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# NASA/UNIVERSITY ADVANCED DESIGN PROGRAM

## PROOF OF PRINCIPAL FOR
## STAIRCASE AUGER CHIP
## REMOVAL THEORY

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[redacted]

AUG 1987

ORIGINAL PAGE IS
OF POOR QUALITY

Group #5
ME 4182
Summer 1987

Dr. W. Williams
School of Mechanical Engineering
Georgia Institute of Technology

Dear Dr. Williams:

Accompanying this letter is the report containing the proof of principle research of the staircase auger. The report contains extensive dynamic analysis of particle motions in the auger. Using a computer program to iterate the governing equations, an optimization of auger constraints was performed and the results were as follows:

Helix angle = 60 degrees
Step height = 0.113 meters
Stroke Length = 0.01 meters
Frequency range = 42 - 67 hertz
RPM range = 0 - 100 rpm
Volume flow rate range = .0054 - .0088 m^3/sec

A column buckling analysis was also performed and the results yielded a minimum inner diameter of 0.07 meters and a wall thickness of 0.05 meters.

The report includes graphs and calculations to supporting our recommendations. The report also includes illustrations and design drawings of the drill bit and the drill string.

Thank you for your help and support through out the quarter. Also thanks to Dr. Brazel for allowing us access to his office and computer.

Sincerely,

Jeffrey B. Barron
Kenneth Kerns
Steven J. Breuch
Richard A. Rossi

Table of Contents

## ABSTRACT

This is a proof of principal design of the staircase auger theory for lunar drilling. The drill is designed to drill holes 30 meters deep and 0.1 meters in diameter. The action of the auger is .01 meter strokes at a varying number of strokes per second. A detailed analysis of the interaction of the auger and particle was done to optimize the parameters of the auger. This optimum design will allow for proper heat removal and reasonable drilling time. The drill bit is designed to scoop the particles into the auger while efficiently cutting through the moons surface.

# PROBLEM STATEMENT

The objective of this project is to design a proof of principal model for the Staircase Auger chip removal theory for lunar drilling. The auger is to be designed to drill a hole 30 meters deep and 0.1 meters in diameter. To prove the staircase auger is effective it is necessary to design a model to work in earth's atmosphere and added gravity. The design should remove the chips at an optimum rate that is both efficient and not time consuming.

Some constraints on the design are:

a) The gravity encountered on earth will greatly change the trajectory of the particle after impact. The angle needed to clear each step must be recalculated to account for this.

b) At the point of impact, the chips need to quickly be removed to decrease heating of the bit. The bit must have holes to "scoop" the particles on to the staircase to begin the path up the drill string.

If the constraints can be feasibly meet, material, structural stability, and other components of the total design will be considered and if time permits working drawings of the design will be developed.

## INTRODUCTION

The need for a drill that can operate on the moon is evident. It will allow for lunar excavation for a manned lunar base as well as technological advancement in the area of rock sampling and temperature data. An ordinary drill used on earth will not operate in the lunar environment. The moon has no atmosphere and is completely void of water. Therefore, the chip removal system nust be some type of auger. It must be completely mechanical in nature with no fluid medium to flush debris out of the hole.

### Lunar Characteristics

There are several characteristics of the lunar environment that will have an effect on the design. The temperature on the moon varies from about 134 C (270 F) in direct sunlight to about -170 C (-270 F) at night. This will limit the times and location the drill can operate. The results of thermometer and heat flow instruments tests concluded that the temperature in the lunar soil decreases about 1.8 C per meter. In the regions of rock below this soil the temperature increases only about 0.03 C per meter. Thus for the purpose of this design, the temperature will be a fairly constant -43 C. The moon has no atmosphere and is completely viod of water and the gravitational force is only 1/6 that of earth.

### Lunar Geology

In considering the problem of lunar drilling it is necessary to know what type of rock will be encountered below the moon's surface. To date, it is not known exactly what the moon is made of below a depth of a few meters. The first few meters of the lunar surface are basically dust from the perticles that constantly bombard the surface of the moon. This layer is called lunar regolith and is composed of igneous rock, breccia, glass beads, and fine perticles knowen as lunar dust. Seismic tests have been conducted of the moon that have given scientists an idea of what lies beneath the thin layer of lunar soil. It is theorized that there is a layer of broken and cracked rock about a kilometer thick. Below this is a more solid layer of rock that extends about 25 kilometers. This rock has properties that closely resemble that of basalt. Basalt is a fine-grained volcanic rock composed primarily of pyroxene and calcium-rich feldspar

Since the moon is primarily volcanic, the effect of molten material has been detected. The smooth flat basins of some of the larger craters are made of this solidified molten rock. As meteors impacted the surface of the moon years ago, the molten basalt was released and filled the crater. One instance where the lava overflowed and covered the surrounding area is mare tranquillitatis (sea of tranquility). Here the layers of basalt are up to 30 meters deep. This type of rock is layered where the original crust is mostly broken rock. This report uses these types of rock as a guidline for the design.

A theory for chip removal has been proposed. It consists of two helical ramps with steps on which the debris rest. This report is a proof of principal for the staircase auger theory. In order to prove this theory will opaerate on the moon it is necessary to test in on earth. An analysis of the theory with the added constraints of the earth's environment is presented here.

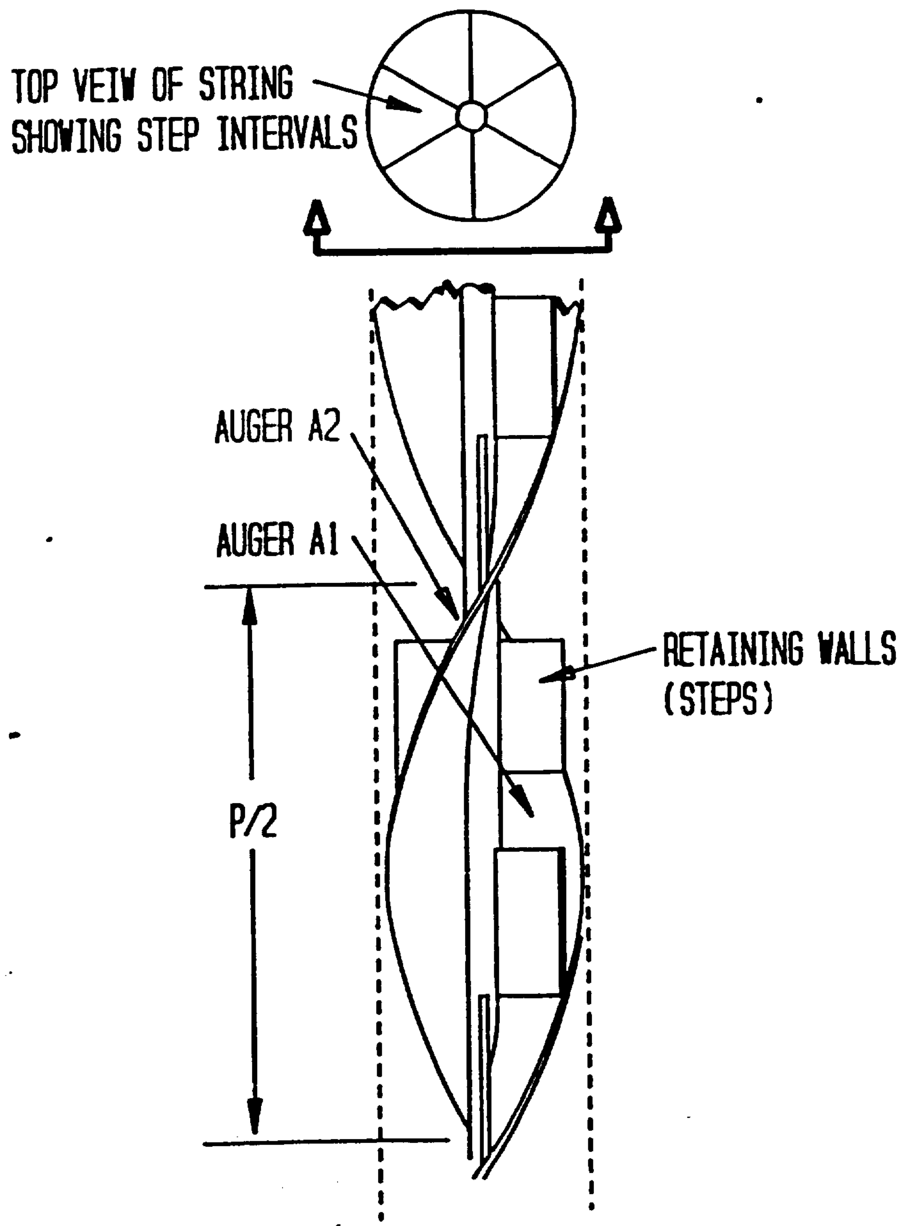
## Drill String

### Description

Flushing the drill hole with water or air to remove drilling cuttings is not feasible in the lunar environment. The lack of any hole cleaning fluid and the prohibitive cost of transportation forces the development of a new and efficient method for completing this task. The staircase auger is a chip removal system which is purely mechanical and does not require any medium to clear the hole of debris.

The drill string consists of ten, three meter long hollow cylinders. Fixed within these segments are two helical ramps that travel the length of the drill string. The ramps have steps at 60 degree intervals that serve as retaining walls to keep particles from sliding down the auger (See Figure 1 on following page). The auger works on the same principal as a jackhammer. A hydraulic pump provides a reciprocating and rotary motion for the drill string. This vibratory motion will "shake" the particle up and out of the auger. When the auger is on the upward half of a cycle the particle is lifted with it. As the auger begins its downward stroke the particle continues to move upward until it impacts the bottom of the helical ramp above it. This impact will cause the particle to reflect back down to a resting position on the next "stair". This motion will be repeated until the particle reaches the top of the drill string. Once at the top the particle will be deflected in the same manner through a hole in the last segment. A deflector is placed just above the hole in the drill string to ensure that the particles do not clog the hydraulic drifter or interfere with the operation of the drill support mechanism. (See figure 7).

FIGURE 1. VEIWS OF THE DRILL STRING



String/String Interface

During drilling, segments of the string need to be added as required or removed in the case of clogging. The interface must be accurate to within 5 degrees to ensure that the helical ramps line up to enable the particles to continue up the ramp. Square threads are chosen to connect the segments to prevent overtightening due to the constant torsional load. The end of the thread will "block" any further tightening that may be caused by the constant torsional load. Two spring loaded fasteners lock the segments in place to prevent any possibility of loosening due to backlash from the torsional load. Figure 6 in Appendix A is a diagram of the interface. When it is necessary to add or remove a segment a robotic arm can be programed to release the fastener as it grips the string segments.

Dynamic Analysis

The Dynamic analysis of the staircase auger is the most important part of this report. It describes the motion of a particle within the auger. From this description parameters of the motion can be optimized for the most efficient chip removal. This analysis was done including the added gravitational force encountered on earth. The equations can be applied to the lunar environment by reducing gravity to 1/6 that of earth. It is necessary to develop a mathematical model for both the auger and a particle inside the drill string.

The auger has two types of motion; an oscillating motion at frequency $w_v$, and an angular rotation at $w_r$. The drill is powered by a hydraulic hammer which inputs power via a square wave.

The hydraulic hammer inputs power via a square wave. The actual acceleration of the drill string is sinusoidal because of inertia. Figure 2 is a comparison of these two waveforms. Figures 3 and 4 show the velocity and position of the drill string.

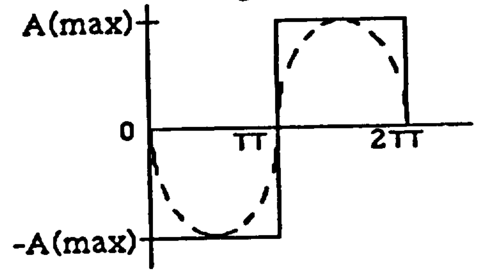



Figure 2 - Force Input From Hydraulic Hammer (Dashed Line-actual)

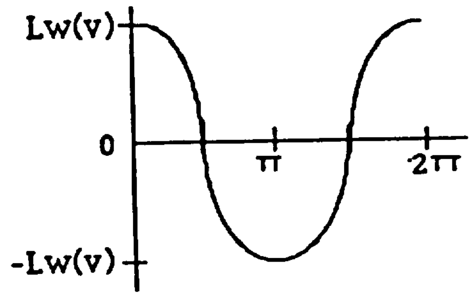



Figure 3 - Velocity of Drill String. Sinusoidal due to inirtia

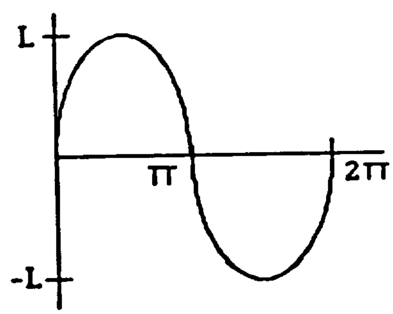



Figure 4 - Vertical Position of the Drill String

The amplitude of the movement of the drill string is stroke length l, therefore the, z, vertical position of the string is, $z = L\sin(w_r t)$. For this analysis, the first helical ramp will be called auger 1 ($A_1$), and the second ramp will be called auger 2 ($A_2$). To mathematically model the auger a moving frame of reference was chosen. At time zero, the first auger, $A_1$, and the particle have a position of $z = 0$. The second auger's position is half the pitch above both the particle and $A_1$ (See Figure 1 in Appendix A).

The auger appears to be moving up the drill string at a slope of

$$m = P/2(pi)D.$$

where pitch is given by $P = (pi)Dtan(psi)$ and $w_r$ is the angular rotation. Therefore, the position of $A_1$ and $A_2$ with respect to time are

$$Z_{A1} = Lsin(w_rt)=(P/2(pi))w_rt$$

$$Z_{A2} = Lsin(w_rt)+(P/2(pi))w_rt+P/2$$

respectively. Taking the derivitives of the position equations with respect to time will give the velocity equation,

$$V_A = Lw_v cos(w_v t) + Pw_r/2(pi)$$

The auger, $A_1$ and the particle are in contact until the drill string reaches its maximum speed,

$$V_{max} = Lw_r + Pw_r/2(pi).$$

At this point the particle separates from A1 and is only slowed by gravity. This gives the particle a velocity and position of

$$V_p = -gt + V_{max}$$

$$Z_p = -.5gt^2 + V_{max}t$$

respectively.

Since the drill string is rotating at $w_{r1}$, most of the particles will be located at the outer portion of the drill string. This causes the particle to move up along the inner wall of the drill string following an arc and to strike the upper ramp $A_2$ at time $t_1$. This happens when $z_1 = z_2 = z_p$. During this time the drill string is rotating under the particle. This rotation, $(theta)_0$, is found by

$$theta_0 = w_r t_1.$$

When the particle strikes A2, we assume that it is an elastic collision where the particle is reflected at angle gamma and velocity

$$V = V_p(t_1) + V_A(t_1) \quad \text{(See Figure 5 below).}$$

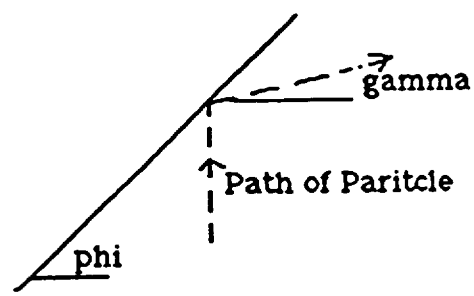



Figure 5 - Reflection Angle Gamma

Using simple geometry, gamma is found by the equation

$$gamma = phi - (180 - (phi + 90))$$

where phi is the helix angle of both augers. The particle is now given both a vertical and horizontal velocity. The position of the particle is now given by two equations. The vertical component is

$$Z_p = -g/2t^2 + V\sin(gamma)t + Z_1$$

The horizontal component is

$$Y_P = V\cos(gamma)t$$

The particie is traveling through an arc creating an arc length, A

$$A = r(theta)$$

A is equal to the horizontal distance Y so that

$$(theta)r = V_p\cos(gamma)t.$$

While the particle is traveling in its arc, the drill string is still rotating under it. This is given by

$$theta_A = w_r(t-t_1)$$

so that the total rotation achieved by the drill string and particle is

$$theta = theta_0 + theta_A + theta_p$$

which is

$$theta = theta_0 + Vcos(gamma)t + w_r(t-t_1).$$

Since the steps are located at 60 degree intervals, the particle passes over the step location at time $t_2$ and height H (See figure 6 below). Time $t_2$ is found from

$$60 = theta_0 + V/rcos(gamma)t_2 + w_r(t_2-t_1).$$

At time $t_2$, the position of $A_1$ is

$$Z_{A1} = Lsin(w_r t2) + Pw_r t_2$$

and the particles vertical position is

$$A_p = -g/2t_2^2 + Vsin(gamma)t_2 + Z_1.$$

Subtracting ZA2 from Zp gives H.

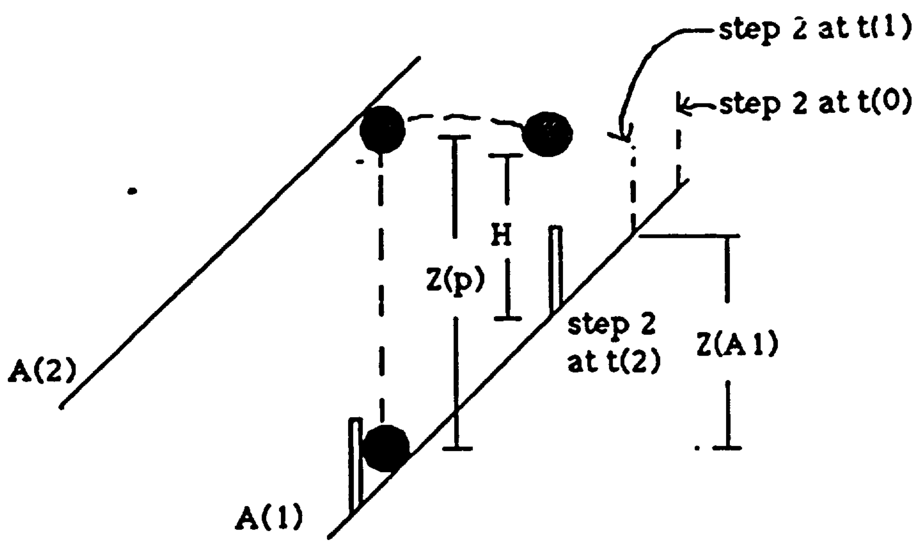



Figure 6 - Height of particle vs. rotation (linearly represented) of drill string and particle.

Once the particle has cleared the first step it will go on and strike A1 elastically and be reflected up toward A2 at an angle greater than 90 degrees. The particle will strike A2 and reflect off at an angle greater than the original gamma thus ensuring it will clear the subsequent step. This will continue until the particle settles down in another step where the cycle will start again. This process will cause the cuttings from the drill bit to travel up and out of the drill string using the vibration and rotation of the drill, thus providing and effective way of removing cuttings without a flushing agent. Figures 1 through 3 in Appendix A give a three dimensional view of the motion of the particle inside the drill string. Figure 4 gives a graphical representation of the motion of the particle and the positions of the augers, $A_1$ and $A_2$.

A computer program was used to calculate the position of the auger and particle over time using the equations derived above. From the position of the particle in its trajectory, the maximum step height the particle is able to clear can be calculated for different helix angles. The computer program was set up in a way that the different parameters could be changed so the effect of each parameter on the system could be observed. For example, frequency was varied to determine the effect on step height. The program iterated to generate data which was plotted. The plots were used to optimize the helix angle and step height for the most efficient chip removal rate. A calculation of step volume as it was used in the program can be found in appendix D. Figures 1 through 7 in the Appendix B show the plots. A documented copy of the program can be found in Appendix D.

The plots show the effect of each parameter on the system. Conclusions about what the optimum stroke length, helix angle, step height, and ranges of rpm and frequency were determined from the plots.

Figure 1 is a plot of step height vs. rpm at various stroke lengths. It shows that as stroke length increases, the maximum step height the particle can clear increases. This is because the particle velocity, Vp, is increased with a higher stroke length. The particle will rebound off auger 2 with more velocity and thus be thrown farther.

Figure 2 is a plot of volume flow rate vs. helix angle at varied frequency and 100 rpm. The curve for each frequency shows a range of helix angles that maximize volume flow rate with a peak angle of about 60 degrees. The volume flow rate is dependent on frequency because at higher frequency, debris is transfered from step to step more times per minute. The volume flow rate is zero for angles between 0 and 21 degrees. This is because the angle is so slight, the particle will not reach the next step. All the curves begin to fall off at an angle of about 70 degrees and will cross the horixontal axis at 90 degrees. This is expected because at 90 degrees the helical ramps are vertical and there will be no collision at all.

Figure 3 is a plot of helix angle vs. step height at varied frequency and 200 rpm. It can be used to optimize step heights. It is seen that above a certain helix angle, each curve levels off. This is because at that particular frequency, the particle is traveling at a velocity at which it cannot reach the upper auger before the auger has rotated 60 degrees. Since the steps are at 60 degree intervals, the particle has cleared the next step before impacting the upper auger. Therefore at a frequency of 42 Hz, the particle can clear a maximum step height of 0.113 meters. Since frequency will be varied from 42 to 67 Hz during drilling for the different hardnesses of rock, this is a maximum step height. This graph shows that step height is only dependent on frequency because it gives the particle the velocity that determines whether or not it will impact the upper auger before a rotation of 60 degrees. Step height is zero for helix angles below 20 degrees for the same reason volume flow rate is zero in this same range, i.e. the angle is so slight the particle will land on auger 1 without traveling the 60 degree interval and reaching the next step.

Figure 4 is a plot of step height vs. frequency. at varied rpm and helix angle of 60 degrees which shows an increase in step height with increasing frequency. It confirms the conclusions of figure 4 that under the worst conditions for particle removal (frequency = 42 Hz and rpm = 200) the maximum step height is 0.113 m.

Figure 5 is a plot of volume flow rate vs. helix angle at varied rpm, frequency of 42 Hz, and stroke length of 0.005 meters. This plot was done as a worst case with the lowest frequency and stroke length. At the optimum helix angle of 60 degrees, the volume flow rate drops off with increased rpm. Some sort of feedback control is necessary in a case like this to vary frequency and rpm to keep volume flow rate maximized. As rpm is increased frequency must be increased to ensure the particle will clear the next step as was discussed above in the section on helix angle vs. step height. This will keep the volume flow rate from dropping off as it does in the plot. This figure is very similar to figure 2 (Volume flow rate vs. helix angle with varied frequency). Both show noticeable peaks and valleys on each curve which are at the same helix angles. For example at about 36 degrees on both plots there is a noticeable valley. This is because at this combination of helix angle and frequency or rpm the partical will have a harder time clearing the next step, thus decreasing volume flow rate.

Figure 6 is a plot of step height vs. rpm with varied frequency and the optimum helix angle of 60 degrees. It supports the conclusion of figure 5 that to keep a maximum step height, frequency must be increased with increasing rpm. Thus a human operator or feedback control loop is necessary to vary frequency and rpm.

Figure 7 is a plot of impact velocity vs. frequency at different stroke lengths. It shows that as frequency increases, impact velocity increases. Also, an increase in stroke length will increase impact velocity. This is expected because at higher frequency, the auger is naturally moving faster. An increase in stroke length will allow more time for the auger to gain velocity.

## Hydraulic Drifter

To produce the type of motion required by the staircase auger theory, a Gardner-Denver HPR1 hydraulic drifter is chosen. It was selected because it delivers a range of force that is satisfactory for this design and the operational impact frequency range was within our estimated requirements. The HPR1 has infinite variability of impact energy and frequency within the operating range. It also can be either fixed at a desired level or remotely controlled to vary frequency and impact energy. This is required because these parameters will need to be varied during drilling for the different hardness of rock that may be encountered. The operational specifications of the drifter are

Weight = 147 Kg

Impact Energy: 170-271 J

Impact Frequency: 4000-2500 BPM (47 - 67 Hz)

Rotation Speed: 0 - 200 RPM

Rotation Torque: 339 Nm (max)

For more information on the HPR1 see Appendix D for manufacturers specifications.

## Force Analysis

In order to complete the analysis of the drill string it is necessary to consider the effect of the constant impact force that the auger requires. The drill will reach lengths of up to 30 meters, and it is only 0.1 meters in diameter. The force required to penetrate rock is quite large and a column of this length is susceptible to failure. A column analysis was done on the drill string using the entire length as a worst case. A Euler column analysis was performed with varying inner and outer diameter. The the inner diameter that yielded the best results was 0.07 m. This allows for a wall thickness of 0.015. The critical load ($P_{cr}$) at which any aditional load will cause failure is 8.7554 N.

The formula used to calculate the force delivered by the auger is

Power = Impact Force x impact velocity.

where Power is the power output of the drifter. From this equation, the worst case of impact force is 10.10 N . Using this impact force and $P_{cr}$, the factor of safety for the column is n = 1.154. This is a conservative estimate since the drill string will have the additional support of the walls of the hole while it is underground. Appendix C contains the supporting calculations for this analysis.

In addition to compressive load, there is a torsional load on the drill string. To determine if failure will occur under this load, the torque delivered by the drifter and the compressive force calculated above are used in a Mohr's circle analysis. From this analysis the maximum shear stress is found to be 2.514 MPa. The endurance limit under shear is compared to this value to determine if any kind of fatigue failure will occur. The shear endurance limit is found to be 73.85 MPa therefore, upon comparison it is seen that the drill string will not fail from the torsional load (See Appendix C for calculation).

Material

The material for the drill string needs to be strong yet ductile so it is able to withstand the constant impact force necessary to penetrate rockwithout fracturing. For the earth application of the auger, plain carbon steel has the most desireable parameters. There are a number of plain carbon steels to choose from, each having a different carbon content. AISI 1045 was selected for this analysis because it has high strength (SY = 245 Kpsi = 1689 MPa) to handle the forces inherent in the system. This steel has a carbon content of .45% which allows enough ductility to prevent fracture (Supporting calculations can be found in

Appendix C). For this type steel, the mass of the drill string is 967.46 Kg.

While steel is the best choice for the earth design of the auger, it is much to heavy for the lunar application. The cost of transportation to the moon and on the moon's surface requires a light weight design. Titanium is chosen for this application because of its strength to weight ratio, even though it is much more expensive than steel.

## Drill Bit

### Description

For the drill to work efficiently, a drill bit must be designed to immediately lift the particles into the helical ramp of the auger. In doing this, heat is removed with the chips. Conventional drill bits cannot be used because they use fluids, such as water or compressed air, to push the particles to the surface and cool the bit.

The drill bit is a flat face design with four cutting edges. Two are designed with three teeth for chipping through rock. In front of these two edges in the direction of rotation are holes to lift the particles into the auger (See Figure 5 in Appendix A). Some of the chips will be knocked directly into the auger from impact. The rest will be scooped into the auger by the rotating action of the drill string. To prevent clogging, the size of the holes are small to limit the size of the chips entering the auger. The other two cutting edges are designed without teeth. If some of the debris is too large to enter the auger, these edges will crush them in to smaller pieces on the next stroke.

### Material

Since the drill bit is the section of the drill that comes into contact with the rock, it has to be able to withstand the impact forces necessary to cut through it. The bit material must be strong yet ductile and be able to withstand the high temperatures caused by friction. Some conventional materials used for drill bits are diamond tip, ceramics, and ferrous alloys. Although ceramics and diamond tip are strong enough to cut through the type of rock that will be encountered on the moon, ceramics are too brittle and diamonds cannot be attached to the bit strongly enough to withstand the constant impact. Plain carbon and low alloy steels exhibit some desirable properties. The level of carbon in the steel has a great deal to do with the strength and ductility of the material. If there is too much carbon present there will be a high level of carbide. Carbide is very strong but it is also brittle and will fracture from the impact force of the auger. However, if the material is heat treated and cooled properly the carbide will have a better shape and distribution and thus higher ductility. This type of material is called Spheroidite. The material which exhibits the best properties is a high alloy tool steel. The advantage of this material is that it is treated in a way which gives it high strength and temperature resistance. H grade steels are used for high temperature applications but because of their low carbon level, secondary hardening is necessary to give strength. M and T grade tool steels are used for high-speed applications and are both strong and fracture resistant.

Cooling

An assumption of the staircase auger theory is that heat will be removed with the debris. The drill bit is designed to immediately scoop the particles into the auger and away from the cutting edges. The hottest area on the drill will be these cutting edges so some additional cooling will be necessary in this area. A configuration similar to that in automobile valves can be used. A solid such as sodium that has a melting point near the temperatures encountered fills a cavity in the teeth. As the temperature of the bit reaches that of the solid, it will melt and begin to move around in the cavity. As it moves it will redistribute the heat, thus getting it away from the cutting teeth. To distribute the heat further, the wall of the drill string can be lined with a conducting sleeve made of a material such as copper. An analysis of the amount of heat that will be encountered will determine how many of the string segments must be lined to properly distribute heat.

## Bit/String Interface

The drill bit is one piece so when it becomes worn, the whole bit must be replaced. The bit and drill string segments are threaded, the bit male, and the bottom of the string segment female. The threads are square and right handed, and the same type pin is used for the same reasons discussed in the string/string interface section. This pin will also serve to lock the bit in place in a way that the helical ramp and cutting holes will be in line. This will allow for efficient cutting removal and help prevent clogging. When a bit needs to be replaced, a robotic arm can easily depress the locking pin and remove the it from the last segment of the drill string. This operation should be done after drilling so the entire drill string need not be disassembled on site.

## PERFORMANCE

The penetration rate of the drill string through rock is given by the equation $P.R. = (\text{impact energy})(f)/(S_c)(A)$

where impact energy is given by manufacturer's specifications, $S_c$ is the compressive strength of the rock, and A is the area of the drill bit. Figure 8 is a bar graph showing various penetration rates of the drill string through various hardnesses of rock. The strength of the rock on the moon would fall between medium and hard rock.

The volume flow rate of the auger is given by the equation

$$VFR = Vf$$

where V is the step volume at the minimum step height of 0.113 m and f is frequency. Figure 9 shows the volume flow rate of the drill string at various frequencies. Also shown in figure 9 is the volume flow rate comming into the drill string. This is calculated by $VFR_{in} = (P.R.)(A)$, where P.R. is penetration rate and A is the area of the auger. Figure 9 shows that the drill string is capable of transporting 83 times more volume, minimum, than the drill can produce.

## CONCLUSION

From the analysis done in this report, it can be concluded that the staircase auger chip removal theory is an effective system for chip removal. The plots generated from itteration of the various parameters of the auger give good results that lead to an optimum chip removal rate. The optimum parameters are

Helix Angle = 60 degrees

Step Height = 0.113 m

Stroke Length = 0.01 m

Frequency Range = 42 - 67 Hz

RPM Range = 0 - 100 RPM

Consideration of the forces involved and the types of failure that might occur lead to sleeve dimensions and material that allow for strength and weight constraints. The optimum sleeve thickness is 1.5 centimeters using AISI 1045 steel. The force analysis revealed that the drill string will not fail under the compressive or torsional loads involved even using conservative assumptions.

The drill bit is designed to cut the rock as well as scoop it into the drill string. To cut through rock and still be able to withstand the constant impact forces.

The staircase auger theory proves to be a very effective chip removal system. Results of penetration rate calculations show that the auger is capable of removing a minimum of 83 times the actual volume being cut from the hole.

# APPENDIX A

## Design Drawings

FIGURE 1. PARTICLES POSITION AT T=0

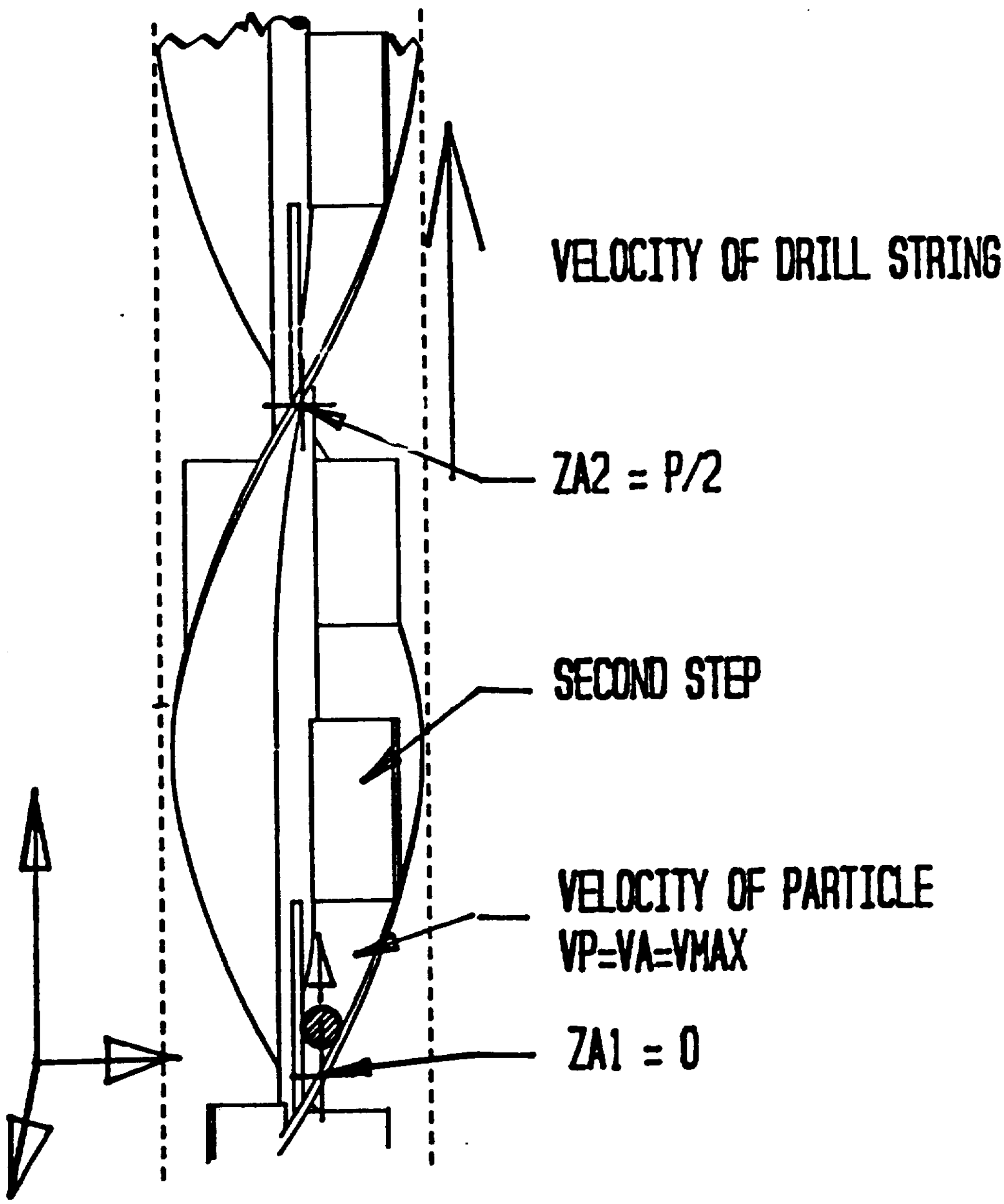


FIGURE 2. POSITION OF PARTICLE AT T=T1

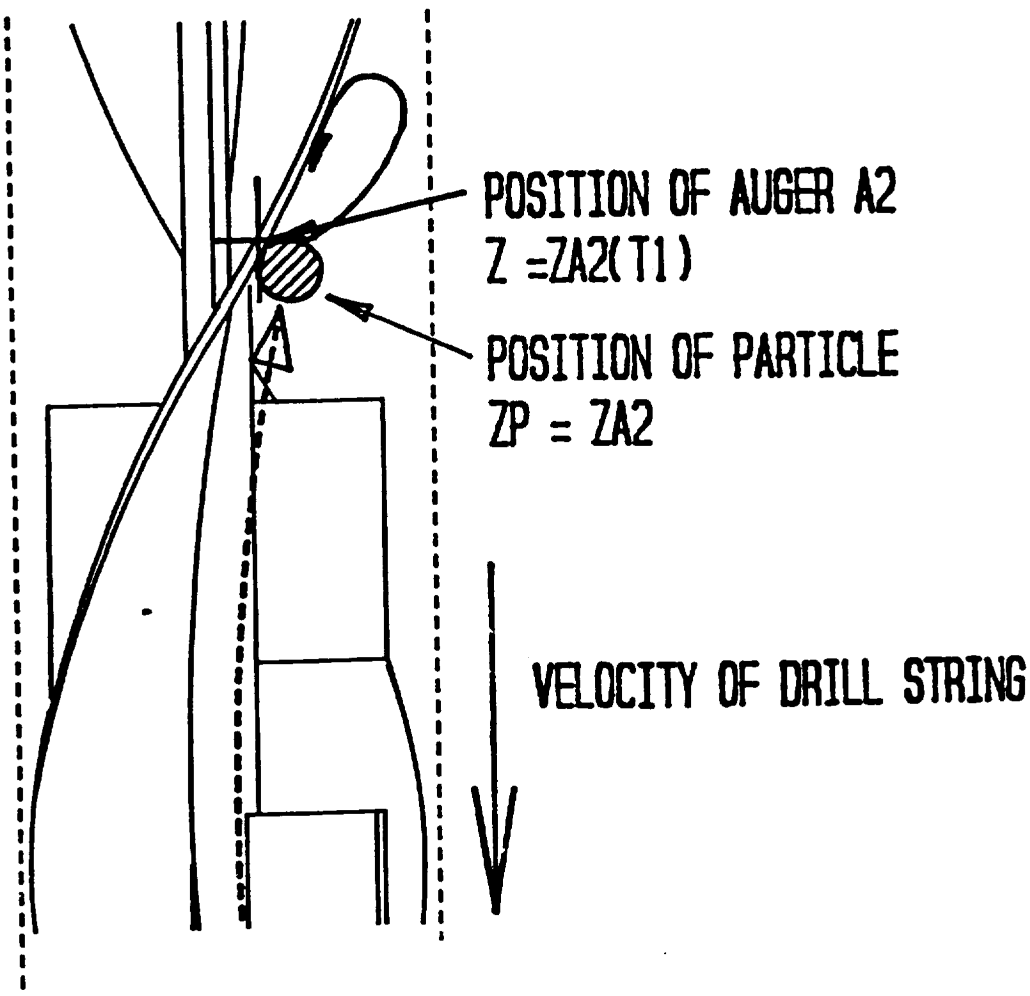
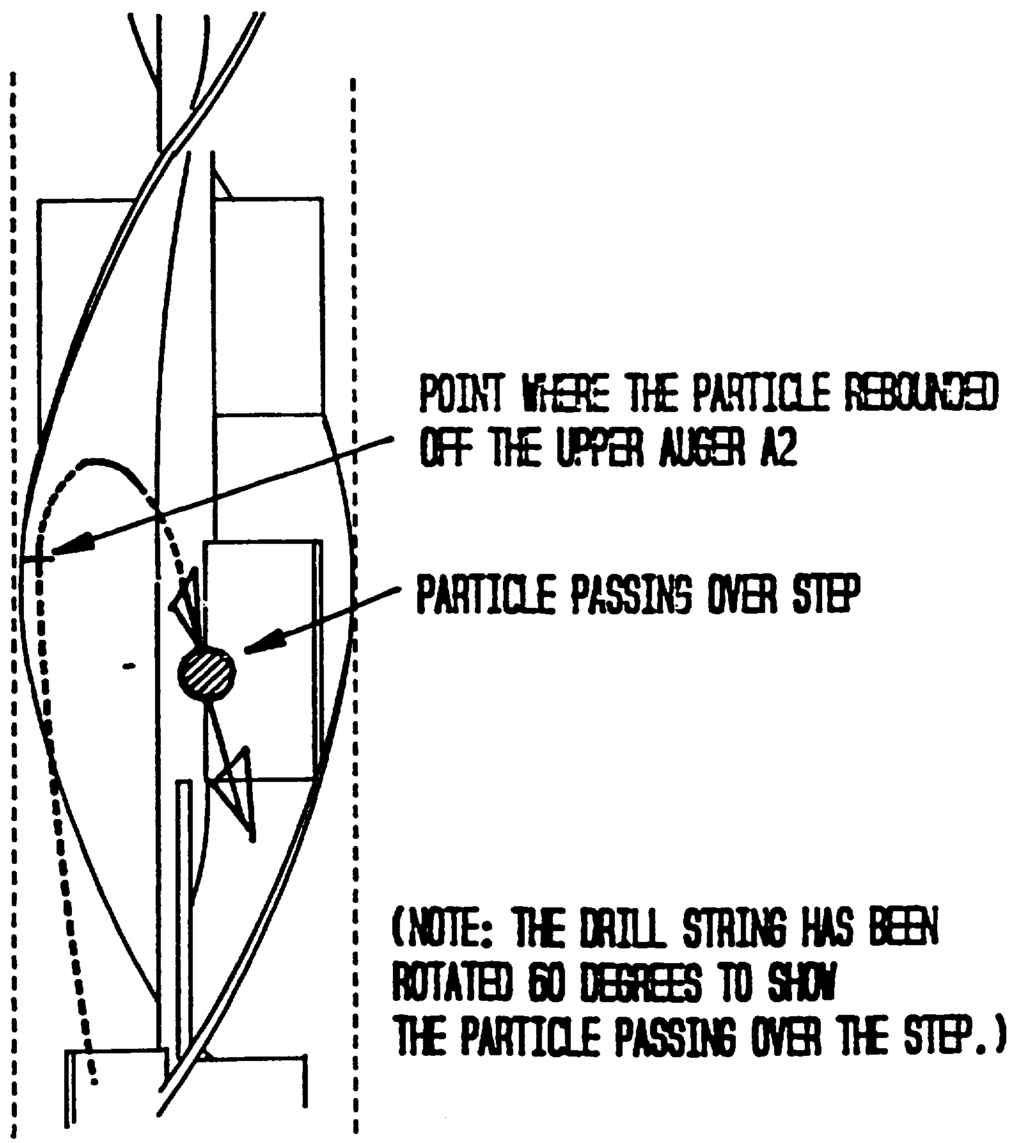


FIGURE 3. POSITION OF PARTICLE AT T=T2



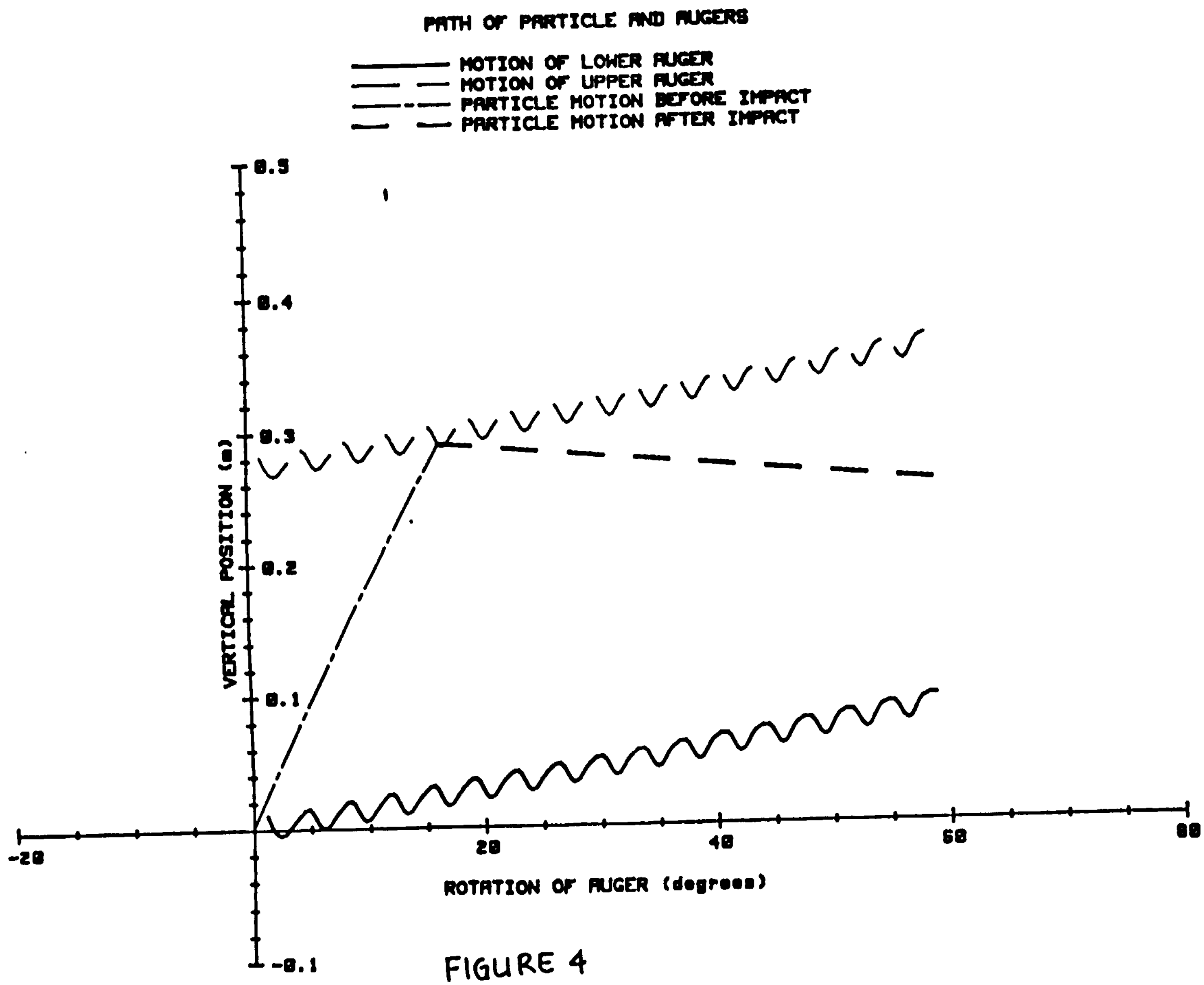
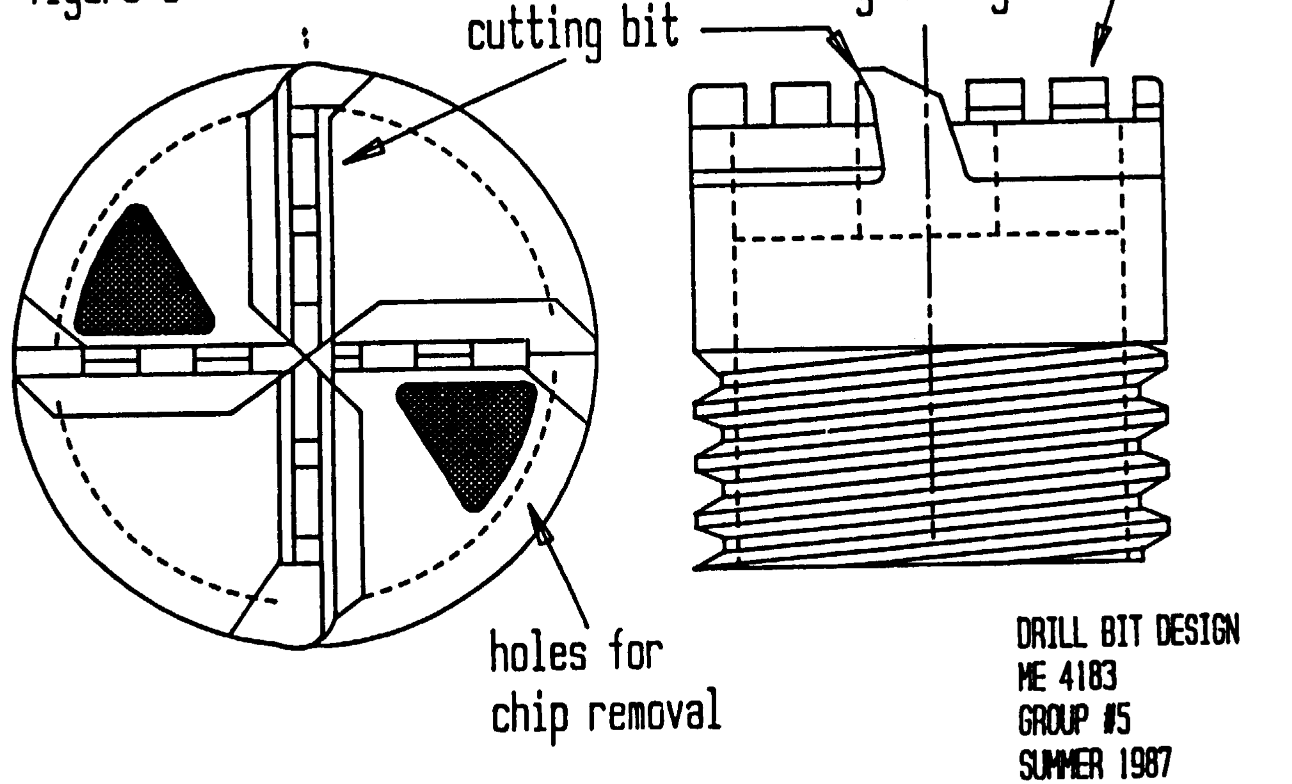
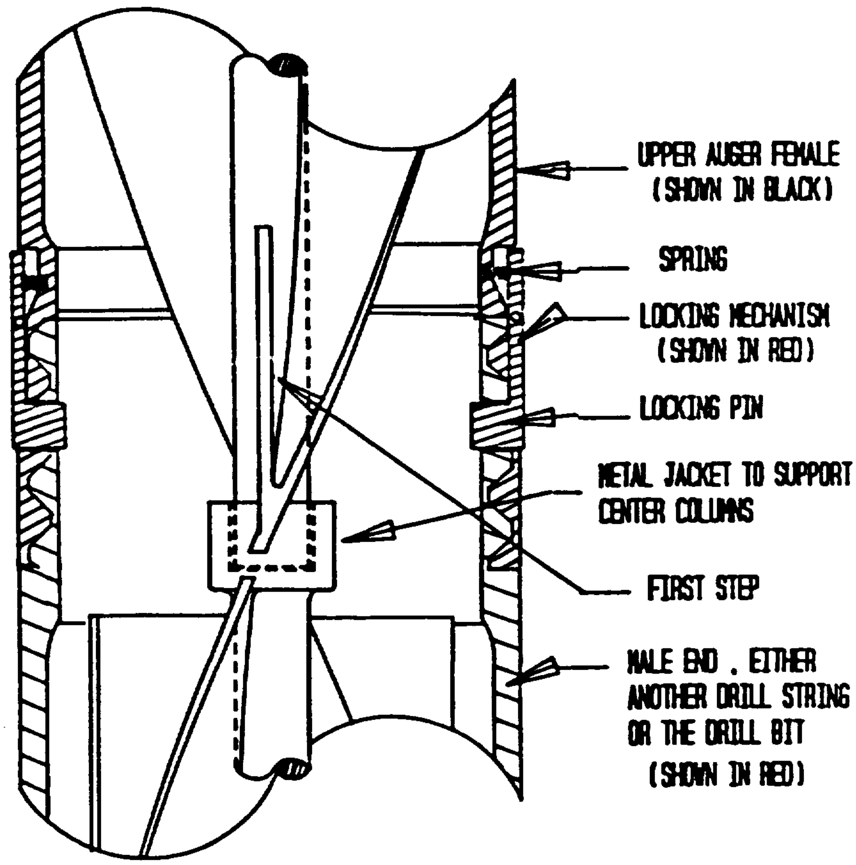

PATH OF PARTICLE AND AUGERS
MOTION OF LOWER AUGER
MOTION OF UPPER AUGER
PARTICLE MOTION BEFORE IMPACT
PARTICLE MOTION AFTER IMPACT
0.5
0.4
0.3
0.2
0.1
-0.1
VERTICAL POSITION (m)
-20
20
40
60
80
ROTATION OF AUGER (degrees)

FIGURE 4

figure 5


cutting bit
grinding bit
holes for
chip removal
DRILL BIT DESIGN
ME 4183
GROUP #5
SUMMER 1987

# CLOSEUP VEIW OF DRILL STRING ATTACHING MECHANISM

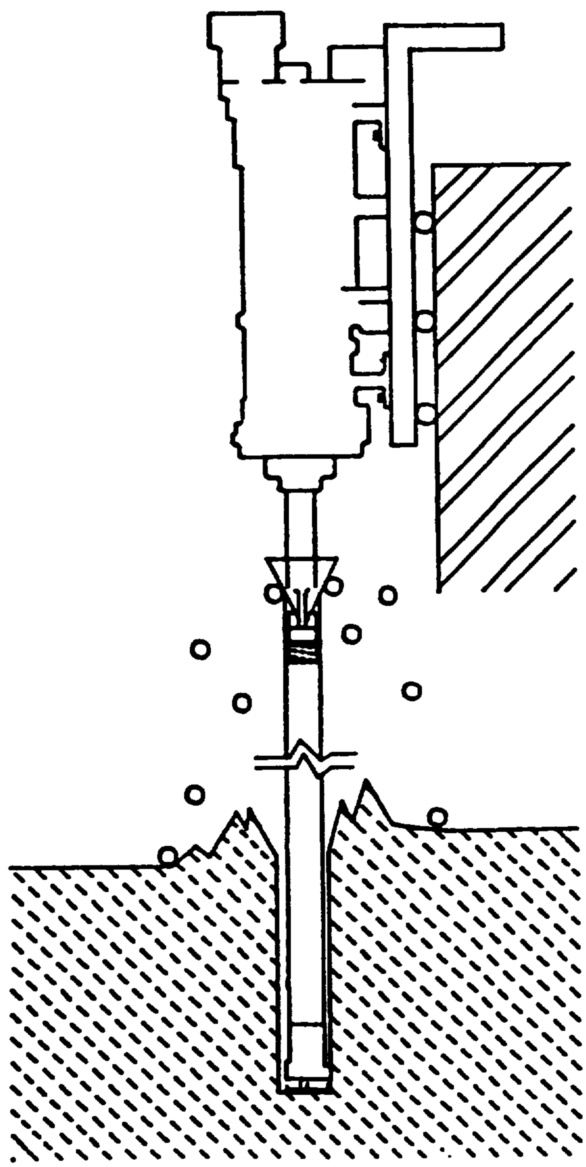



(NOTE: AUGERS HAVE NOT BEEN CUT FOR CLARITY.)

| | |
|---|---|
| ME 4182 DESIGN | SUMMER |
| GROUP NUMBER 5 | 8/25/87 |
| DESIGN DRAWING | |

FIGURE 6

FIGURE 7. HYDRAULIC HAMMER SET UP



( NOTE: A cone is deflecting the particals.)

# APPENDIX B

## Graphs

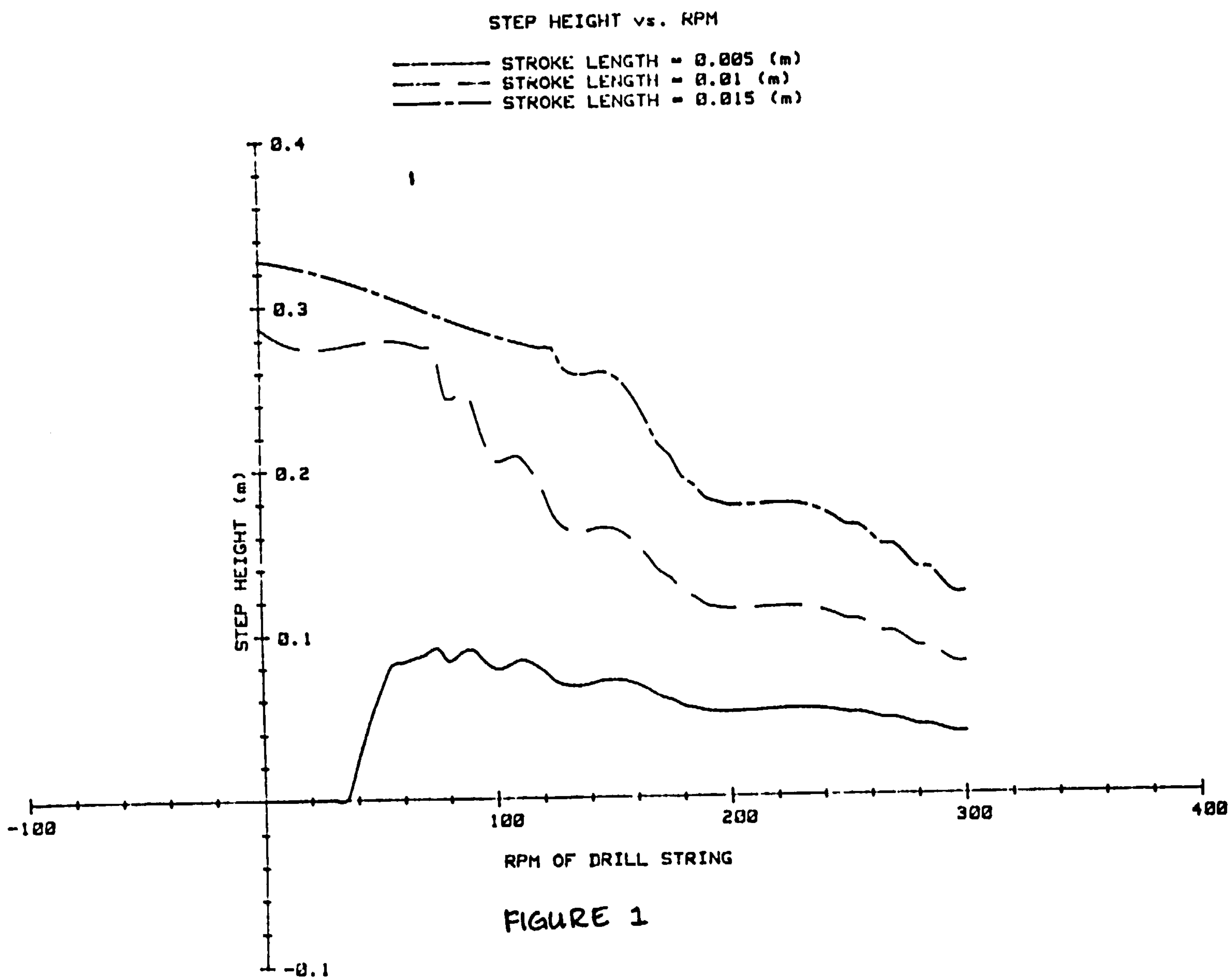

STEP HEIGHT vs. RPM
STROKE LENGTH = 0.005 (m)
STROKE LENGTH = 0.01 (m)
STROKE LENGTH = 0.015 (m)
0.4
0.3
0.2
0.1
-0.1
STEP HEIGHT (m)
-100
100
200
300
400
RPM OF DRILL STRING

FIGURE 1

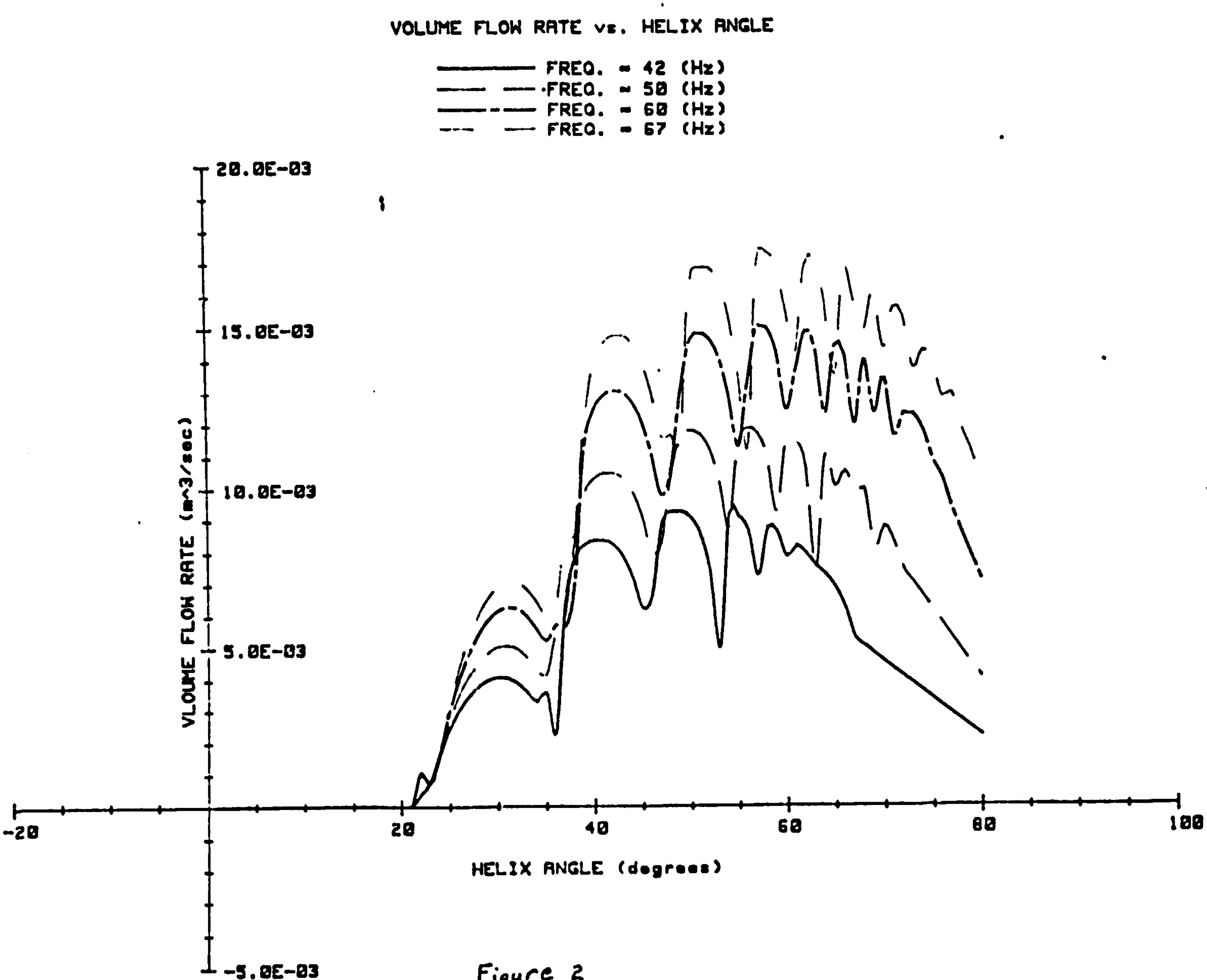

VOLUME FLOW RATE vs. HELIX ANGLE
FREQ. = 42 (Hz)
FREQ. = 50 (Hz)
FREQ. = 60 (Hz)
FREQ. = 67 (Hz)
20.0E-03
15.0E-03
10.0E-03
5.0E-03
-5.0E-03
VLOUME FLOW RATE (m^3/sec)
-20
20
40
60
80
100
HELIX ANGLE (degrees)

Figure 2

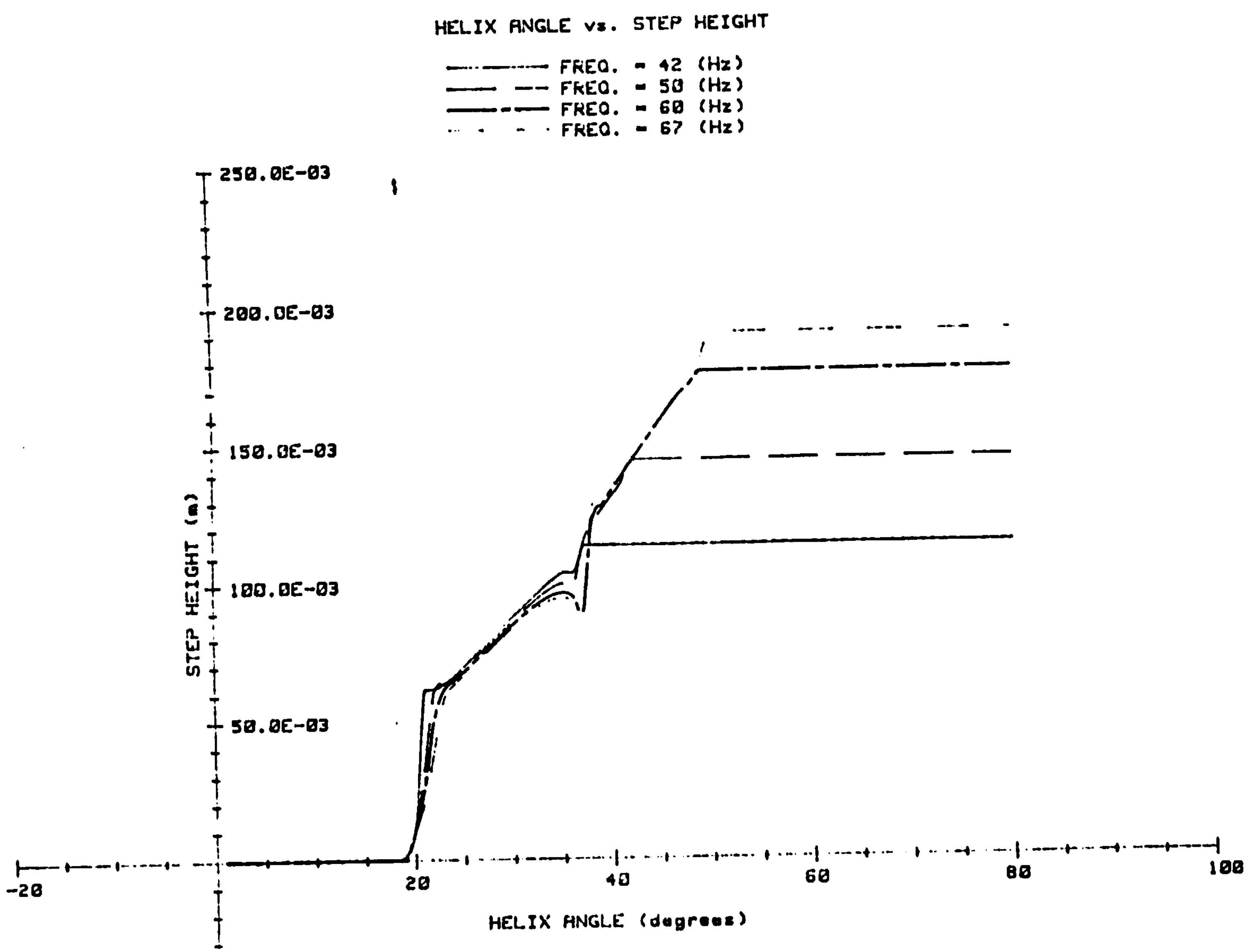



FIGURE 3

ORIGINAL PAGE IS
OF POOR QUALITY

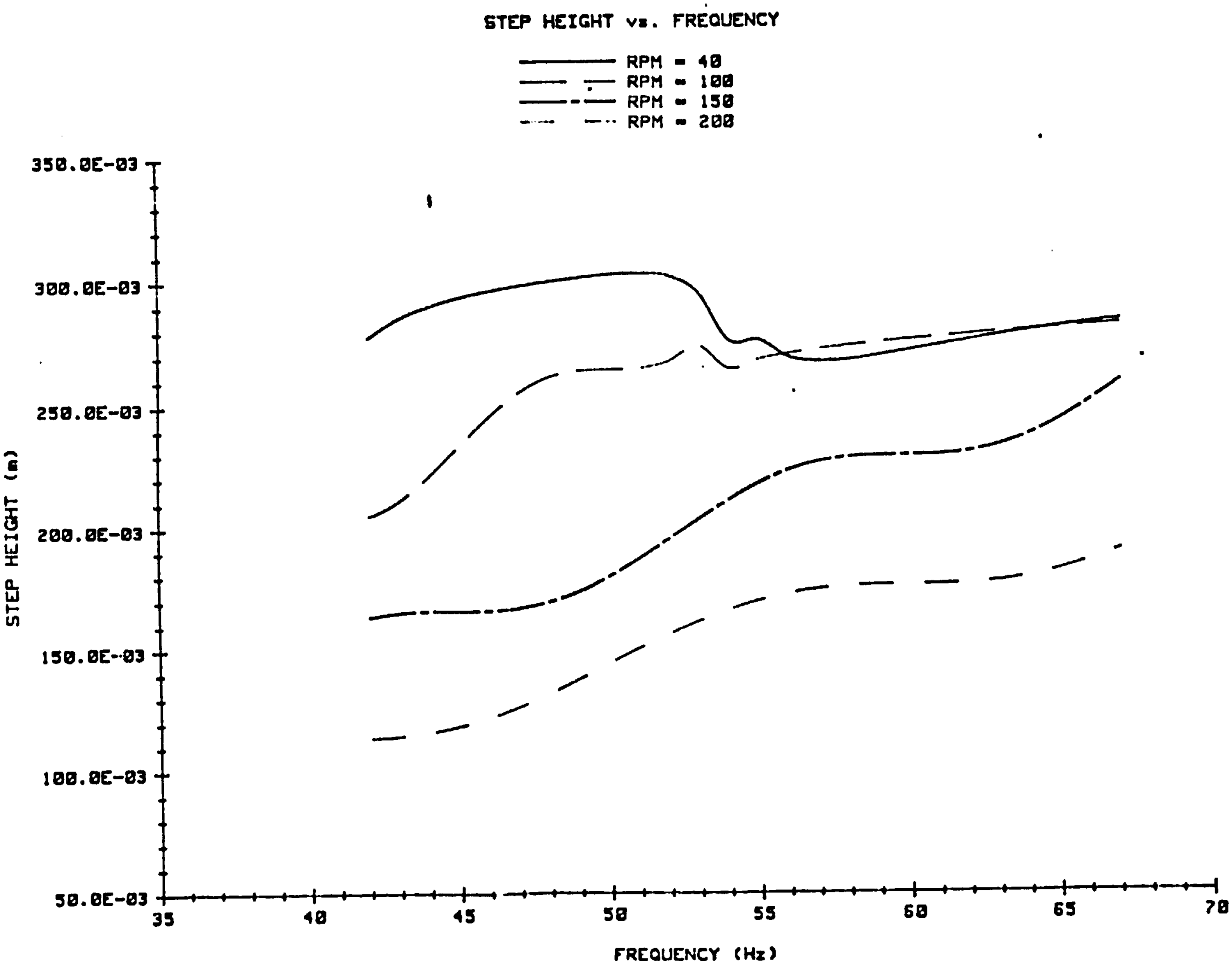



Figure 4

ORIGINAL PAGE IS
OF POOR QUALITY

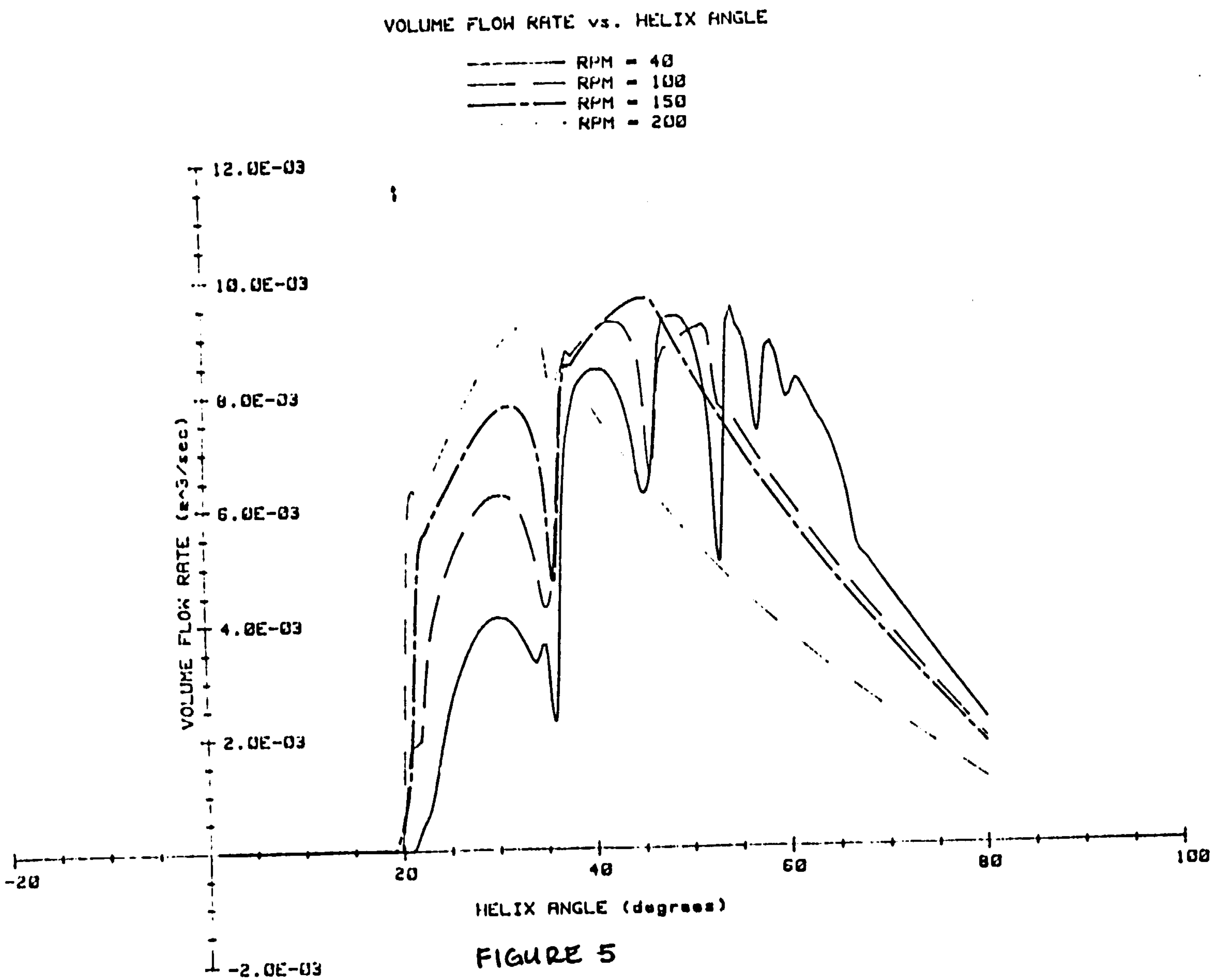

VOLUME FLOW RATE vs. HELIX ANGLE
RPM = 40
RPM = 100
RPM = 150
RPM = 200
12.0E-03
10.0E-03
8.0E-03
6.0E-03
4.0E-03
2.0E-03
-2.0E-03
VOLUME FLOW RATE (m^3/sec)
-20
20
40
60
80
100
HELIX ANGLE (degrees)

FIGURE 5

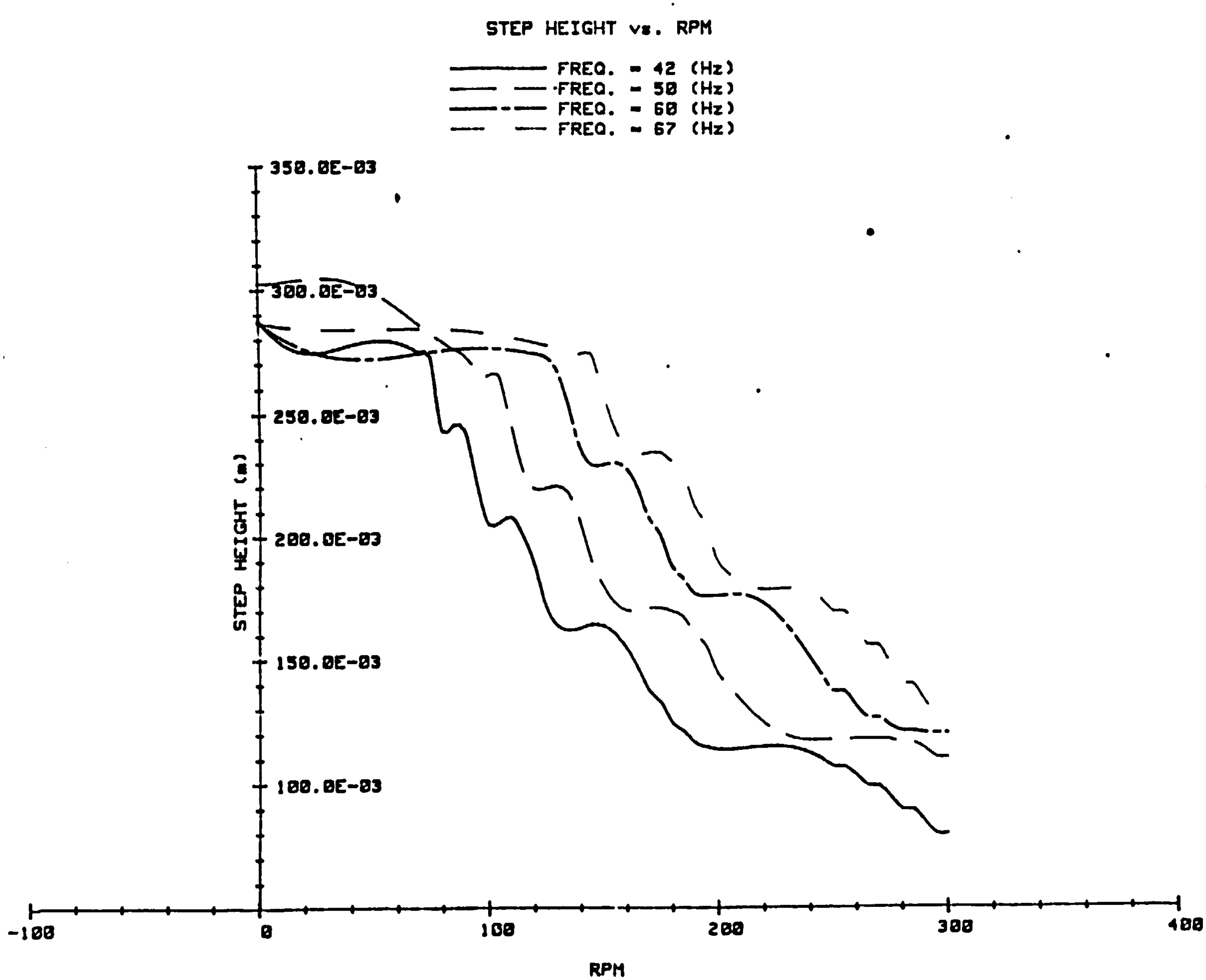
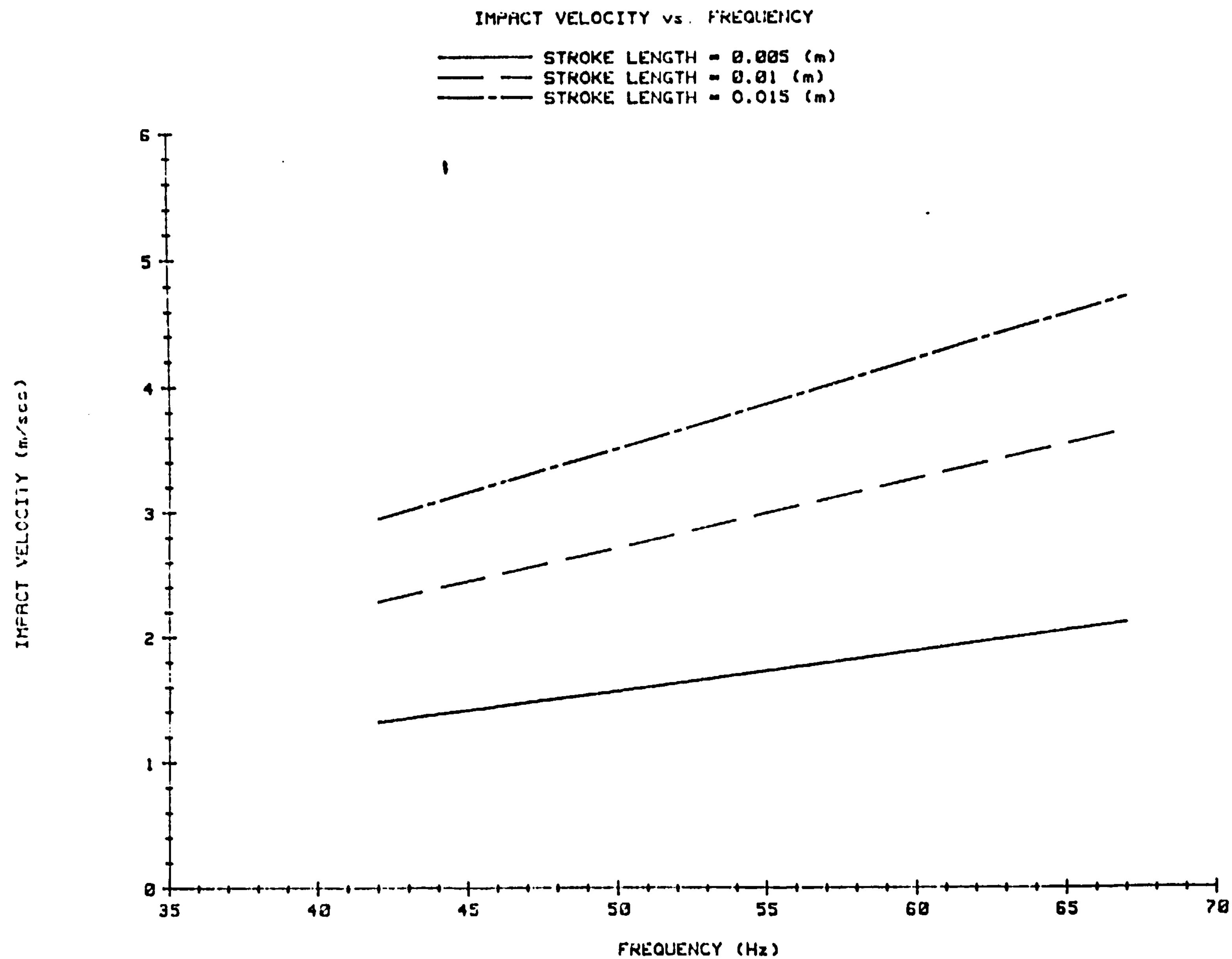

STEP HEIGHT vs. RPM
FREQ. = 42 (Hz)
FREQ. = 50 (Hz)
FREQ. = 60 (Hz)
FREQ. = 67 (Hz)
350.0E-03
300.0E-03
250.0E-03
200.0E-03
150.0E-03
100.0E-03
STEP HEIGHT (m)
-100
0
100
200
300
400
RPM

Figure 6



IMPACT VELOCITY vs. FREQUENCY
STROKE LENGTH = 0.005 (m)
STROKE LENGTH = 0.01 (m)
STROKE LENGTH = 0.015 (m)
IMPACT VELOCITY (m/sec)
0
1
2
3
4
5
6
35
40
45
50
55
60
65
70
FREQUENCY (Hz)


FIGURE 7

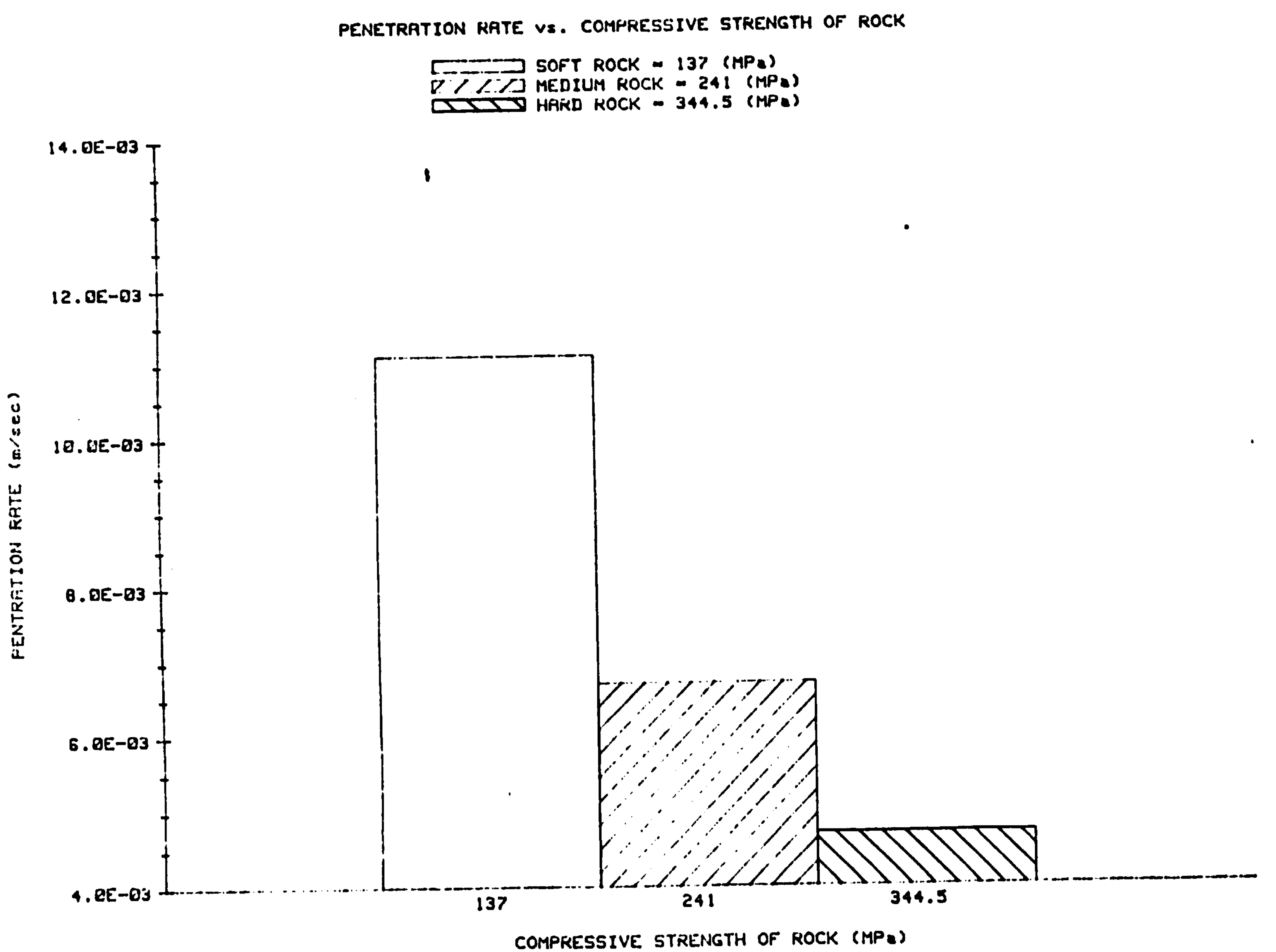

PENETRATION RATE vs. COMPRESSIVE STRENGTH OF ROCK
SOFT ROCK = 137 (MPa)
MEDIUM ROCK = 241 (MPa)
HARD ROCK = 344.5 (MPa)
14.0E-03
12.0E-03
10.0E-03
8.0E-03
6.0E-03
4.0E-03
PENTRATION RATE (m/sec)
137
241
344.5
COMPRESSIVE STRENGTH OF ROCK (MPa)

FIGURE 8

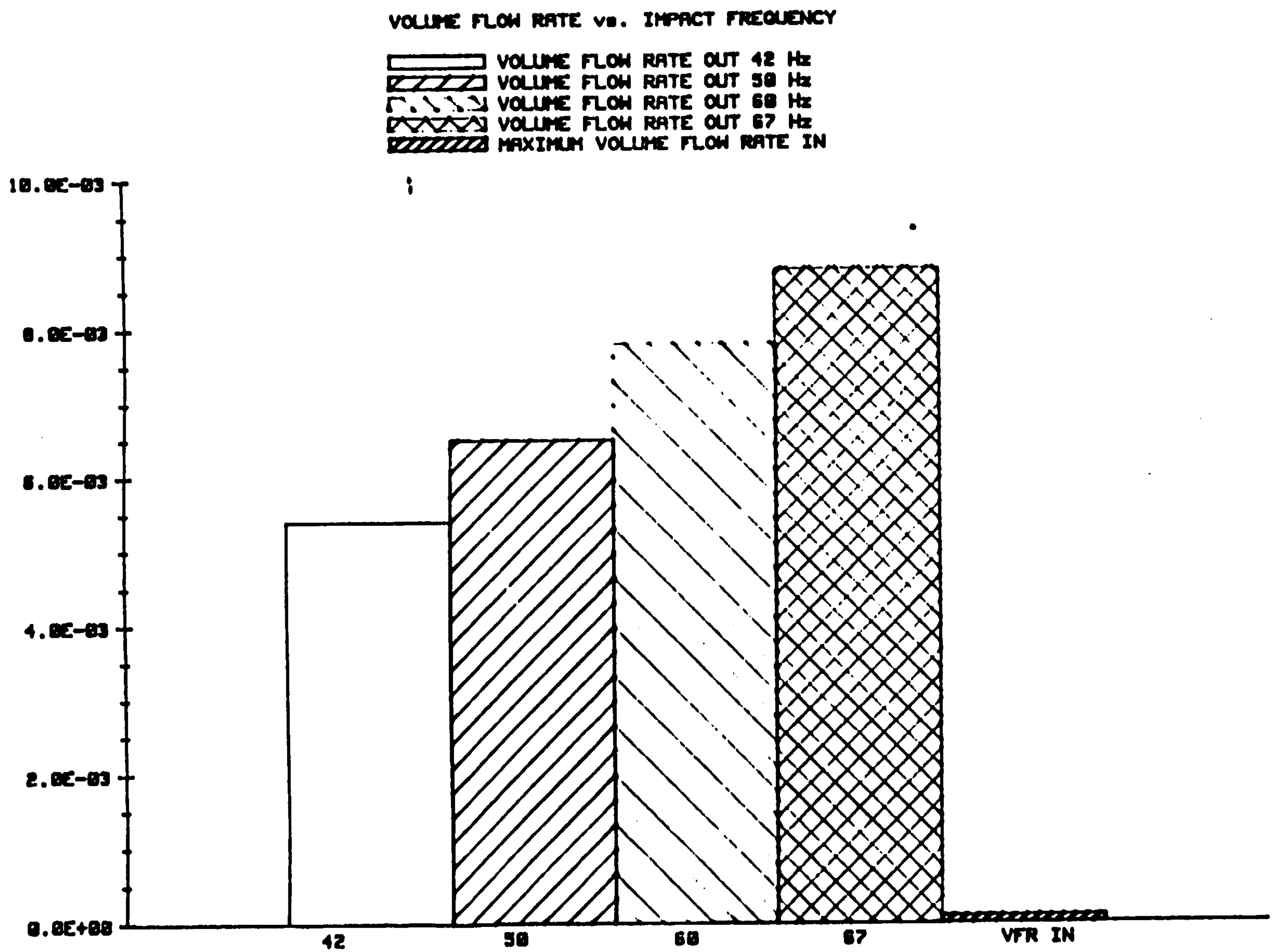

VOLUME FLOW RATE vs. IMPACT FREQUENCY
VOLUME FLOW RATE OUT 42 Hz
VOLUME FLOW RATE OUT 50 Hz
VOLUME FLOW RATE OUT 60 Hz
VOLUME FLOW RATE OUT 67 Hz
MAXIMUM VOLUME FLOW RATE IN
10.0E-03
8.0E-03
6.0E-03
4.0E-03
2.0E-03
0.0E+00
VOLUME FLOW RATE (m^3/sec)
42
50
60
67
VFR IN
IMPACT FREQUENCY (Hz)

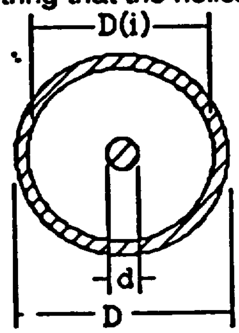
FIGURE 9

# APPENDIX C

## Calculations

## Column Analysis Calculation

This analysis takes into account both the drill string sleeve and the rod in the center of the string that the helical ramp is connected to.




End View of Drill String

First it is necessary to determine if the drill string will act as an Euler or Johnson column. If $(l/k)_1$ is greater than $(l/k)$ then the column will be Johnson. If not then an Euler analysis is necessary. Iteration was done with varying sleve thickness to design for the thinnest column that will not fail (See table below).

Necessary equations:

$$P_{cr}/A = (pi)^2 E/(l/k)^2$$

$$(l/k)_1 = (2(pi)^2 CE/S_Y)^{.5}$$

$$k = d/4 \text{ for center column}$$

$$k = (D^2 + D_i^2)^{.5}/4 \text{ for sleeve}$$

$$k_{tot} = (d + (D^2 + Dt^2)^{.5})$$

Choose end constant, C to be 1 which is a conservative value for a column having fixed ends.

Choose AISI # 1045 steel CD ($S_Y$ = 245 Kpsi = 1689 MPa; E = 206,700 MPa) because it is a low carbon steel that will not be too brittle. The value of $S_Y$ is representative of a typical value for plain carbon steels of this type.

## Euler Analysis Results

| d (m) | $D_i$ (m) | $P_{cr}$ (KN) | |
|---|---|---|---|
| .005 | .080 | 7.14 | |
| .010 | .080 | 7.14 | |
| 015 | .080 | 8.71 | |
| .C20 | .080 | 9.75 | |
| | | | |
| 005 | .090 | 4.16 | |
| .005 | .090 | 7.14 | |
| .005 | .070 | 9.18 | |
| .005 | .060 | 10.57 | |
| .005 | .050 | 11.42 | |
| | | | |
| .010 | .090 | 4.63 | |
| .010 | .080 | 7.85 | |
| .010 | .070 | 10.10 | ——Optimum value |
| .010 | .060 | 11.59 | |
| .010 | .050 | 12.55 | |

Now it is necessary to calculate the force delivered by the drifter. The drifter has a constant power output, therefore, using the highest impact energy (from manufacturers specifications), 271 J which is equal to force/time, gives

Power = (impact force)(velocity)

Power = (271 J)(42 Hz) = $1.1382 \times 10^4$ Watts

Force = Power/velocity = $1.1382 \times 10^4$ Watts/1.3 m/s

= $8.7554 \times 10^3$ N

where 1.3 m/s is a conservative value obtained from graph of impact velocity vs. frequency. This graph was generated using a sinusoidal motion equation with amplitude = stroke length, w = 2(pi)f. Using these values, Pcr and a safety factor are calculated as follows

P = F = 8.7554 N, and

Safety Factor, n = $P_{cr}/P$ = 10.10/8.75 = 1.154

The value chosen for $P_{cr}$ was 10.10 because it optimizes the size criteria.

## Shear Load Analysis

Justification of method: The applied torque is carried entirely by the sleeve of the drill string because the center shaft cannot transmit a torque.

| Forces | Dimensions |
|---|---|
| Torsion: 339 Nm | d = .01m |
| Compression: 8.755 KN | D = .01 m |
| $P_{cr}$: 10.10 | $D_i$ = .07 m |

Vertical compressive stress = 8.55/4.08 x $10^{-3}$ = 2.15 MPa

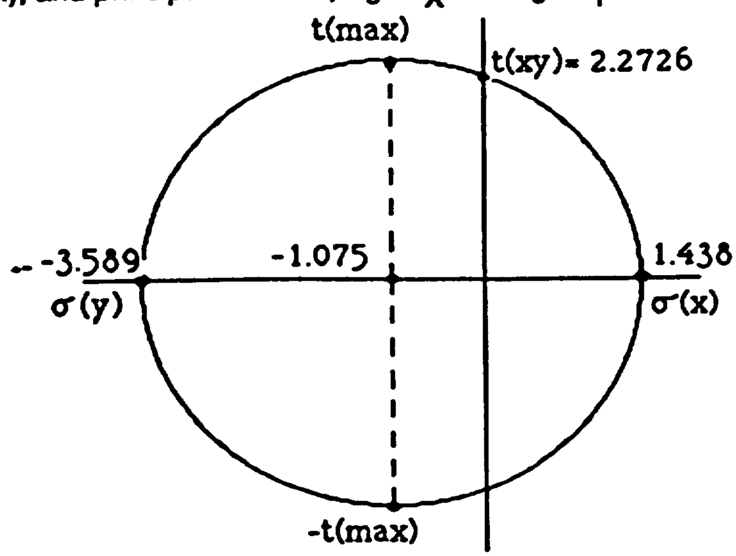
Polar Moment of inirtia, J = (pi)[$(0.1)^4$ - $(0.7)^4$]/32 = 7.46 x $10^{-6}$ $m^4$

Outside Radius = 0.05 m

Shear Stress, $t_{XY} = T_r/J$ = (339 N-m)(0.05 m)/(7.46 x $10^{-6}$ $m^4$)

$t_{XY}$= 2.272 Mpa

A Mohr's circle analysis will give the maximum shear stress, $t_{XY}$(max), and principal stresses, $sigma_X$ and $sigma_Y$.




The analysis gives principal stresses of:

$sigma_Y$ = -3.589 MPa

$sigma_X$ = 1.4385 MPa

and a maximum shear stress of $t_{XY}$(max) = 2.514 MPa

## Fatigue Failure Analysis

The maximum shear stress must be compared with the shear endurance limit, $S_{se}$.

$$S_{se} = k_a k_b k_c k_d k_e S_e'$$

Tensile strength for AISI 1045 steel is greater than 200 Kpsi so use $Se' = 100Kpsi = 689.5$ MPa.

$k_a = 0.63$ (machined or cold drawn material)

$k_b = 1.189d^{-.097}$ where $d = [(.95)(pi)(D^2 - D_i^2)/4(.0766)]^{.5} = 8.775$ in.

$= .96$

$k_c = .814$ (99% reliability)

$k_d = 1$ Because it is assumed that operating temperature < 450 C

$k_e = 1/kf = 1/2.3 = 0.435$ (2.3 from threaded stress concentration)

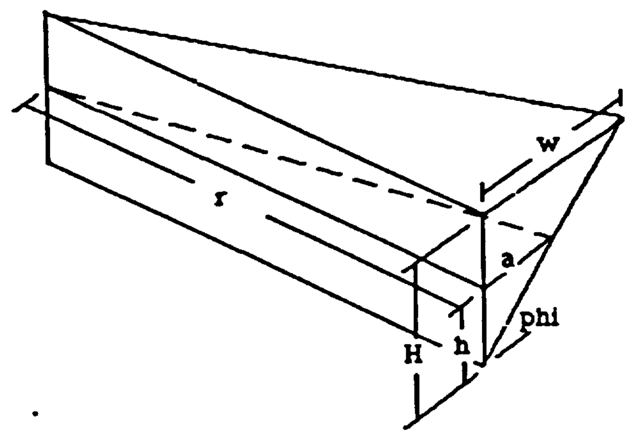
so,

$S_e = (.63)(.96)(.814)(1)(.435)(689.5) = 147.7$ MPa

This is the endurance limit in bending. The endurance limit in shear is $S_{se} = 0.5Se = 73.85$ MPa. When compared to maximum shear stress calculated above, it is seen that the drill string will be operating in the safe range.

$$73.85 \text{ MPa} > 2.514 \text{ MPa}$$

## Volume Calculation




The picture above is a representation of the volume filled by particles resting on a step.

h = height from bottom of step

H = height of step

r = radius of drill string

w = width of step

a = width of slice

Phi = helix angle

This analysis was done assuming that pitch and curvature of the drill string sleeve will have little effect on volume. This assumption will yield a volume that is less than the actual which is a conservative estimate.

By similar triangles:

$h/H = a/w$ which gives, $a = wh/H$

From simple trigonometry:

$\tan(phi) = H/w = h/a$ which gives, $a = h/\tan(phi)$

The area of the horizontal slice (or wedge), which varies with height, h is given by

$A = ar/2 = .5r(h/\tan(phi))$

$A = [hr/2\tan(phi)]$

From integration, volume is given by

$$[rh/2\tan(phi)]dh = rH^2/4\tan(phi) = 1/4rH^2\cot(phi)$$

This volume is multiplied by two to include the second auger

# APPENDIX D

## Computer program

## Drifter Specifications

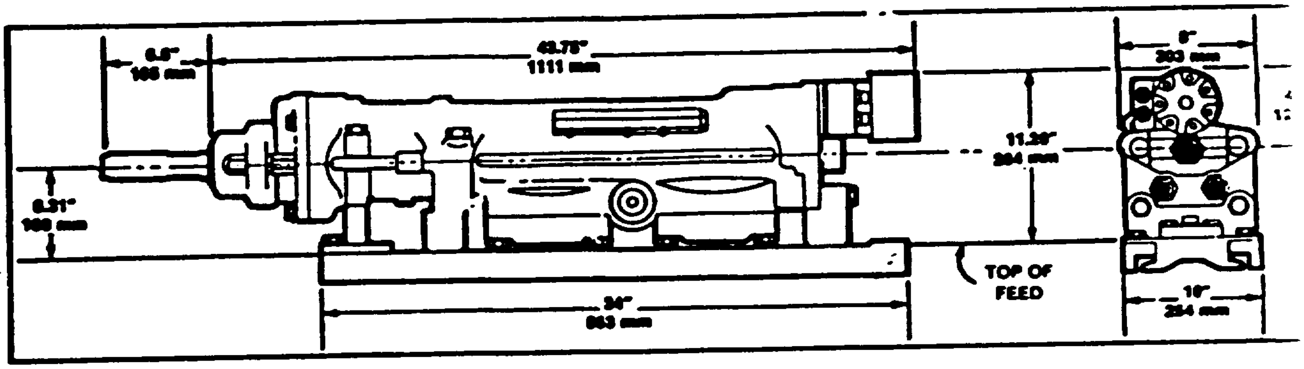
```
10    REM*********************************************
20    REM THE PURPOSE OF THIS PROGRAM IS TO GENERATE THE PARAMETERS
30    REM ASSOCIATED WITH THE DRILLSTRING AUGER DESIGN.
40    REM*********************************************
50    REM T = TIME FOR PARTICLE TO HIT UPPER AUGER
60    REM T2 = TIME OF PARTICLE TRAVEL FROM IMPACT TO NEXT STEP
70    REM Ts = TIME OF IMPACT OF THE DRILL STRING WITH GROUND
80    REM G = GRAVITY VALUE
90    REM L = STROKE LENGTH
100   REM D = STRING DIAMETER
110   REM F = FREQUENCY OF IMPACT
120   REM Rpm = ROTATION OF DRILL STRING
130   REM Phi = HELIX ANGLE OF THE AUGER
140   REM Wr = ANGULAR VELOCITY OF DRILL STRING
150   REM Wv = VERTICLE RADIAN VALUE OF FREQUENCY
160   REM A = THE TIME INCREMENT FOR ROOT SOLVER
170   REM P = PITCH OF AUGER
180   REM Va2 = VELOCITY OF UPPER AUGER
190   REM Vmax = INITIAL VELOCITY OF PARTICLE DUE TO AUCER
200   REM Vp = VELOCITY OF PARTICLE
210   REM Vp1 = VELOCITY OF PARTICLE AFTER IMPACT
220   REM Vs = VELOCITY OF IMPACT
230   REM V = VOLUME OF ONE STEP
240   REM Vfr = VOLUME FLOW RATE OF PARTICLES
250   REM Za1 = POSITION OF LOWER AUGER
260   REM Za2 = POSITION OF UPPER AUGER
270   REM ZP = VERTICLE POSITION OF PARTICLE
280   REM Theta0 = ANGULAR ROTATION OF AUGER FOR T
290   REM Thetaa = ANGULAR ROTATION OF AUGER FOR T2
300   REM Thetap = ANGULAR ROTATION OF PARTICLE AT T2
310   REM Gamma = DEPARTURE ANGLE OF PARTICLE FROM UPPER AUGER
320   REM Drill = ANGULAR ROTATION NEEDED TO REACH NEXT STEP
330   REM H = STEP HEIGHT
340   REM*********************************************
350   REM
360   RAD
370   T=0
380   G=9.81
390   L=.01
400   D=.1
410   F=42
420   Rpm=200
430   REM*********************************************
440   REM OPENING DISK OUTPUT FILE
450   REM*********************************************
460   CREATE ASCII "PHI7",80
470   ASSIGN @Path_1 TO "PHI7"
480   REM*********************************************
490   REM BEGIN CALCULATING TIME OF IMPACT OF PARTICLE WITH AUGER.
500   REM*********************************************
510   REM
520   FOR Phi=1 TO 80
530   Phi=Phi*PI/180
540   Wr=(Rpm*2*PI)/60.0
550      A=.001
560      P=(PI*D)*(TAN(Phi))
570      Wv=2*PI*F
580      Vmax=L*Wv+(P/(2*PI))*Wr
590      T=A
```

```
600     T2=0
610     Za2=L*SIN(Wv*T)+(.5*P)+(P*Wr*T/(2*PI))
620     Thetao=Wr*T
630     Za1=L*SIN(Wv*T)+((Wr*T*P)/(2*PI))
640     Zp=-.5*G*T^2+(Vmax*T)
650     IF Thetao>PI/3 THEN GOTO 1110
660     IF ABS(Za1-Zp)<.00001 THEN GOTO 1110
670     IF Za1>Zp THEN 730
680     IF ABS(Za2-Zp)<.00001 THEN GOTO 760
690     IF Za2-Zp<0. THEN GOTO 730
700     IF A<.001 THEN A=A/2
710     T=T+A
720     GOTO 610
730     A=A/2
740     T=T-A
750     GOTO 610
760     REM*********************************************
770     REM AFTER CALCULATING IMPACT TIME, VELOCITIES ARE CALCULATED
780     REM AS FOLLOWS.
790     REM*********************************************
800     Va2=L*Wv*COS(Wv*T)+(P*Wr/(2*PI))
810     Vp=-G*T+Vmax
820     Vp1=Vp-Va2
830     REM*********************************************
840     REM CALCULATING ROTATIONAL PARAMETERS.
850     REM*********************************************
860     Gamma=PI/2-2*(PI/2-Phi)
870     REM*********************************************
880     REM CALCULATING THE TIME (T2) AT WHICH THE PARTICLE
890     REM IS OVER THE NEXT STEP.
900     REM*********************************************
910     T2=0
920     A=.001
930     K=Zp
940     Thetao=Wr*T
950     Thetap=2*Vp1*COS(Gamma)*T2/D
960     Thetaa=Wr*T2
970     Drill=PI/3-(Thetao+Thetaa)
980     Zp=(-G*T2^2)/2+Vp1*SIN(Gamma)*T2+K
990     IF ABS(Drill-Thetap)<.00001 THEN GOTO 1070
1000    IF Drill>Thetap THEN GOTO 1040
1010    A=A/2
1020    T2=T2-A
1030    GOTO 950
1040    IF A<.001 THEN A=A/2
1050    T2=T2+A
1060    GOTO 950
1070    REM*********************************************
1080    REM CALCULATING STEP HEIGHT, TIME OF IMPACT, AND VELOCITY
1090    REM AT IMPACT.
1100    REM*********************************************
1110    H=Zp-((L*SIN(Wv*(T+T2)))+(P*Wr*(T+T2)/(2*PI)))
1120    IF H<0 THEN H=0
1130    V=.25*D*(H^2)/TAN(Phi)
1140    Vfr=V/(T+T2)
1150    Ts=ASN((L-.005)/L)/Wv
1160    Vs=Wv*L*COS(Wv*Ts)
1170    Phi=Phi*180/PI
1180    REM*********************************************
1190    REM WRITING TO AND THEN CLOSING OUTPUT FILE
```

DATA SHE

January

# HPR
# HYDRAUL
# DRIFTE




The HPR 1 is an all-hydraulic percussion rock drill used for underground drilling. The hole size range is 1½" to 2½" The c is mounted on the Gardner-Denver HFM Hydraulic Feed. The two units mount on the Garnder-Denver Mark III All-Hydrau Jumbo making a complete underground hydraulic drilling team.

## SPECIFICATIONS

| | | METRIC |
|---|---|---|
| WEIGHT | 325 lbs | 147 kg |
| IMPACT ENERGY | 125 - 200 ft-lbs | 170 - 271 J |
| IMPACT FREQUENCY | 4000 - 2500 BPM | |
| OPERATING PRESSURE | 3000 lbs/in²(Max) | 204 bar (Max) 20,400 kPa |
| OIL FLOW-OSCILLATOR | 25 gal/min (Max) | 95 l/min (Max) |
| ROTATION SPEED | 0 - 200 RPM | |
| ROTATION TORQUE | 250 lbs-feet (Max) | 339 Nm (Max) |
| FEED FORCE | 2000 - 3000 lbs | 8.9 - 13.3 kN |
| FLUSHING WATER | 20 gal/min | 76 l/min |
| RECOMMENDED WATER PRESSURE | 75 - 120 lbs/in² | 5 - 8 bar 500 - 800 kPa |
| TOTAL CONNECTION POWER REQUIRED DURING DRILLING | 50 kw | |

## WHY THE HPR 1 IS THE BEST BUY

Impact Energy and Frequency are infinitel variable within operating range while maintaining constant power output.

Impact Energy and Frequency may be remote controlled or fixed at any desired level.

Chuck End of the Drill is completely sealed an grease lubricated.

Shanks are easily replaced.

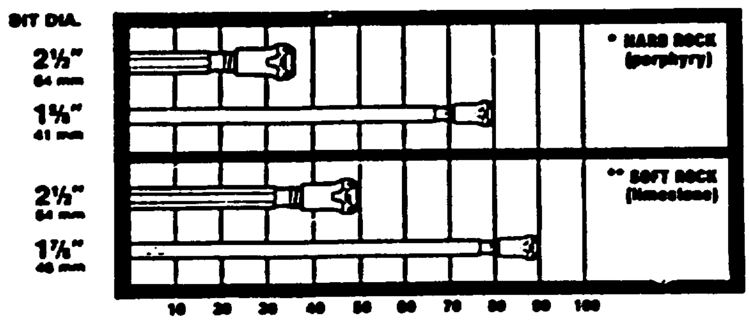
No part of the Drill is lubricated with oil mist. c sequently, no air compressor is required

GARDNER-D

ORIGINAL PAGE IS
OF POOR QUALITY

# HPR1 HYDRAULIC DRIFTER

## PENETRATION RATE IN INCHES PER MINUTE




* Compressive strength of 50,000 lbs/sq in.
** Compressive strength of 20,000 lbs/sq in.

Drilling at various locations has shown effective penetration rates in both hard and soft rock. The chart gives examples of penetration rates actually achieved in two specific types of rock. A general projection of other rock applications can be made from this chart.

Because of the wide variation in user applications, equipment maintenance practices, and bit replacement practices, these examples of penetration rates are not to be construed in any manner as a performance specification or as a warranty of performance

END