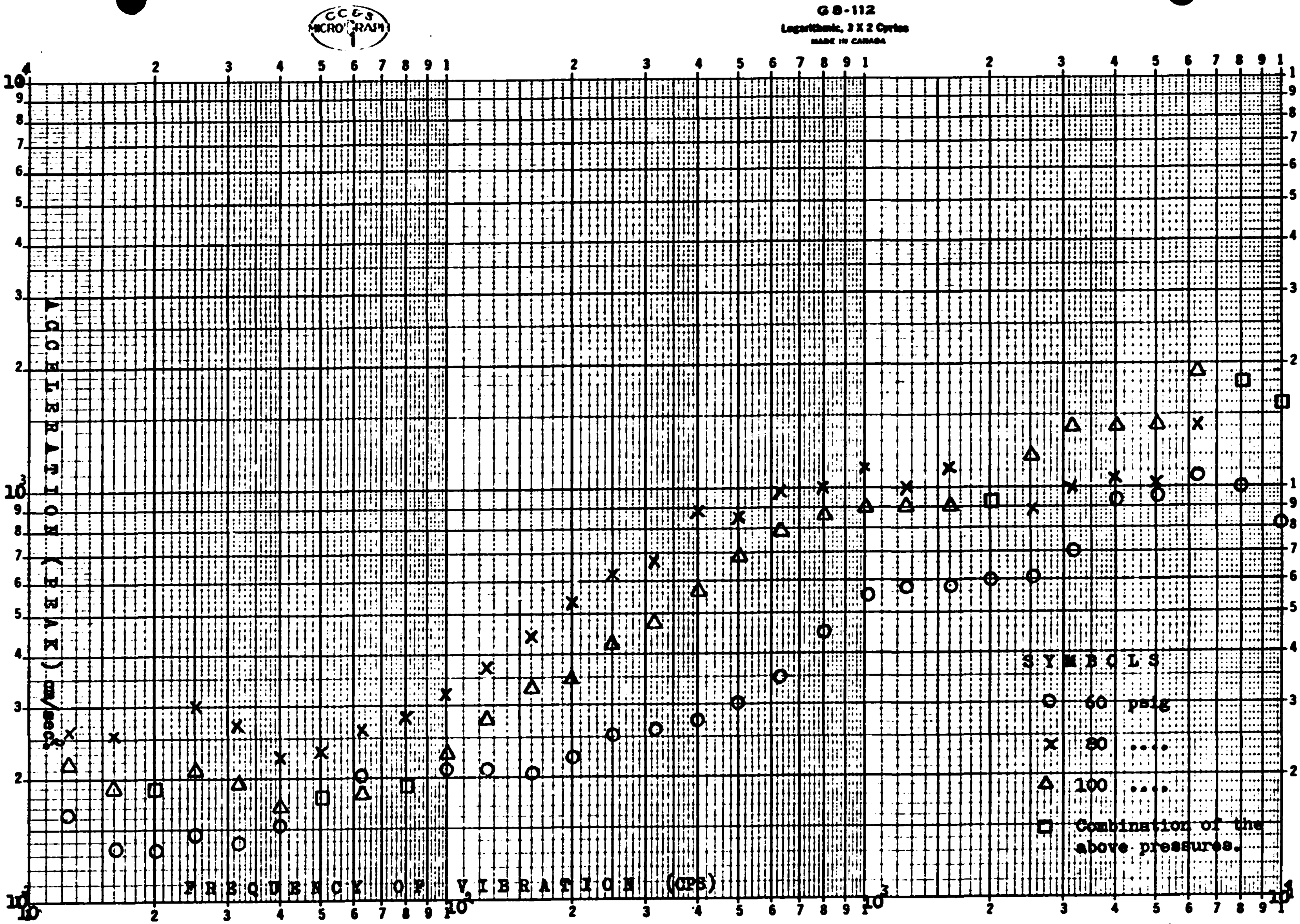
Graph 14: Relationship between acceleration and frequency of vibration under horizontal drilling conditions.

discussion on the operating at no-load conditions. In considering possible tissue damage for the vibration range of 34-50 cps, acceleration values of 310 to 510 cm/sec^2. occur.

iii) Vertical Down Drilling

As indicated on graph (15) much the same values exist as for the operating at no-load case, except that the variations of values in the 100-1000 cps range is much more diverse. The maxima in the 1000 to 10,000 cps range also occurs at 8000 cps, but has a range somewhat reduced to the 2000-900 cps area. As in the other cases, acceleration values decline at higher frequencies. The tissue damaging vibration in the 34-50 cps. range result in accelerations ranging from 140 to 280 cm/sec^2.

V.A.



Graph 15: Relationship between acceleration and frequency of vibration under vertical down drilling conditions.

SUGGESTIONS FOR FURTHER RESEARCH

It is suggested that in further research the results for a number of different drills should be obtained. This would be especially appropriate in studying new, muffled drills in which some new features have been incorporated.

More realistic results could be obtained by drilling in situ rock, instead of huge surface boulders.

By drilling underground, under environmental conditions approximating that of either a wet or dry mine, more realistic experimental values could be obtained. Wet drilling is considered more dangerous than dry drilling (8).

Drilling should be done by experienced drillers; the experience of these drillers could be helpful in getting more consistent results.

Two students working on the project could get more comprehensive, statistically viable results.

When the machine is collaring a hole it requires a two-hand grip and produces some very high amplitude, low frequency vibrations that are potentially dangerous. This should be analyzed in a separate study.

VII. CONCLUSION

Overseas research has confirmed the relationship between miners diseases of the hands and mechanical vibrations of drills. It is felt that more research in this field can be done in North America, especially with regard to the effect of cold temperatures on miners hands. It would appear that rigorous techniques should be used in determining the effect of cold air and vibrations because results up to now have not been well documented. Also more research could be done on the beneficial effects of artificial supports such as jumbos, mechanical feed drilling platforms and air-leg support that substantially reduce the amount of hand contact by miners. It can be estimated that actual hand contact with these machines will be at least 10-25 % of what it has been in the past.

In this research project, an appraisal of the actual vibrations of an operating rock drill was made. It was decided that of the measurements made, that is, displacement, velocity and acceleration, the displacement (or amplitude) of vibration was the most useful and informative. Hence the displacement readings for drills operating down vertically and horizontally were considered to be of most value in analyzing vibrations for operations between 34 and 50 cps. This is considered to be the occupational danger zone for vibrations. Even though there is less hand contact in present day drilling through the use of air-leg supports, drilling platforms and other modern equipment, short durations of hand contact is unavoidable. The percentage of drilling time which involves hand contact, depends upon many things including the skill of the operator, physical features of the rock being drilled, speed of drilling, amplitude and frequency of the drill piston, the compressed air pressure used and the usual operating position of the tool. Another important condition is that the commonly used air pressures of 100 psig gave lower amplitudes of vibration than lower pressures, which means that smoother drilling and mechanical operation results from having sufficient air pressure, i.e. 100 psig. Since penetration rates were found to be highest with higher air pressures, it can be concluded that a more efficient overall drilling situation results from drilling at 100 psig.

It can also be concluded that the measurement of the vibration is best accomplished by the use of electrical instruments. The mechanical device was good for measuring the axis of principal oscillation, but not a break down of the aggregate vibration characteristics as done by the electrical equipment.

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APPENDIX A

Experimental Results

Included in this section are the average values of the readings taken by the electrical instruments for displacement, velocity and acceleration. These readings were taken peak value for various air pressures as will be indicated, as well as for different drilling conditions. In each case, a minimum of two readings and for some of the cases up to six readings were taken.

Also included in this section of the Appendix are the experimental results of determination of most significant vibration direction in rock drill, with the mechanical instrument (Askania Hand Vibrograph).

Finally the values used for determining penetration rates for horizontal and vertical drilling are listed.

MEASUREMENT OF DISPLACEMENT, VELOCITY AND ACCELERATION

1. Operating at No-load conditions

i) At 110 psig - average of four readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration $cm/sec.^2$
12.5	.26	2.10	170
16	.19	1.65	160
20	.095	1.40	150
25	.065	1.75	180
31.5	.070	1.45	200
40	.030	.70	145
50	.017	.55	140
63	.014	.55	190
80	.008	.45	200
100	.007	.41	230
125	.005	.36	260
160	.0035	.31	290
200	.0024	.29	340
250	.0019	.28	380
315	.0014	.27	450
400	.0009	.24	515
500	.0007	.22	605
630	.00055	.21	715

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
800	.00040	.19	870
1000	.00025	.17	945
1250	.00016	.15	1040
1600	.00011	.13	1100
2000	.00008	.11	1200
2500	.000065	.10	1600
3150	.000053	.10	1825
4000	.000041	.09	2025
5000	.000030	.08	2325
6300	.000020	.07	2400
8000	.000013	.062	2200
10000	.000007	.040	1925
12500	.0000055	.028	1700
16000	.0000050	.021	1375
20000	.0000040	.014	1225
25000	.0000040	.010	900
31500	.0000040	.007	686
40000	.0000040	.005	538

ii) At 100 psig -average of four readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.29	2.4	180
16	.23	1.7	160
20	.09	1.3	155
25	.075	1.4	183
31.5	.065	1.1	193
40	.028	.7	153
50	.018	.6	147
63	.017	.7	205
80	.009	.5	218
100	.008	.41	230
125	.006	.37	260
160	.0045	.35	312
200	.0029	.32	340
250	.0017	.30	395
315	.0016	.28	490
400	.0012	.28	580
500	.0008	.26	655
630	.00055	.24	785
800	.00045	.22	940

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.00034	.18	1030
1250	.00018	.16	1075
1600	.00012	.14	1100
2000	.00007	.11	1175
2500	.00006	.10	1525
3150	.000056	.09	1725
4000	.000042	.08	1850
5000	.000031	.084	2325
6300	.000017	.08	2475
8000	.000014	.05	2150
10000	.0000065	.036	1800
12500	.0000055	.034	1785
16000	.0000045	.024	1585
20000	.000004	.013	1185
25000	.000004	.0095	825
31500	.000004	.0065	630
40000	.000004	.0050	518

iii) At 90 psig - average of six readings

Frequency cps	Displacement mm	Velosicity cm/sec.	Acceleration cm/sec.^{2}
12.5	.30	2.7	263
16	.21	2.3	232
20	.12	1.6	200
25	.10	2.1	268
31.5	.0[illegible]	1.2	230
40	.036	1.0	238
50	.024	.8	265
63	.018	.7	258
80	.013	.7	280
100	.009	.6	332
125	.007	.53	366
160	.005	.48	446
200	.0037	.47	570
250	.0027	.45	653
315	.0020	.40	726
400	.0015	.38	840
500	.0010	.34	956
630	.0007	.30	1130
800	.0005	.27	1210

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.00032	.23	1280
1250	.00022	.18	1293
1600	.00012	.14	1176
2000	.00007	.09	1126
2500	.000053	.09	1350
3150	.000050	.10	1816
4000	.000041	.09	2133
5000	.000027	.08	2266
6300	.000018	.07	2483
8000	.000012	.07	2616
10000	.000006	.042	2016
12500	.000005	.040	2016
16000	.000004	.025	1883
20000	.000004	.014	1333
25000	.000004	.011	1113
31500	.000004	.007	713
40000	.000004	.005	570

iv) At 80 psig - average of four readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.26	2.1	210
16	.17	1.7	180
20	.10	1.3	160
25	.11	2.0	285
31.5	.062	1.2	265
40	.031	1.0	284
50	.027	1.0	295
63	.016	.8	265
80	.012	.64	295
100	.009	.62	335
125	.0068	.59	385
160	.0050	.51	500
200	.0035	.48	535
250	.0025	.42	590
315	.0020	.40	675
400	.0014	.36	850
500	.0009	.32	915
630	.0007	.29	1015
800	.0005	.27	1150

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.00034	.25	1250
1250	.00022	.20	1250
1600	.00014	.16	1313
2000	.00008	.12	1313
2500	.00007	.11	1412
3150	.00005	.11	1750
4000	.00004	.10	1800
5000	.000027	.09	2175
6300	.000019	.08	2250
8000	.000013	.065	2675
10000	.000007	.050	2075
12500	.000005	.035	2050
16000	.000004	.028	1950
20000	.000003	.017	1525
25000	.000003	.012	1100
31500	.000003	.008	775
40000	.000003	.005	613

v) At 70 psig - average of four readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.23	2.1	220
16	.16	1.7	165
20	.13	1.4	192
25	.12	2.0	260
31.5	.05	1.0	250
40	.03	.9	230
50	.027	.85	310
63	.017	.75	290
80	.010	.60	265
100	.009	.60	355
125	.0075	.58	420
160	.0060	.54	500
200	.0045	.48	510
250	.0027	.39	570
315	.0022	.38	707
400	.0013	.35	800
500	.00095	.33	920
630	.00070	.29	1025
800	.00055	.28	1162

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.00040	.23	1375
1250	.00028	.22	1350
1600	.00018	.20	1300
2000	.00010	.11	1188
2500	.00007	.10	1250
3150	.00005	.095	1350
4000	.000035	.075	1600
5000	.000030	.075	1800
6300	.000022	.075	2500
8000	.000015	.070	2300
10000	.000006	.045	1825
12500	.0000045	.030	1625
16000	.0000035	.020	1525
20000	.0000030	.011	1200
25000	.0000030	.009	900
31500	.0000030	.007	760
40000	.0000030	.005	570

vi) At 60 Psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.22	2.2	215
16	.16	1.7	155
20	.12	1.4	150
25	.11	1.9	240
31.5	.06	1.0	230
40	.042	1.0	225
50	.025	.9	250
63	.016	.7	265
80	.010	.6	285
100	.0085	.5	315
125	.007	.56	340
160	.0056	.52	380
200	.0042	.45	440
250	.0026	.36	475
315	.0024	.37	520
400	.0012	.34	635
500	.0009	.32	800
630	.0008	.28	870
800	.00052	.27	950

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.00038	.25	900
1250	.00021	.21	1020
1600	.00019	.18	1100
2000	.00009	.10	1050
2500	.00008	.09	975
3150	.000055	.09	1115
4000	.000033	.08	1200
5000	.000031	.08	1225
6300	.000024	.07	1750
8000	.000011	.06	1500
10000	.000007	.040	1275
12500	.000006	.032	1100
16000	.000004	.023	990
20000	.000003	.010	850
25000	.000003	.008	810
31500	.000003	.007	745
40000	.000003	.005	560

2. Horizontal Drilling Conditions

i) At 100 psig- average of two readings

Frequency cps	Displacement mm	Velocity cm/sec	Acceleration cm/sec.^{2}
12.5	.9	20.0	575
16	.7	14.0	475
20	.5	12.0	400
25	.4	18.0	500
31.5	.3	15.0	450
40	.2	13.0	350
50	.2	10.0	375
63	.1	8.0	355
80	.1	4.0	350
100	.06	3.0	340
125	.03	1.8	325
160	.018	1.2	340
200	.010	.7	350
250	.008	.6	360
315	.005	.5	365
400	.0035	.4	380
500	.0030	.25	400
630	.0015	.20	430

Frequency cps	Displacement mm	Velocity cm/sec	Acceleration cm/sec.^{2}
800	.0009	.15	435
1000	.0007	.14	440
1250	.0005	.14	445
1600	.0003	.12	510
2000	.0002	.08	525
2500	.00016	.08	615
3150	.00012	.06	685
4000	.00009	.05	800
5000	.00006	.04	955
6300	.00003	.03	850
8000	.000025	.025	740
10000	.000025	.025	610
12500	.000020	.020	450
16000	.000015	.015	375
20000	.000015	.015	285
25000	.000015	.010	165
31500	.000010	.010	115
40000	.000010	.010	86

ii) At 90 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	2.5	25.0	550
16	1.5	23.0	400
20	1.2	20.0	390
25	1.0	23.0	450
31.5	.7	18.0	320
40	.5	12.0	325
50	.4	10.0	340
63	.2	7.0	350
80	.1	4.0	340
100	.08	3.0	330
125	.05	2.7	340
160	.03	1.1	320
200	.02	1.0	340
250	.011	.9	335
315	.008	.8	370
400	.006	.7	385
500	.005	.6	405
630	.002	.4	425
800	.0012	.3	455

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.0009	.25	480
1250	.0007	.21	490
1600	.0005	.17	510
2000	.0004	.11	545
2500	.0003	.09	590
3150	.00025	.08	750
4000	.00017	.08	850
5000	.00013	.07	880
6300	.00008	.05	690
8000	.00005	.04	650
10000	.00004	.04	450
12500	.00003	.03	375
16000	.000025	.025	275
20000	.000025	.020	200
25000	.000025	.015	165
31500	.000020	.015	130
40000	.000020	.015	90

iii) At 80 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	6.0	34.0	500
16	4.0	30.0	450
20	3.0	28.0	460
25	2.0	32.0	550
31.5	.8	22.0	520
40	.5	12.0	465
50	.3	10.0	425
63	.2	6.0	415
80	.15	4.0	430
100	.13	4.0	440
125	.10	3.3	425
160	.08	2.3	425
200	.07	1.9	445
250	.07	1.2	410
315	.06	1.0	405
400	.04	.7	410
500	.03	.6	420
630	.015	.4	425
800	.010	.4	465

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.007	.4	455
1250	.002	.34	475
1600	.0016	.32	475
2000	.0012	.31	485
2500	.0010	.28	490
3150	.0008	.21	750
4000	.0007	.20	1100
5000	.0006	.19	1050
6300	.0005	.17	825
8000	.0004	.15	740
10000	.0003	.14	565
12500	.0002	.12	490
16000	.0001	.11	420
20000	.0001	.08	335
25000	.0001	.03	250
31500	.0001	.025	165
40000	.0001	.021	115

iv) At 70 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	8.0	36.0	475
16	6.0	30.0	400
20	3.5	23.0	425
25	2.4	24.0	550
31.5	.7	20.0	500
40	.5	15.0	400
50	.5	12.0	400
63	.3	8.0	400
80	.20	2.4	345
100	.17	1.6	400
125	.12	1.5	360
160	.09	1.3	300
200	.08	1.1	280
250	.07	.9	270
315	.06	.7	250
400	.045	.5	265
500	.035	.40	270
630	.019	.38	280
800	.015	.36	285

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.011	.35	305
1250	.005	.32	310
1600	.003	.26	330
2000	.0024	.24	340
2500	.0025	.23	500
3150	.0012	.22	550
4000	.0009	.20	750
5000	.0008	.17	1000
6300	.0005	.16	725
8000	.0004	.15	625
10000	.0002	.13	590
12500	.0001	.12	540
16000	.0001	.10	490
20000	.0001	.08	380
25000	.0001	.05	280
31500	.0001	.035	155
40000	.0001	.025	100

v) At 60 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	8.5	41.0	350
16	6.5	35.0	330
20	3.75	32.0	270
25	2.85	40.0	400
31.5	1.25	32.0	380
40	.7	23.0	360
50	.5	18.0	355
63	.4	13.0	360
80	.19	8.0	360
100	.17	1.5	360
125	.12	1.3	280
160	.09	.9	280
200	.08	.6	280
250	.07	.6	280
315	.06	.5	255
400	.045	.5	275
500	.038	.4	285
630	.025	.30	290
800	.019	.28	310

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.012	.27	320
1250	.006	.25	320
1600	.004	.25	350
2000	.0027	.23	490
2500	.0022	.22	655
3150	.0014	.21	650
4000	.0011	.18	805
5000	.0009	.17	1150
6300	.0008	.16	825
8000	.0004	.15	700
10000	.00025	.13	675
12500	.00015	.12	575
16000	.00013	.10	525
20000	.00013	.09	425
25000	.00012	.07	350
31500	.00012	.04	275
40000	.00012	.03	200

vi) At 50 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	9.5	44.0	350
16	7.0	38.0	365
20	5.0	27.0	400
25	4.0	29.0	465
31.5	2.0	27.0	350
40	1.3	24.0	350
50	.7	18.0	375
63	.5	15.0	415
80	.19	9.0	350
100	.17	4.0	375
125	.15	3.0	350
160	.10	2.0	400
200	.09	1.3	340
250	.08	.9	320
315	.07	.7	335
400	.046	.7	365
500	.038	.4	350
630	.024	.35	340
800	.017	.21	365

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.011	.23	385
1250	.007	.25	360
1600	.005	.26	390
2000	.0042	.25	430
2500	.0037	.24	590
3150	.0024	.23	660
4000	.0017	.22	850
5000	.0015	.19	900
6300	.0013	.16	800
8000	.0009	.13	635
10000	.00060	.11	505
12500	.00035	.10	465
16000	.00030	.10	430
20000	.00025	.08	290
25000	.00020	.05	150
31500	.00020	.035	115
40000	.00020	.030	90

3. Vertical Down Drilling Conditions

i) At 100 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.24	2.8	220
16	.16	2.4	190
20	.10	2.2	190
25	.07	2.4	210
31.5	.054	1.1	195
40	.029	.7	170
50	.016	.6	175
63	.012	.5	185
80	.008	.4	190
100	.005	.35	230
125	.004	.32	275
160	.0033	.31	330
200	.0024	.29	350
250	.0017	.29	420
315	.0012	.28	470
400	.0010	.25	560
500	.0007	.24	690
630	.0005	.21	790
800	.00031	.19	860

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.00022	.16	900
1250	.00015	.13	900
1600	.00011	.11	900
2000	.00007	.09	910
2500	.00005	.08	1175
3150	.000045	.09	1400
4000	.000039	.08	1400
5000	.000026	.07	1400
6300	.000018	.06	1900
8000	.000013	.06	1800
10000	.000007	.05	1550
12500	.000005	.04	1300
16000	.000004	.025	1200
20000	.000003	.020	1000
25000	.000003	.015	900
31500	.0000025	.010	750
40000	.0000025	.008	550

ii) At 90 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.40	4.3	210
16	.22	3.7	195
20	.15	3.3	180
25	.13	3.8	215
31.5	.09	2.1	245
40	.07	1.9	215
50	.03	1.6	200
63	.02	.9	225
80	.012	.7	235
100	.009	.6	240
125	.0075	.5	270
160	.0058	.5	305
200	.0043	.48	340
250	.0034	.45	390
315	.0025	.41	450
400	.0018	.38	500
500	.0012	.36	630
630	.0009	.32	740
800	.0007	.29	835

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.00045	.24	910
2150	.00030	.20	940
1600	.00016	.16	975
2000	.00007	.11	1000
2500	.000045	.08	1250
3150	.000035	.07	1500
4000	.000025	.06	1513
5000	.000015	.05	1513
6300	.000012	.04	1500
8000	.000010	.04	1850
10000	.000009	.04	1600
12500	.000008	.03	1450
16000	.000005	.03	1200
20000	.0000035	.025	1000
25000	.0000025	.025	850
31500	.0000025	.020	600
40000	.0000025	.020	440

iii) At 80 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.55	8.0	260
16	.35	7.0	255
20	.21	6.0	190
25	.19	8.2	300
31.5	.11	5.5	270
40	.09	4.0	225
50	.04	2.7	230
63	.03	1.6	260
80	.018	.8	280
100	.012	.7	320
125	.010	.6	370
160	.007	.55	440
200	.005	.52	530
250	.0035	.49	625
315	.0031	.45	665
400	.0024	.42	880
500	.0020	.40	850
630	.0012	.37	975
800	.0009	.34	1000

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.0008	.28	1125
1250	.0004	.22	1000
1600	.00025	.16	1125
2000	.00017	.11	950
2500	.00012	.07	875
3150	.00009	.06	975
4000	.00006	.06	1050
5000	.000055	.05	1025
6300	.000060	.04	1400
8000	.000045	.04	1800
10000	.000025	.04	1600
12500	.000015	.03	1300
16000	.000015	.02	1000
20000	.000010	.02	1000
25000	.000010	.01	850
31500	.000010	.01	750
40000	.000010	.01	650

iv) At 70 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.75	10.0	210
16	.60	9.0	195
20	.40	8.0	165
25	.35	10.0	205
31.5	.24	6.0	170
40	.20	5.0	210
50	.15	3.0	205
63	.06	1.7	210
80	.035	.9	205
100	.030	.8	205
125	.019	.9	190
160	.017	.7	220
200	.010	.6	245
250	.008	.5	245
315	.007	.43	275
400	.006	.40	315
500	.003	.35	510
630	.002	.24	605
800	.0018	.20	740

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.0012	.22	805
1250	.0006	.17	745
1600	.00033	.14	730
2000	.00021	.12	760
2500	.00017	.11	805
3150	.00010	.12	820
4000	.00009	.12	1125
5000	.00011	.10	1200
6300	.00007	.08	1150
8000	.00003	.06	905
10000	.00003	.05	875
12500	.000025	.04	730
16000	.000025	.03	640
20000	.000015	.02	560
25000	.000015	.01	430
31000	.000010	.01	385
40000	.000010	.01	265

v) At 60 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	.9	12.0	165
16	.7	10.0	135
20	.5	8.0	135
25	.5	9.0	170
31.5	.35	5.0	140
40	.26	3.5	155
50	.17	3.0	175
63	.08	2.3	200
80	.045	2.0	195
100	.040	1.7	210
125	.032	1.6	210
160	.024	1.4	205
200	.012	1.5	225
250	.011	1.3	255
315	.008	1.2	260
400	.004	.9	275
500	.002	.5	300
630	.0012	.4	350
800	.0010	.3	450

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.0009	.29	550
1250	.0006	.25	585
1600	.00045	.22	585
2000	.00025	.19	595
2500	.00019	.17	610
3150	.00015	.14	705
4000	.00009	.14	935
5000	.00007	.13	965
6300	.00005	.11	1080
8000	.00004	.10	1000
10000	.000025	.09	810
12500	.000020	.08	675
16000	.000020	.06	525
20000	.000010	.03	485
25000	.000010	.025	350
31500	.000010	.020	305
40000	.000010	.015	255

vi) At 50 psig - average of two readings

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
12.5	1.1	15.0	150
16	.8	14.0	130
20	.7	13.0	130
25	.6	16.0	185
31.5	.43	9.0	175
40	.35	6.0	180
50	.27	5.0	170
63	.10	3.0	130
80	.07	2.4	145
100	.045	2.0	165
125	.037	2.0	175
160	.027	2.2	200
200	.012	1.9	210
250	.009	1.4	235
315	.006	1.4	250
400	.004	1.2	265
500	.003	.8	305
630	.0015	.6	365
800	.0009	.5	485

Frequency cps	Displacement mm	Velocity cm/sec.	Acceleration cm/sec.^{2}
1000	.0006	.32	985
1250	.0004	.23	580
1600	.00017	.20	570
2000	.00011	.19	590
2500	.00010	.16	595
3150	.00007	.12	665
4000	.00004	.10	785
5000	.00006	.09	840
6300	.00005	.12	925
8000	.00004	.12	1025
10000	.00003	.08	875
12500	.000015	.05	790
16000	.000015	.03	630
20000	.000010	.025	470
25000	.000010	.020	340
31500	.000010	.015	280
40000	.000010	.015	245

Table 8. Results to find the most significant vibration direction of rock drill which was used for experiments.

Air pressure (psig)	LOCATION OF MEASUREMENT											
	Xa		Ya		Za		Xb		Yb		Zb	
	Freq. cps	Disp. mm	Freq. cps	Disp. mm	Freq. cps	Disp. mm	Freq. cps	Disp. mm	Freq. cps	Disp. mm	Freq. cps	Disp. mm
60	22	3.3	22	.12	22	.40	22	3.2	22	.25	22	.14
70	24	3.5	24	.17	24	.35	24	3.5	24	.65	24	.13
80	28	3.7	27	.20	27	.50	28	3.7	27	.60	28	.13
90	30	3.8	07	.50	29	1.20	30	3.8	30	.50	30	.46
100	31	4.0	07	1.00	07	3.50	31	3.9	07	.60	07	2.50

Measuring instrument: Askania Hand Vibrograph

Operating at No-load.

Table 9. Results of vibration Measurements, the Atlas-Copco, Model Lion BBC 25 Rock Drill, Operating at no-load.

Air Pressure (psig)	Fundamental Freq. (cps)	Amplitude mm.
60	22	3.3
70	24	3.5
80	27	3.7
90	30	3.86
100	31	4.00
110	32	4.25

The measurements were taken by Askania Hand Vibrograph.

Table 10-a and 10-b show the relationship between rate of penetration and pressure of compressed air.

Table 10-a. Penetration Rate (Drilling Horizontal)

Air Pressure (psig)	First Measurement(in.)	Second Measurement(in.)	Average (in.)	Time (min.)	Rate of penetration(in./min.)
50	2.05	2.45	2.25	1	2.25
60	3.35	3.85	3.60	1	3.60
70	5.00	5.20	5.10	1	5.10
80	6.60	7.00	6.80	1	6.80
90	8.50	9.00	8.75	1	8.75
100	9.25	9.65	9.45	1	9.45

Table 10-b. Penetration Rate (Drilling down vertical)

Air Pressure (psig)	First Measurement(in.)	Second Measurement(in.)	Average (in.)	Time (min.)	Rate of penetration(in./min.)
50	1.42	1.38	1.40	1	1.40
60	2.10	2.20	2.15	1	2.15
70	3.15	3.35	3.25	1	3.25
80	5.00	5.30	5.15	1	5.15
90	6.65	6.85	6.75	1	6.75
100	7.70	8.00	7.85	1	7.85

APPENDIX B

Statistical Analysis of Operating Data

SYMBOLS

N = No. of readings

D_i = Displacement

$\bar{D}$ = Average displacement

Δ_D = $D_i - \bar{D}$

V_i = Velocity

$\bar{V}$ = Average velocity

Δ_V = $V_i - \bar{V}$

A_i = Acceleration

$\bar{A}$ = Average acceleration

Δ_A = $A_i - \bar{A}$

σ = Standard deviation

$$= \sqrt{\frac{\Sigma (\Delta_D)^2}{N}}$$

α = Standard error of the mean

$$= \frac{\sigma}{\sqrt{N}}$$

In determining standard deviations and standard errors, the calculated values for $\Sigma (\Delta_D)^2$ were used to evaluate σ. The mathematics of these operations are shown above, and it was not felt that it would be necessary to show their step by step calculation. However, as it has been mentioned on page 75, since it would not be possible to include all the statistical analysis data, only one page containing some of these data is enclosed here.

Freq. cps	Di	$\bar{D}$	Δ_D	$(\Delta_D)^2$	σ	α
12.5	.28		.02	.0004		
	.32		.02	.0004		
	.26		.04	.0016		
	.30		-	-		
	.32		.02	.0004		
	.34		.04	.0016		
	1.82	.30		.0044	2.71×10^{-2}	1.11×10^{-2}
16	.18		.03	.0009		
	.25		.04	.0016		
	.16		.05	.0025		
	.18		.03	.0009		
	.24		.03	.0009		
	.26		.05	.0025		
	1.27	.21		.0093	3.94×10^{-2}	1.60×10^{-2}
20	.12		-	-		
	.14		.02	.0004		
	.08		.04	.0016		
	.08		.04	.0016		
	.12		-	-		
	.16		.04	.0016		
	.70	.12		.0052	2.94×10^{-2}	1.20×10^{-2}
25	.09		.01	.0001		
	.13		.03	.0009		
	.08		.02	.0004		
	.10		-	-		
	.12		.02	.0004		
	.08		.02	.0004		
	.62	.10		.0022	1.92×10^{-2}	$.79 \times 10^{-2}$