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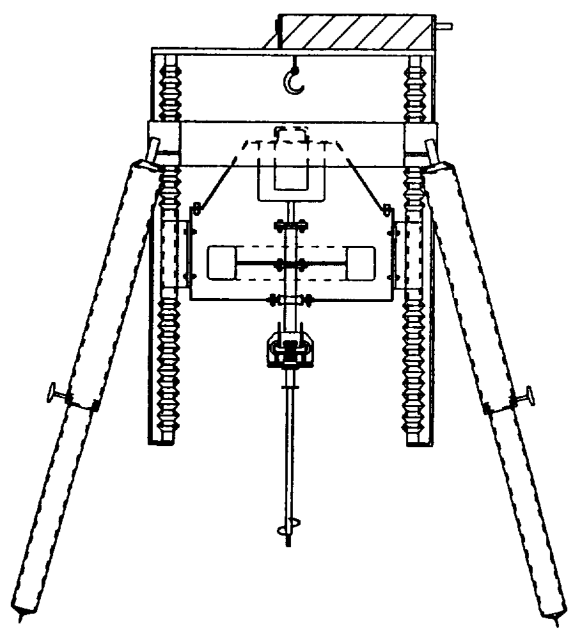
A LUNAR/MARTIAN ANCHOR EMPLACEMENT SYSTEM

A Senior Capstone Design Project
Sponsored by the NASA/USRA Advanced Design Program

Group Members: Dustin Clinton, Andrew Holt, Erik Jantz, Teresa Kaufman, James Martin, Reed Weber
Professor: Larry Stauffer
Teaching Assistant: John Gershenson



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University of Idaho
Dept. of Mechanical Engineering
University of Idaho
Moscow, Idaho

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ABSTRACT

On the Moon or Mars, it is necessary to have an anchor, or a stable, fixed point. The anchor must be able to support the forces necessary to rescue a stuck vehicle, act as a stake for a tent in a Martian gale, act as a fulcrum in the erection of general construction poles, or support tent-like regolith shields. The anchor emplacement system must be highly autonomous. It must supply the energy and stability for anchor deployment. The goal of the anchor emplacement system project is to design and build a prototype anchor and to design a conceptual anchor emplacement system. Various anchors were tested in a 1.3 cubic meter test bed containing decomposed granite. A lunar soil simulant was created by adjusting the moisture and compaction characteristics of the soil. We conducted tests on emplacement torque, amount of force the anchor could withstand before failure, anchor pull out force at various angles, and soil disturbances caused by placing the anchor. A single helix auger anchor performed best in this test bed based on energy to emplace, and the ultimate holding capacity. The anchor was optimized for ultimate holding capacity, minimum emplacement torque, and minimum soil disturbance in sandy soils yielding the following dimensions: helix diameter (4.45 cm), pitch (1.27 cm), blade thickness (0.15 cm), total length (35.56 cm), shaft diameter (0.78 cm), and a weight of 212.62 g. The experimental results showed that smaller diameter, single-helix augers held more force than larger diameter augers for a given depth. The emplacement system consists of a flywheel and a motor for power, sealed in a protective box supported by four legs. The flywheel system was chosen over a gear system based on its increased reliability in the lunar environment.

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1.0 INTRODUCTION

The future of space exploration has created many new engineering design challenges. One such challenge is creating a system for anchoring to the lunar surface. Anchoring is a fundamental way of supporting forces by using rock or soil to provide holding power. This anchor, or fixed point will aid in the establishment of manned bases on the moon. New construction techniques which function in reduced gravity and are less massive than conventional construction systems will be required.

Future missions to the Moon will include excavation and construction of roads, emplacement of habitation modules, solar arrays, and lunar liquid oxygen (LLOX) production facilities[1]. These missions will require massive construction efforts as well as mining and transportation operations. These operations will require equipment that is anchored for stability to perform their tasks. An anchor is also needed for rescuing vehicles, rovers, or construction equipment "stuck" in the lunar regolith. Moving Lunar soil will be an important part of operations because of the need to shield habitat structures from harmful radiation. Regolith will be used extensively to create shields for this purpose[2]. Due to the Moon's lack of large boulders[3], and its lack of sufficient gravity, there is a need for a anchor which will engage itself into the lunar soil.

Anchor applications on Earth include rock anchors which support the inside of large bore holes or mines, and mobile home anchors which are used in areas which experience high winds[4]. Rock climbers and mountaineers use anchors to fix their lines to rock faces. Electric utility companies use anchors to support the many power poles that transport electricity. These terrestrial anchors are often not suitable for lunar applications due to their weight, emplacement energy requirements, and their inability to hold in sandy soils.

On Earth, most construction and mining equipment use weight to provide stability and traction which is essential to their operation. These methods will not work in low gravity applications unless the equipment is prohibitively heavy[5]. It is not feasible to send heavy equipment to the Moon. Even if lighter equipment were ballasted with lunar soil to provide useful weight, the power necessary to maneuver the added bulk would be extensive[6].

Construction and mining techniques in low gravity situations have been described by Steven Kent in his paper *Outpost Service and Construction Robot (OSCR)*[7]. He proposes an autonomous "winch cart" which is equipped with a set of helical auger-type anchors. These anchors allow the winch cart to secure itself to the soil and use its winch assembly to pull passive excavators and digging implementations which work by being pulled through the soil. These tools could then be used to dig the lunar regolith for radiation shielding, installation of paths or roads, construction, etc. This system is useful because it replaces tractor-like devices which rely on gravity to provide the necessary traction. A useful feature is that the winch cart can be scaled to virtually any task requirement. Different sizes could be used depending on the required forces. A patented go-cart sized prototype of the "winch cart" was built and tested[8].

The remaining sections of this paper will describe the design problem and the environment in which the anchor emplacement system must work. A brief overview of the lunar environment characteristics is explained in next section. Section 2.0 describes the design process. This includes the requirements of the anchor emplacement system, and how our design team came up with our design. Section 3.0 presents a math model for help in understanding the physical characteristics of a lunar anchor. We will then discuss our experimental analysis in section 4.0. This information was invaluable for us to develop specifications for a prototype anchor. Sections 5.0 and 6.0 discuss our prototype testing results and also our ideas for an autonomous emplacement system. The final section 7.0 will outline our conclusions and ideas for future work.

1.1 The Lunar Environment

The environment in which the anchor emplacement system must work will have an important effect on its design and operation. An understanding of these effects was important for our design team. In the following sections we discuss the individual environmental effects on the anchor emplacement system.

1.1.1 Radiation

The lunar environment has mainly three types of ionizing radiation: large fluxes of low-energy solar-wind particles, solar cosmic rays, and smaller fluxes of high-energy galactic cosmic rays[9]. The radiation causes particles to penetrate the surface of the Moon from micrometers to meters, interacting with the exposed rocks and soils. This interaction results in erosion of the lunar soil, and the structure of certain materials can be changed.

The solar wind damages the crystalline structures of minerals in its path, creating altered material at the outermost layers of the lunar surface. The average speed of the wind is approximately 500 km/s. This high speed wind causes some of these ions to become implanted within the regolith. Solar cosmic rays interact with the soil from the top millimeter to a few centimeters in depth. Since these rays depend on sunspot activity, the intensity of the cosmic rays vary from nothing, to very high levels for several hours, although this is rare. Galactic cosmic rays penetrate the soil the greatest with depths ranging as deep as several meters.

Radiation may cause failure of the anchor emplacement system. These failures are contributed to the decomposition of a material on a molecular level, thus changing the characteristics of a material over time. Certain materials like plastics and composites are affected more adversely by the high levels of radiation. Because of this, metals would be a preferred choice of material for the anchor emplacement system.

1.1.2 Temperature

Due to the slow rotation of the Moon, a lunar day and night cycle corresponds to twenty-nine Earth days. This, and the lack of atmosphere causes a wide range of expected temperatures on the Moon. The lunar surface temperature ranges from approximately 73

K (-200C) during the lunar night to 398 K (125C) during the day. At 1 m below the surface, the temperature stays approximately constant at 223 K (-50C)[10].

A larger difference in mean temperature, or the temperature averaged over a complete day-night cycle, is found just below the lunar surface. At the Apollo 15 site, the temperature measured at approximately 35 cm deep was 45 K higher than that of the surface[11]. This was due to the thermal conductivity of the soil.

Temperature extremes will influence the selection of material for the anchor emplacement system. The chosen material will have to resist brittle failure at lower temperature and resist thermal creep at higher temperatures. The material must then resist fatigue due to thermal cycling over time.

1.1.3 Meteoroid Impact

The micro meteorites that commonly collide with the Moon have diameters less than 1 mm and masses less than 10^{-2} g[12]. These projectiles are formed from asteroid collisions or are small particles released from comets. Some meteorites can be large enough to create craters that are several kilometers wide, though these are not common. The typical impact velocities range from 15 to 25 km/s[13]. The repetitive and frequent small impacts disrupt the lunar soil by shattering, burying, tumbling, and moving individual grains of soil at random. These meteoritic impacts over eons have created a fine-grained, powdery top layer of soil which is called regolith. The meteorite impacts can also cause premature equipment failure if equipment is not sufficiently protected.

1.1.4 Vacuum

The Moon's atmosphere is a near total vacuum. It is often referred to as having no atmosphere, since the pressure of the lunar atmosphere is approximately 14 orders of magnitude less than the Earth's atmosphere[14]. The lack of atmosphere causes the pressure to be near zero (absolute pressure). The total mass of the ambient atmosphere of the Moon is about 10^4 kg. The theory of what the atmosphere contains is based on the Apollo missions. The main constituents of the lunar atmosphere are neon, hydrogen, helium, and argon[15]. The helium, neon, and hydrogen come from solar winds, and the argon from radioactive decay.

The lack of atmosphere or pressure will cause problems with the lubrication of components. If it is used, lubrication will easily evaporate from the anchor emplacement system. The anchor emplacement system design should avoid the need for lubricants wherever possible. Also, the vacuum environment will cause problems with dust adhering to the materials.

1.1.5 Gravity

The force of gravity on the Moon is approximately one-sixth of the gravitational pull of the Earth. The gravity at the Moon's equator is 1.62 m/sec^2 compared to 9.81 m/sec^2 at the Earth's equator[16]. The lack of gravity can make some tasks difficult. This effect is hard to model on earth since we have no means of generating reduced gravity for prolonged periods of time. Inertial forces play a more important role for objects on the moon. Walking on the Moon is much like walking on a trampoline, and it takes much energy to start or stop.

Because of the lack of gravity, downward forces will be reduced which may adversely affect the operation of equipment. Design of the anchor emplacement system will have to account for the reduced gravity. An anchor would have to be emplaced with a minimum amount of downward force.

1.1.6 Surface

Much of The lunar surface was formed by extrusion of basaltic lava between 3000 and 3700 million years ago[17]. The moon crust is theorized to be solid rock covered with a layer of meteoritic dust and soil with patches of bare rock[18]. Lunar missions have found that the top 4 cm of the lunar surface is composed of loose, gray, pulverized material underlain by a dark gray, sintered crust approximately 6 mm thick. A porous layer exists 4-400 cm below the surface. The top layer of regolith has a density of 0.5-0.9 g/cm^3 and a void ratio of 4.0. The porous layer has a density of 0.9-1.2 g/cm^3 and a void ratio of 1.5[19].

Regolith consists mainly of local bedrock material, but it also consists of breccias, which are coherent rocks consisting of fragments of other rocks. The breccias are all set in a fine-grained unconsolidated matrix[20]. This fine grain matrix consists of fragmented bedrock, which is the end product of repeated impact shattering. The effects of these impacts range from simple shattering of rocks, to complete melting which produces glasses that are often present in the form of spherical beads. Many breccias are hardened accumulations of regolith material that have been welded together by shock[21].

Only five percent of the lunar area consists of exposed granite or basaltic rock faces[22]. The surface may consist mainly of silica with a solid phase density of about 2400 kg/m^3[23]. This is similar to the density of the solid phase of volcanic rocks. The closest terrestrial analog of lunar soil with respect to the chemical and mineralogical compositions, density and mechanical properties is artificial sand from crushed basalt. Volcanic, silty sand of basaltic composition from unaltered recent deposits is similar to the lunar soil[24]. No terrestrial soils are completely identical to lunar soils with respect to all of the properties. Some breccias brought back from the Moon contain basalts with granulated olivines and pyroxenes. Others contain non-mare basalts and glass fragments[25].

In general, the moon is composed of materials that are poor thermal conductors and poor reflectors of light. The mean bulk density of the Moon's crustal rocks is less than that of terrestrial rocks by about five to two. This can affect the strength of the lunar rock causing them to break apart easier than Earth rock. The strength of the lunar material is less than that of the average terrestrial matter. The mechanical strength of lunar soil has been tested by using a spring scale penetrometer in a nitrogen chamber. At a density of 1.36 g/cm^3 and an area of 2.68 cm^2, the soil did not resist penetration and the penetrometer spring did not compress. At a density of 1.77 g/cm^3, and the same area, the soil did compress the penetrometer spring[26]. These results help in comparing the lunar regolith to Earth soils.

Radial surface cracks on the Moon's surface range from 15-18 cm from the point of application of an external load. Therefore, the lunar soil has a cohesive force similar to some terrestrial sands with a low moisture content[27]. The cohesion of the lunar soil is approximately 0.00035-0.015 kg/cm^2 depending on the compaction of the lunar soil. The total cohesive force can be divided into two categories, mechanical entanglement and true cohesive forces. Mechanical entanglement is due to the irregular, complex shapes of the soil's grains . The lunar soil has some lateral bearing capacity due to its range of cohesive forces. The regolith readily adheres to any surface in contact , therefore the soil has a high adhesive force.

Astronauts have determined that the top 10-12 cm of the lunar surface can be readily worked with a variety of tools. The strength and compaction of the soil increases with depth[28]. For example, core sampling tubes could be driven by hand to a maximum depth of approximately 25 cm. As the core samples were removed, the walls of the hole did not collapse. Therefore, this demonstrates the lunar soil's cohesive force.

The lunar soil compressibility was determined from how the foot wear of astronauts and landing pads of the Apollo-11 lunar module indented the soil. Foot wear depths averaged 1.27 cm at a mean pressure of 0.07 kg/cm^2. This data resulted in a settlement factor (the ratio of the mean pressure under the indentor to the indentation depth) of approximately 0.055 kg/cm^3. However, the foot wear indentation increased 12-16 times near the edge of fresh craters, where the soil is looser and finer. The landing pads of the Apollo-11 lunar module yielded a mean pressure of 0.056-0.147 kg/cm^2, an indentation depth of 2.25-7.62 cm, and a settlement factor of 0.025-0.019 kg/cm^3[29].

According to the Apollo-11 mission, "the surface of the lunar soil in mare regions is a gently rolling, in places horizontal, plain with numerous craters and pits ranging from a few centimeters to hundreds of kilometers"[30]. The landing site could be divided into three distinct areas. The first being the immediate area around the spacecraft and was composed of a moderate density soil that had sufficient bearing capacity for locomotion of the astronauts and equipment. The second was found in the environs of the Sharp crater and consisted of lunar soil that could be easily dug. Here, foot wear tracks were the deepest. The third area consisted of more coarse-grained soil and resembled dirt that had been slightly moistened by rain.

Most of craters on the Moon are less than a few kilometers across and have a characteristic bowl shape. Fresh craters have well defined blankets of material ejected from the crater called ejecta[31]. The inner walls of craters 10-20 km in diameter have slopes of up to 35-50 degrees. Smaller craters usually have larger slopes, and larger craters usually have smaller slopes. Interiors of well-formed small craters tend to be paraboloidal[32]. For most of the lunar surface, slopes are not steep.

Design of the anchor emplacement system is highly dependent on the lunar soil characteristics. Since the layer of regolith is at least 4 meters deep in most regions, an anchor will not be able to penetrate to solid rock. An anchor system must rely on the strength of the lunar soil. The porous layer of the regolith, with its higher compaction, and cohesive qualities will be the best place to support an anchor.

2.0 DESIGN PROCESS

Our first goal in the design process was to understand the design problem. We needed to know the customer, and what kind of requirements the anchor emplacement system must meet. After determining the customer requirements we could use design methods to determine the relative importance of each of them. The product could then be defined by using functional decomposition, a house of quality, and constructive brainstorming. Since all of these tasks needed to be completed within a certain time, a time line was created to keep our design team on schedule.

2.1 Primary Customer Requirements

Listed below are the actual design criteria which were given to us by the sponsors the National Aeronautics and Space Administration (NASA) and the Universities Space Research Association (USRA).

2.1.1 General Requirements:

The anchor system must:

- Support previously conceived tent-like regolith shields.
- Support forces to rescue a "stuck" vehicle or rover.
- Aid in the erection of general construction poles.
- Anchor a tent in a Martian gale.
- Be inexpensive (budget of roughly $800 to prototype and test).

One of the first design concerns was how much force should the anchor hold or withstand. After speaking with engineers at NASA, we found the size of the anchor would be very task dependent. Different sized anchors would be needed for different operations. They suggested our anchor be designed for a load of around 200 kg. This load represents small autonomous rovers which may be used on the Moon, or light construction loads. The anchor would need to support this load without pulling loose no matter which direction the force or load came from. If there is a need for stronger holding power for full size rovers or heavy construction, an anchor system can be designed to scale.

2.1.2 Physical Requirements:

- Minimal total life-cycle cost for system deployment to Moon/Mars.
- Useful on both lunar and Martian surfaces (if possible).
- Mostly autonomous; the anchor emplacement system can be mobilized and placed by an existing robot or vehicle but the emplacement system must supply the energy and capability for the employment.

- Lightweight and requiring minimal payload volume.
- Minimal, preferably self-supplied energy requirements.
- Deployable from lightweight rovers.
- Reliability and simplicity of the anchor and its deployment (to decrease costs, increase additional uses, and minimize service cost and functional failures).
- Environmentally compatible (creating as little pollution as possible).

The anchor emplacement system must be lightweight and have a miminal payload volume. The cost per weight for deployment is so expensive that it is imperative to keep the anchor emplacement system light. Also, with minimal space available on future missions, the design needs to be as small and compact as possible. The availablity of power on the lunar surface is also minimal, so the system needs to have low power requirements. There are methods for generating power in space, but this power is not available at high rates.

2.1.3 Environmental Requirements:

The anchor emplacement system must:

- Operate in decreased gravity.
- Operate in a light, sandy, desert like soil with interspersed rocks and bedrock.
- Operate in a dusty and gritty environment.
- Operate in soil without moisture.
- Operate in a vacuum environment
- Withstand high levels of radiation.
- Withstand large temperature swings.

The anchor emplacement system must be able to withstand dusty, gritty soil that will cling to it and be very difficult to remove. Complex parts, like gears, with small spaces for the soil to remain in will not be reliable in this type of environment. Lubricated parts will also have a short life, as the lubrication will evaporate easily in the vacuum environment. The components of the anchor emplacement system must withstand the long day-night cycle of the Moon which will cause the components to expand or contract with the changing temperatures. Finally, the emplacement system must also endure micrometeor impacts without being damaged.

2.2 Product Definition

After understanding the customer requirements our design team could begin defining the product. Quality Function Deployment (QFD) was used to help the design team accomplish the tasks. The first goal of the design team was to set up a time structure that could be used as a schedule. A gantt chart of the time line for the project is shown in Appendix A.

In order to better understand the problem, we researched various books and articles that dealt with the different project aspects. We also spoke with the engineers at NASA who are the customers. After knowing the project requirements, a House of Quality was formed, as seen in Figure 1. This house of quality helps to determine the relative importance of all the necessary requirements for the anchor system by relating the customer requirements to the engineering requirements. This gave the design team insight as to which requirements should receive the most attention.

The design team focused on devising a system that would work on the Moon. If a system was functional under the lunar conditions, then it would be feasible to be used in future expeditions to Mars. After understanding what kind of environment the anchor system would need to endure, time was spent researching the different materials, and how they could be used. The expected environment for the anchor system is so diverse that only certain materials could withstand the extremes.

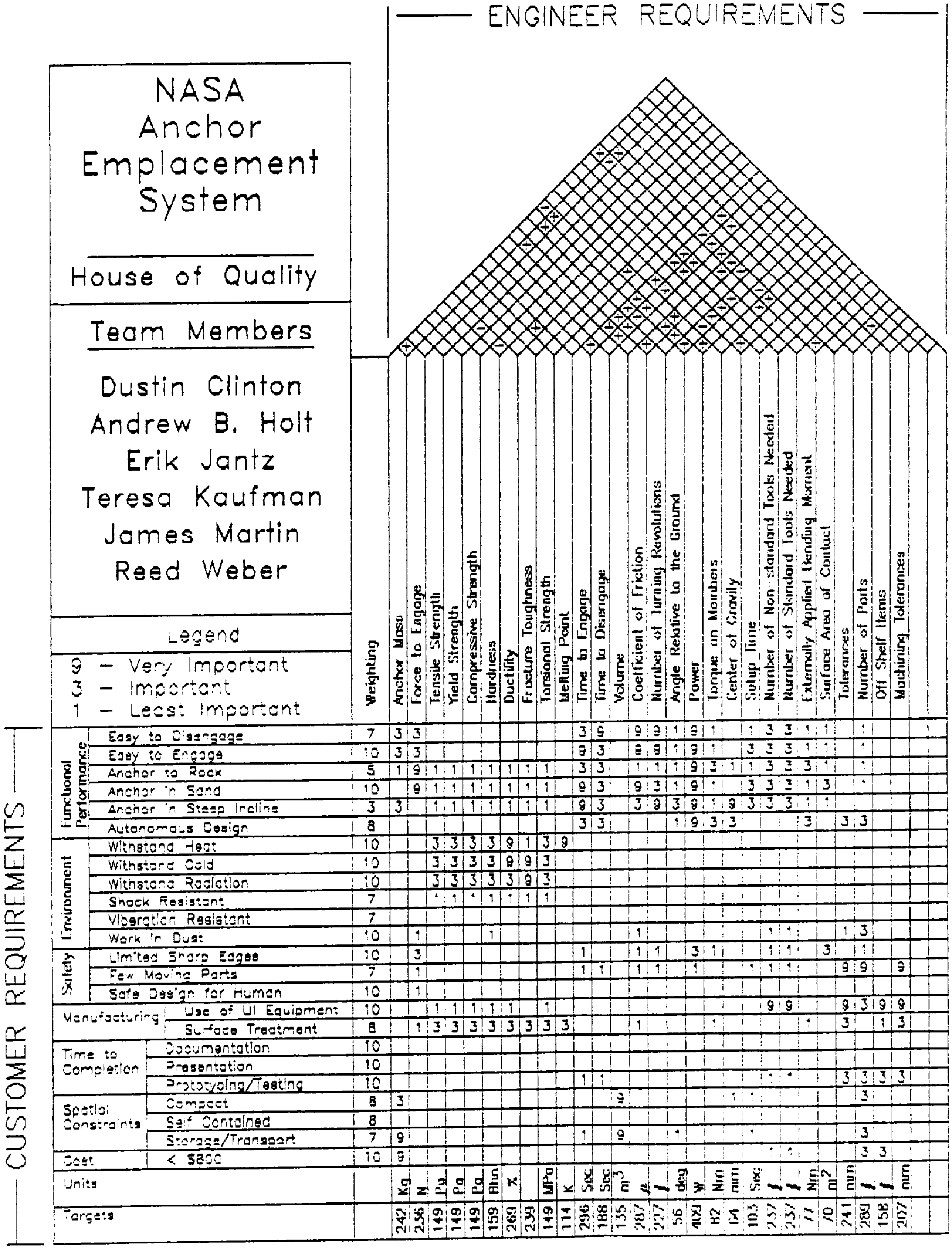


Figure 1. House of Quality

2.3 Materials Research

The anchor emplacement system must maintain its mechanical stability based on a temperature range from 114 K to 390 K, a high energy radiation of 60 rem/year, and a near vacuum atmosphere of approximately 10^{-4} atm. The system should also have high corrosive resistance, yield and tensile strengths. Material selection and mechanical design are based on these environmental factors.

2.3.1 Lubrication

The near zero gravity, high-energy radiation, and ultra-high vacuum considerably affect lubrication requirements[33]. The vacuum effects result in increased rates of vaporization of lubricants and creepage of the oil along the surface. Cold welding of metals results from the loss of surface films. It therefore becomes necessary to try to balance the effects of evaporative loss with the amount of lubricant needed, or use a material which does not require lubrication. Not only is lubrication hindered, but exposed surfaces are also affected as discussed in the next section.

2.3.2 Surface Treatments

A component's temperature on the moon is dependent upon and controlled by radiation characteristics of the external surface. White solar reflector surfaces are most susceptible to damage. Tests of the best black and white painted surfaces have been performed. The results were that the best black painted surface performed adequately at a temperature of 2015 K. The best white paint failed at temperatures above 1475 K. Black silicone paint remained undamaged at temperatures as high as 2105 K, and degradation of black and aluminum paints are not affected by lowering the pressure to 10^{-6} atm[34]. Surface treatments may be utilized to protect the emplacement system.

2.3.3 Material Selection

The three main materials selected from the research are: types 301 and 310 stainless steels and titanium alloys. Type 301 stainless steel is characterized by its high tensile strength, ease of weldability, good corrosion resistance, and adequate resistance to brittle fracture at temperatures as low as 20 K. It is frequently used at room temperature and it has yield and tensile strengths of 1.38×10^{9} Pa and 3.03×10^{18} Pa respectively. The high strengths are due to the inclusion of martensite in an austenitic matrix. Austenite has excellent resistance to brittle fracture at most all cryogenic temperatures (223 K to near absolute 0), whereas martensite becomes brittle. Tests on 301 stainless steel including irradiation at 519 K resulted in no significant changes in mechanical properties. Most of the radiation induced defects annealed out at 302 K, and those remaining did not have a measurable effect on the notched tensile strength. Lastly, cryogenic irradiation (treatment by exposure to radiation) increased the butt weld joint strength by approximately 17,895 Pa[35].

Type 310 stainless steel is very similar to 301, but is has a micro structure that is fully austenitic. Therefore, its micro structure results in a very high order of resistance to brittle fracture, and does not have the moderate embrittlement that 301 stainless steel has at 20 K. In an extra, full, hard temper it has a slightly lower tensile strength. Irradiation tests at

519 K resulted in no significant changes in yield or tensile strength or elongation[36]. Either type of stainless steel may be a good choice of material for the anchor.

Titanium may be an exceptional choice for the anchor emplacement system material. Titanium's density is only a little more than half that of steel's. Its melting point is at 1922 K, and it has better corrosion resistance in certain environments than stainless steels. Though it is relatively expensive, for temperatures of 573-773 K, it is superior to any other material for light-weight structural applications in strength and creep resistance[37]. Titanium's strength at 773 K is approximately 689×10^6 Pa. Even though the strength that can be obtained from stainless steels is about twice this, if looked at from a strength to weight ratio, the stainless steel advantage almost disappears. Titanium's surface embrittlement at high temperatures still needs to be researched but, it has already been used as a material for space vehicles[38]. Titanium is a conceptually superior choice of material for parts of the emplacement system.

2.4 Concept Generation

To help in concept generation, we used a functional decomposition of the individual operating requirements for the anchor system. This aided the design team in understanding the overall function of the system we were designing. The function structure is seen in Figure 2.

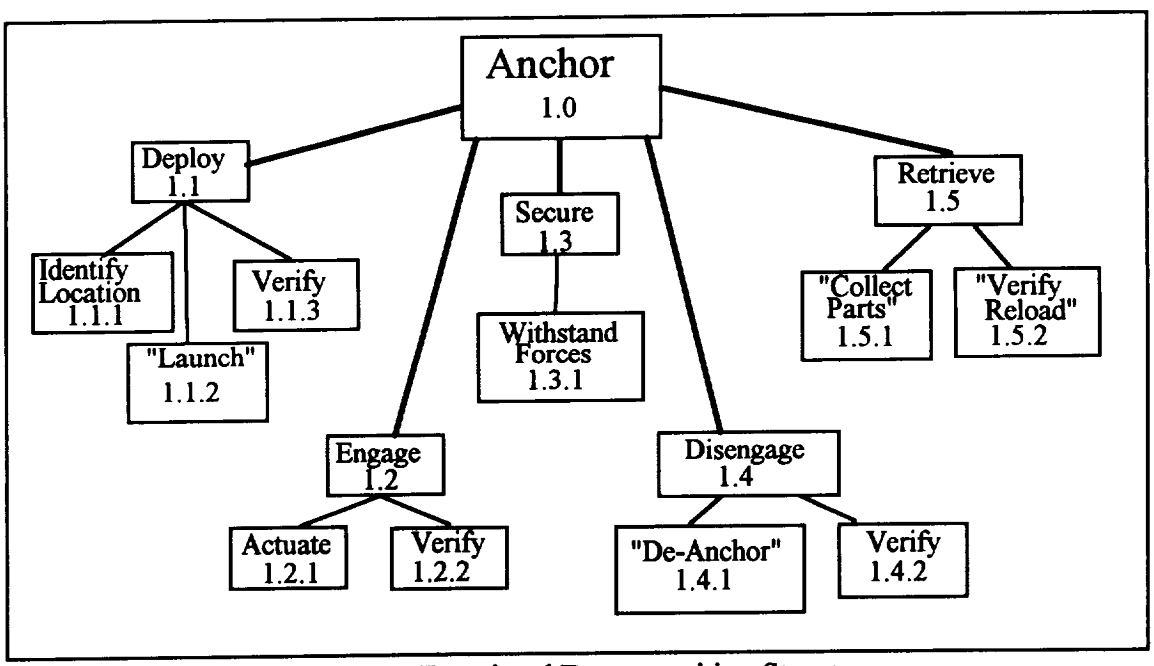


Figure 2. Functional Decomposition Structure

The next step in the design process was to come up with as many design ideas as we could. We made an effort to discuss each design idea and realistically look at the advantages and disadvantages for using them as part of an anchor system. Initially, numerous ideas for anchor designs were considered. The ease of emplacement, automation, reliability, and other requirements were evaluated for each idea.

Some of the ideas were simple in design, for example the harrow anchor shown in Figure 3. Harrows are used to break up clods of dirt for farming. A harrow has rows of tines evenly spaced on metal bars. When pulled over the soil, the tines are slightly angled in the direction of the pull. Used as an anchor, the harrow could be placed on top of the lunar soil. The direction of the tines would be angled against the direction of pull so as to dig into the soil and counteract the forces. The problem with this anchor is that it does not work well with forces oriented in an upward direction.

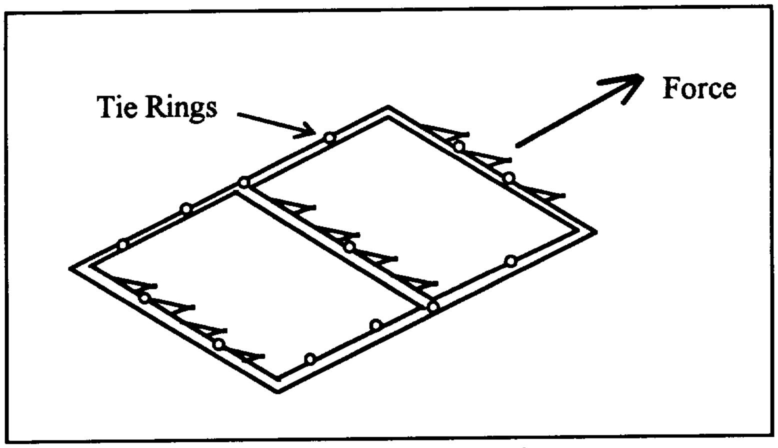


Figure 3. Harrow Anchor

Another simple anchoring device was the bent shovel as shown in Figure 4. The bent shovel anchor could be driven, or wedged in the soil to maximize its holding force. A connection could be attached to the anchor point at the top. The major sources of holding power are the weight and cohesion forces of the soil in front of the blade. This type of anchor is not useful if it is pulled out in a direction that is angled upwards. It may be useful since it is so simple.

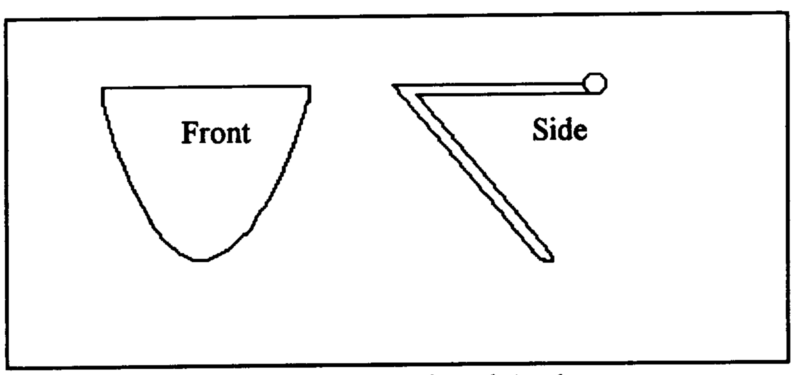


Figure 4. Bent Shovel Anchor

The angle iron anchor, as shown in Figure 5, would be pushed or driven into the soil much like the shovel anchor. It is considerably smaller than the shovel, and it relies more upon compressive forces of the soil for holding power. This anchor would support forces in any direction other than upwards. This could be a problem if anchoring forces were needed in this direction. this type of anchor would also be hard to automate.

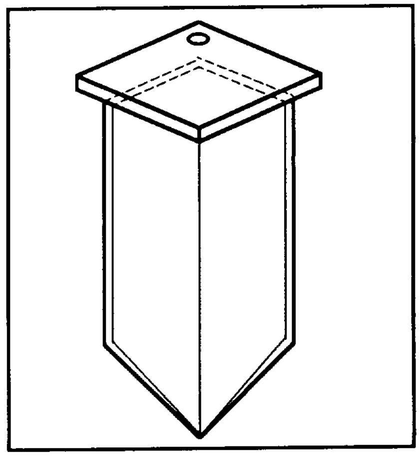


Figure 5. Angle Iron Anchor

The cork screw anchor seen in Figure 6 is small and lightweight. The body of this device has a cork screw shaft with a tether connection at the top. To emplace the cork screw anchor, a torque is required to emplace it into the ground. This anchor is very similar to the auger anchor concept. The auger anchor would have blades instead of the cork screw's continuous strand of material. This type of anchor would be easy to automate since all it needs is a torque to emplace. An auger concept may be better though, because it has a more stable surface which cuts into the soil.

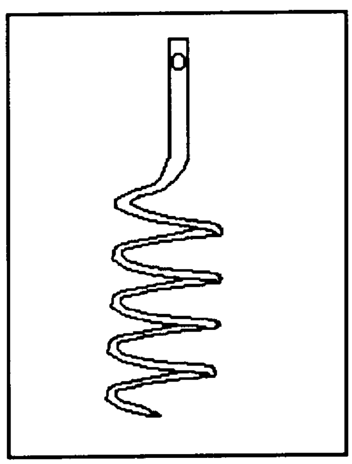


Figure 6. Cork Screw Anchor

Similar in looks to an actual screw, is the screw stake with clip anchor shown in Figure 7. It has a hollow shaft with a slit up one side. The slit allows the screw to contract upon insertion and then maintain a force with the soil after emplacement. The clip, which has a hole in the end, allows for anchoring in any direction. This design was modeled after existing ice anchors. This type of anchor may work in harder materials but it is unlikely to be useful in softer soils.

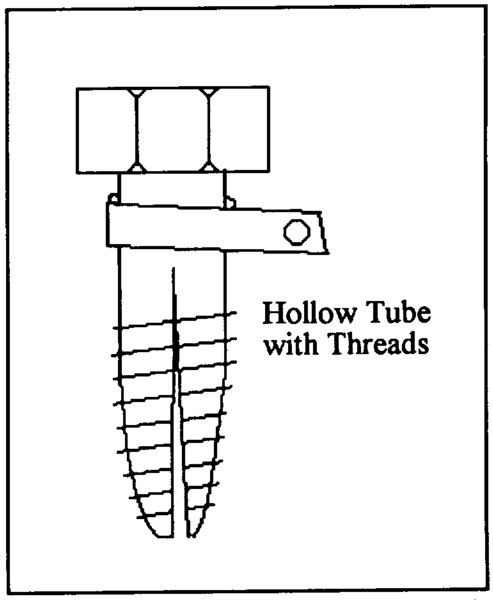


Figure 7. Screw Stake With Clip Anchor

The worley bolt design, in Figure 8, is used as a rock anchor for mining[39]. A hole is bored previous to emplacement. The worley bolt has two ribbed pieces of metal that fit close to each other when inserted. The strips are long and narrow with a bolt down the center. When tightened, the central bolt allows the metal ribs to slide past one another increasing the worley diameter. The enlarged worley bolt diameter increases the anchor's holding force. This type of anchor may not be useful in softer soils. Another problem would be that you need to bore a hole before it can be used. This makes the operation of anchoring more complex, and less reliable.

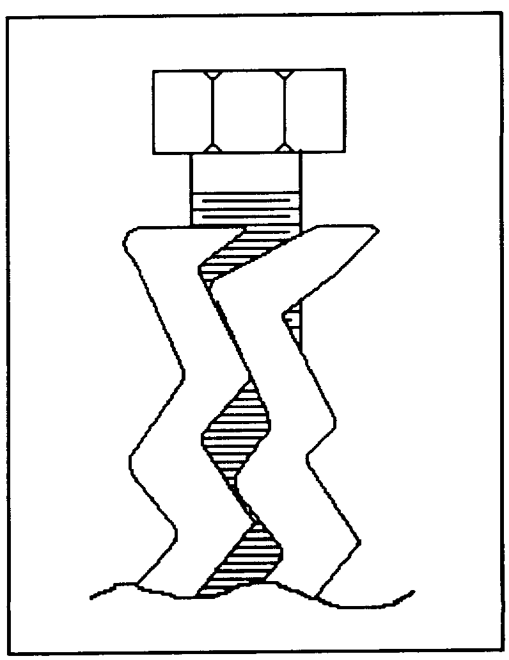


Figure 8. Worley Bolt Anchor

The umbrella anchor concept seen in Figure 9 looks like an inverted umbrella without the cloth. After the umbrella anchor is drilled or pounded into the soil, a mechanism at the top of the anchor is tripped which allows the rods to fan out into the soil. An upward force is applied to the anchor which helps to further fasten the device into the soil. The main problem with this anchor is that it has too many moving parts. This would cause problems with reliability in the sandy and gritty environment.

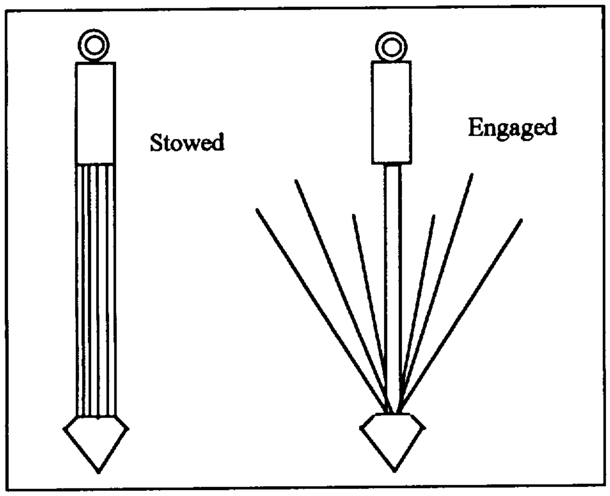


Figure 9. Umbrella Anchor

Some of the designs were not as simple, nor as safe. The explosive stake ball anchor, shown in Figure 10 looks like a whiffle ball. There are holes in the surface of the ball, while on the inside there are explosive mechanisms which shoot arrows that tether into the soil. This idea for an anchor may be useful but our design team will have no way of testing and evaluating this concept.

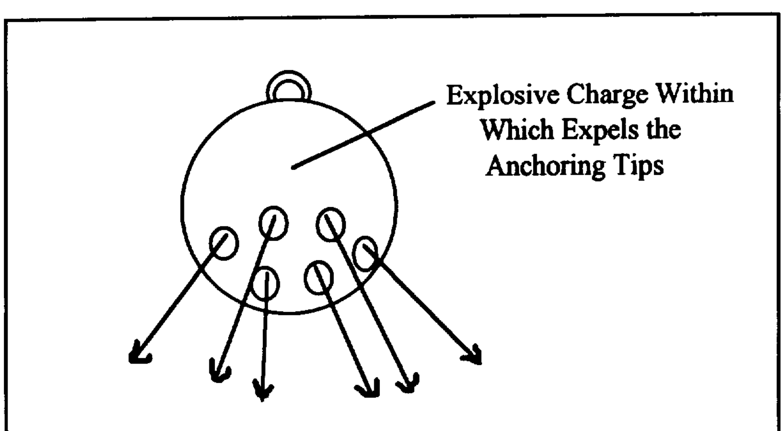


Figure 10. Explosive Stake Ball Anchor

Figure 11 shows the explosive harpoon anchor. The anchor could be left behind where it would explode causing the anchor tip to be embedded into the soil. This sort of anchor would need a heavy top piece to allow the force of the explosion to propel the anchor into the soil.

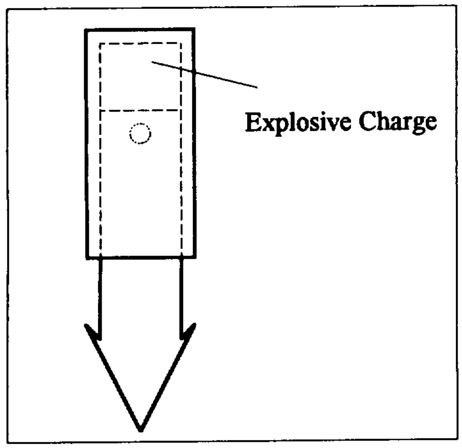


Figure 11. Explosive Harpoon Anchor

Not as dangerous, but more futuristic was the walking crab anchor. This device shown in Figure 12 looks similar to a crab. It has a small main body, about the size of a man's hand, with six crab-like legs. The crab is remote controlled to walk wherever directed. It can then dig itself into the soil or, in the case of rocky terrain, latch itself onto a rock by wrapping it legs around the rock. problems with this anchor would be caused by its complexity. The moving parts would be susceptible to the dust and grit, and reliability would be low.

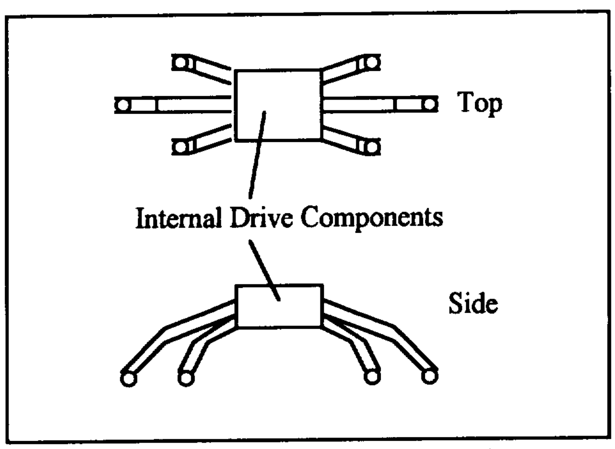


Figure 12. Walking Crab Anchor

Another concept which is similar to a living creature is the star dome anchor shown in Figure 13. This anchor looks similar to a star fish. The anchor could be thrown out into the soil similar to the harrow anchor. Any pulling on the connections would cause the star dome anchor to set itself into the soil more firmly. This anchor would not work well unless the pulling forces were horizontal. Also, being unstable it may flip over and not work at all.

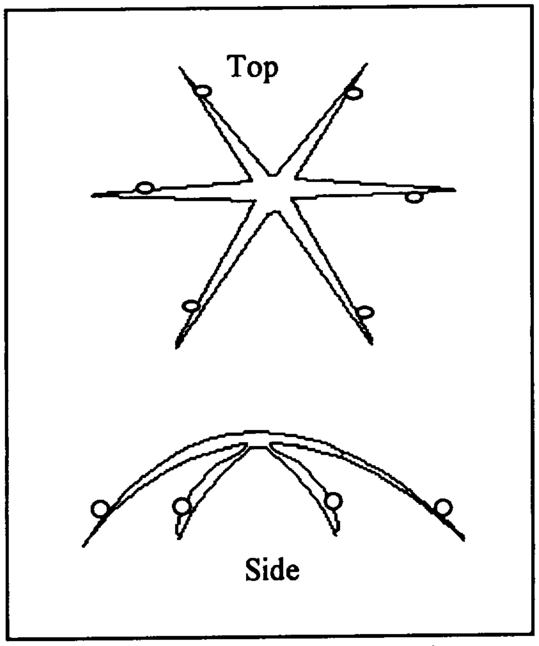


Figure 13. Star Dome Anchor

To narrow the conceptual ideas down, the team applied the technique of multi-voting. Anchoring ideas which used explosive methods were ruled out immediately due to our inability to test them. Important qualities that the anchor must have were weighted according to importance. For example, being an absolute customer requirement, an autonomous design was assigned a weight of 10 on a scale of 1 to 10. The team proceeded as a group to vote on each quality or requirement for each design. In this case, 1 was given for very difficult, and 10 was given for easy to make autonomous. Then, we multiplied the two numbers. After repeating the procedure for other criteria, we added up the total scores for each design, and kept the top four designs. The resulting four design ideas were the cork screw anchor, the shovel, the angle iron anchor, and the auger anchor.

2.5 Preliminary Testing

The four surviving conceptual designs were tested for feasibility. We used commercially available prototypes of each. The angle iron anchor was composed of a 2.54x2.22x0.32 cm piece of angle iron with a 7.62x7.62 cm steel plate on top. The cork screw anchor was composed of a 0.63 cm solid galvanized tube twisted in a screw shape. The length of the anchor was 25.4 cm and it had a diameter of 5.08 cm. An actual shovel with a spade 20.32 cm wide and about 0.32 cm thick was used to model the shovel concept. The auger device tested resembled a hand drill. The auger was about 33.02 cm long with a 2.54 cm diameter. The point of the auger was slightly beveled but not pointed. The thickness of the helix was approximately 2.54 cm and the taper was 0.76 cm.

An excavation site which had varying soil conditions was chosen as the initial experimental site. Moisture content, compaction, and soil density were not able to be measured at that time. Using a spring scale, hammer, and ruler as measuring tools, the following experimental procedure was used on each of the four concepts. First the soil type (soft, medium, or compact) was noted. Then, the device was emplaced into the soil, noting the qualitative ease or difficulty to insert. After measuring the depth of insertion, we used the spring scale to measure the pull out force at 0, 45, and 90 degrees with the soil surface. Failure was defined as the maximum force, after which the anchor device released itself from the soil.

The test results showed that the best performances came from the cork screw anchor and the auger anchor. The cork screw anchor and auger were both inserted into the ground with the least downward force, approximately 11.3-13.6 kg in medium to hard compact soil, and 4.5 kg in soft soil. The largest downward force was exerted on the angle iron and the shovel. The angle iron was pounded into the soil using a hammer which required considerable effort. Exact downward force measurements were not measured on the angle iron or shovel as it was difficult to attach measuring devices. The pull out forces were around 222 N for both the shovel and the angle iron. The auger and cork screw anchors held roughly 378 N in medium soil. In hard soil conditions, the scale measured only to a maximum of 378 N, and neither the cork screw anchor nor the anchor could be pulled out. In soft soil, none of the four devices held much force and they all pulled out easily. The cork screw anchor did not displace as much soil upon insertion as the auger. The design of the auger was such that its intended purpose was boring. The auger, however, was easier to start into the soil than the cork screw anchor. The cork screw anchor had a tendency to "walk around" due in part to its blunt tip which was more parallel to the ground than perpendicular to it.

The design team decided the auger anchor was the best choice for a lunar anchor. This came from the preliminary testing and also from the multivoting on the different design ideas. The one thing that made the auger anchor better than cork screw anchor was that it would be easier to automate. The cork screw anchor was unstable as it entered the soil. The auger anchor did not exhibit this effect so it was decided that we would focus on the application of an auger anchor.

3.0 ANCHOR MATH MODEL ANALYSIS

Our goal was to find a model which could predict the characteristics of an auger-type anchor. This information would later help us in understanding our experimental results. We found some equations which related the parameters of helical anchors and we calculated the holding force that could be supported in sandy soils.

Helical anchors consist of a shaft with one or more helices attached to it. The anchors are driven into the ground in a rotating manner. An axial load is applied to the shaft while rotating to advance it in the ground. Ideally, these anchors minimize disturbance of the soil during emplacement, therefore they can utilize much of the original in-situ state of stress and shear strength of soil[40]. The anchors can also resist tensile loads on the foundation and, at the same time, can supply additional bearing capacity to the foundation developed at the helix-soil interface (under a downward-loading condition)[41]. Helical anchors can consist of single or multiple blades. Their ultimate load in sand depends upon the relative density and degree of uniformity of the sand, and the fixed anchor geometry and dimensions (mainly the length and to a lesser degree, the diameter)[42].

For multi-helix anchors (two or more blades), it is very important that the pitch and center to center spacing of the helices are properly space. This allows the upper helices to follow the lower ones to reduce the disturbance of the soil. If the helices are sufficiently close together, then the soil between the helices becomes an effective cylinder. If the helices are widely spaced, the anchor behaves as a summation of several single helix anchors. A cylindrical soil failure surface develops above the top helical shaped plate during pullout. The holding force is dependent on the depth from the top of the soil to the uppermost helix, as well as the depth of the lowermost helix .

For single helix anchors, the shearing resistance along the failure surface will be controlled by the friction angle of the soil, and the state of stress in the disturbed cylinder-shaped area of soil above the anchor. The failure of this single helix anchor is dependent on the soil above the top of the helix. Therefore, the depth and diameter of the helix are the critical factors.

3.1 H/D Relationship of Helical Anchors in Sand

A shallow anchor condition is when the cylindrical failure surface above the top helix extends to the surface of the soil. Cracks in the soil may be evidenced. If the cylindrical failure surface does not reach the ground surface, the situation is called a deep anchor condition. Both these identifying failure surfaces for helical anchors can be seen in Figure 14.

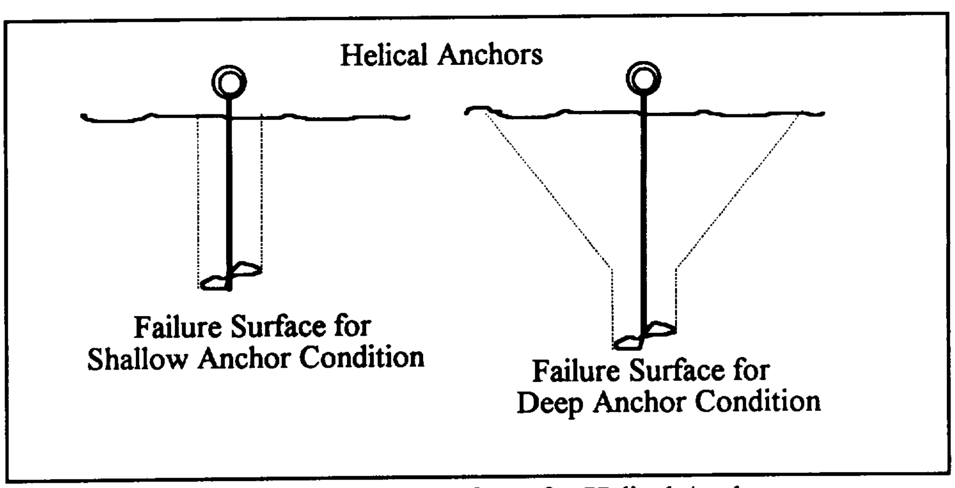


Figure 14. Failure Surfaces for Helical Anchors

These anchor conditions are determined by the parameter H/D, where H is the depth of the top helix to the ground surface, and D is the diameter of the helix. The critical value where the anchor changes from a shallow to deep anchor condition depends on the soil friction angle. The soil friction angle is a property of the soil and it will be different for various soils. For a soil friction angle of forty-five degrees, the critical H/D ratio is

9[43]. For soil with relative densities ranging from forty-seven to ninety percent, anchors with H/D less than five behave as shallow anchors[44]. These findings would predict that for a given depth, smaller diameter augers may have better holding power than larger diameter augers.

3.2 Model for Ultimate Holding Capacity For Shallow Anchor Condition

Using reference material we found equations that would predict the ultimate holding capacity of helical anchors. We wished to model our anchor in a shallow anchor condition since this would provide more conservative results than a anchor modeled in a deep anchor condition. We wanted to model the anchor for use in lunar soil. We did this by using the equations, substituting values that were appropriate for lunar soils.

Using equations for the holding strength for helical anchors in sandy soils, we could estimate the ultimate holding capacity (Q_u) by the following equation[45].

$$Q_u = Q_p + Q_f \qquad (1)$$

Where Q_p is the bearing resistance for the top helix, and Q_f is the friction resistance derived at the interface of the inter-helical soil which is cylindrical in shape. Q_f is zero in the single helix auger case. Thus, the equation for the net ultimate load is reduce to:

$$Q_u = Q_p = (\pi/4)F(\gamma)D^{2H} \qquad (2)$$

Where γ is the unit weight of the soil and F is the breakout factor, which is dependent on the friction angle and the H/D ratio. A table for values of F was used for a friction angle of forty-five degrees, and based on this column of values, F fluctuated depending on H/D. The equations included in this math model were programmed into Maple software to help the team in the dimensional analysis of the single helical anchor. The data was generated using the equations in Appendix B.

3.3 Results of Auger Math Model

For this auger analysis, the deep anchor condition critical value of 9, and a friction angle of forty-five degrees was used. It is important to note that the math model is conservative in many ways. For one, the shear angle for the regolith is known to be higher than forty-five degrees[46]. In general, the lunar regolith has been found to have a shear angle of up to sixty degrees. The cohesion of the soil was also neglected. The lunar soil will have high cohesion. This will allow the anchor to hold better than this model predicts. Regolith has been described to be similar to a soft, brick-like substance at its full density. Apollo mission data has also indicated that the soil can reach its full density within the first 20 cm of depth[47]. The math model is also for loose, dry sand, and pullout forces for sand are less than for other soils. This model was chosen because it best represented our anchoring situation. The unit weight (γ) used for the sand was 13,667 N/m^3. The unit weight was then adjusted for the lunar gravity, which is approximately 1/6 of Earth's gravity. By keeping the H/D ratio less than 9, this resulted in a math model which represented the anchor in a shallow anchor condition. A deep anchor condition would increase the pullout capacity of the anchor.

Figure 15 shows the math model's results for the pullout force of a single helix auger with different diameters, at depths of 229 mm and 305 mm.

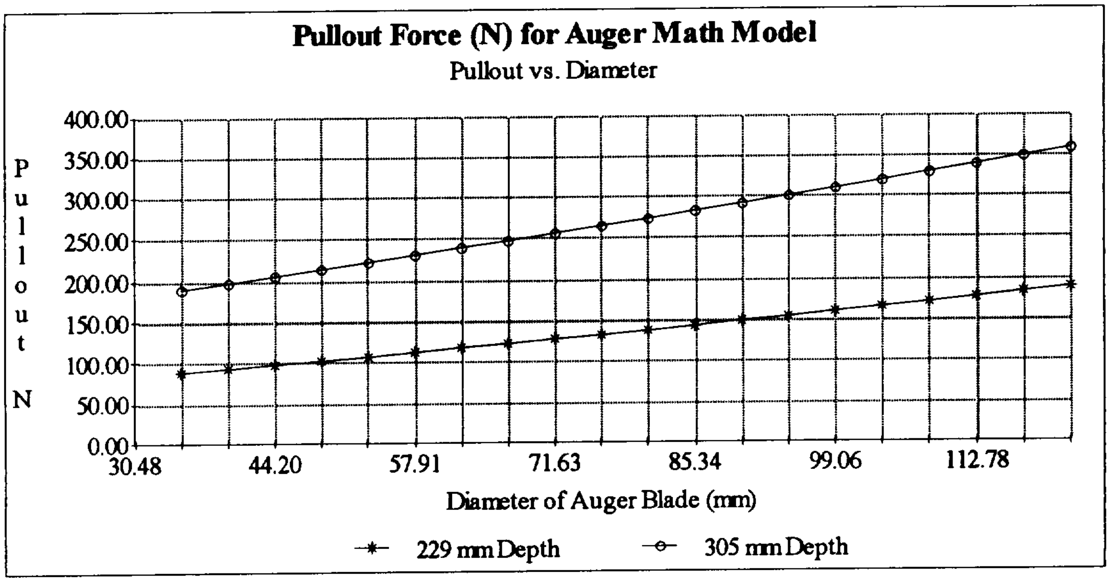


Figure 15. Pullout Force versus Diameter

Figure 16 shows the pullout force of a single helix auger at different depths, for helix diameters of 45.7 mm and 91.4 mm.

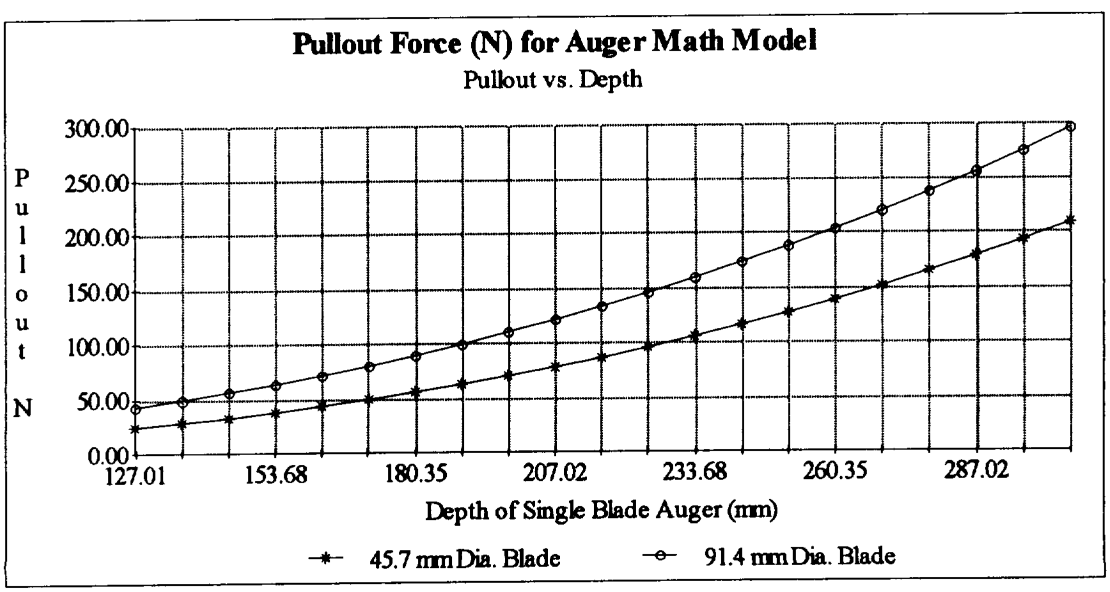


Figure 16. Pullout Force versus Depth

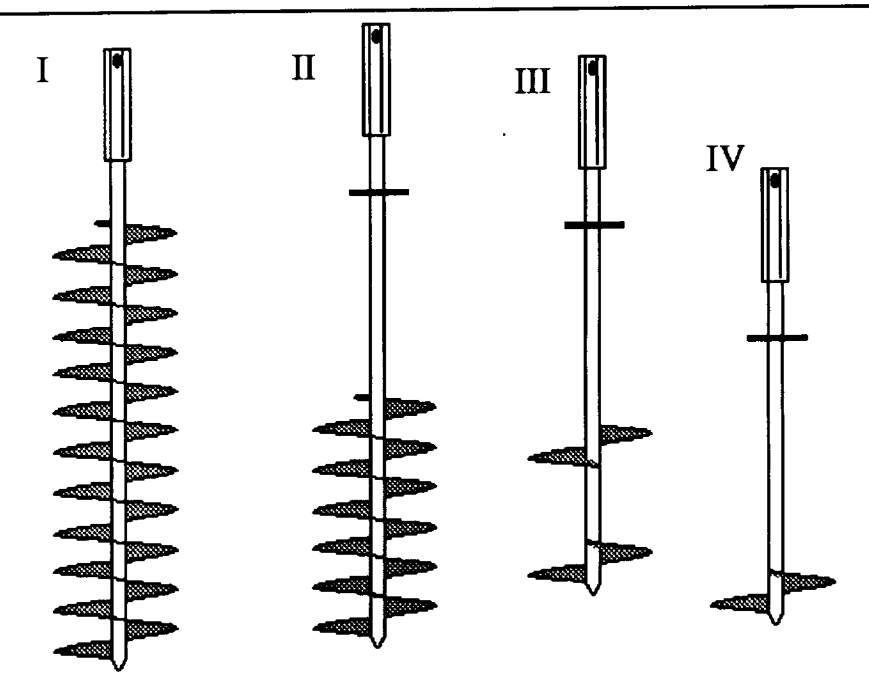
The results show that the pullout capacity is more affected by the depth of the auger than the diameter of the blade. Having the anchor modeled in a deep anchor condition would show the pullout force to be higher.

4.0 ANCHOR EXPERIMENTAL ANALYSIS

Our design team conducted tests on various augers. We were interested in finding out what dimensions were best to maximize the holding power of the auger and minimize the energy to emplace the auger. Having chosen an auger-type anchor as the surviving concept, an effort to evaluate and compare the performance of different auger configurations was necessary. We built an experimental test box and measured the performance of different augers. Augers with variations in diameter, pitch, length, and number of helices were useful in determining the best combination of dimensions.

4.1 Auger Descriptions

Eight different augers of four different styles were tested. The four different styles of augers are shown in Figure 17. Some of the augers had helices all the way up the shaft, others had only just one helix. We tested similar augers with different numbers of helices. Another style of auger had two helices that were separated from each other. The effect of using different diameters, and also helices that tapered at the bottom was also tested.



Different Pitches, Tapers, and Sizes were Tested

Figure 17. Four General Styles of Augers

The physical descriptions of the augers are as follows:

Auger #1: Shaped like I, but with no tapered point at the bottom. It has seven revolutions, a hollow tube, and a 114.3 mm hexagonal rod welded to the top.

Auger #2: Shaped like III, and it is a mobile home anchor. It has a total of two revolutions at the bottom, a solid tube, 127.0 mm hexagonal rod welded to the top, and a blunt tip welded to the bottom.

Auger #3: Shaped like III, but is has a tapered bottom for approximately one revolution. It has four revolutions, a solid tube, a 114.3 mm hex rod welded to the top, and a blunt tip welded on the bottom.

Auger #4: Shaped like IV, and this auger was bought from a hardware store. It has one revolution at the bottom, a solid tube, and a hexagonal rod welded to the top.

Auger #5: Shaped like III, but much smaller than auger #2. It has two revolutions at the bottom, a solid tube, a hexagonal rod welded to the top, and a blunt tip welded on the bottom.

Auger #6: Shaped like IV. It has one revolution at the bottom, a solid tube, and a hexagonal rod welded to the top.

Auger #7: Shaped like IV. It has one revolution at the bottom, a solid tube, and a hexagonal rod welded to the top.

Auger #8: Shaped like II, but it has only two revolutions. This auger fits into a 9.525 mm electric drill.

The specifications of the eight augers appears in more detail in Appendix C.

4.2 Experimental Test Box

To determine how the auger dimensions affected performance, a test box was constructed and filled with a suitable soil. The test box was 1.2 m long, 1.2 m wide, and 0.9 m deep, lined with a plastic tarp. We decided on these dimensions because we wanted a test bed that would be useful to test augers that were at least half a meter in length. The 1.2 m width and length was useful so that we could do more than one test without repacking the soil.

The test box was filled with decomposed granite as the soil simulant, and when not in use, the soil was covered with the tarp to hold in the moisture. A container of water was also kept in the covered soil to keep the humidity high. This kept the soil from drying out completely. The moisture in the soil was necessary to help the soil have some cohesion. Decomposed granite was chosen because it could be easily re-worked and re-packed. The soil was pre-tested by being packed, and then dried in an oven. When dry, it became brick-like and could be crushed into silty sand. The soil readily accepted water when hard and easily became soft as before. Thus, if the soil was allowed to dry and get hard-packed, water could easily penetrate it without it having to be broken up and mixed while in the test box. The soil moisture could be monitored to provide high cohesive forces, or it could be left dry to allow for sandy, silty soil with very little cohesion. As mentioned before, the lunar soil is soft on top but hardens to a soft brick-like consistency within only about 20 cm[48]. The soil needed seventeen percent moisture by weight for optimum compaction. This information was determined with help from a civil engineering student who was familiar with the construction applications of the soil that was used.

4.3 Measurement Devices

The materials used to gather the performance specifications of the augers included a vernier caliper, tape measure, and an electronic scale. Other materials used in the actual testing included two spring scales, a pulley/crane system, rope, a torque wrench, weights, and a steel and plastic ruler. Refer to the Appendix C for the tolerances on the measuring devices. Figure 18 shows the test box and crane assembly used for testing.

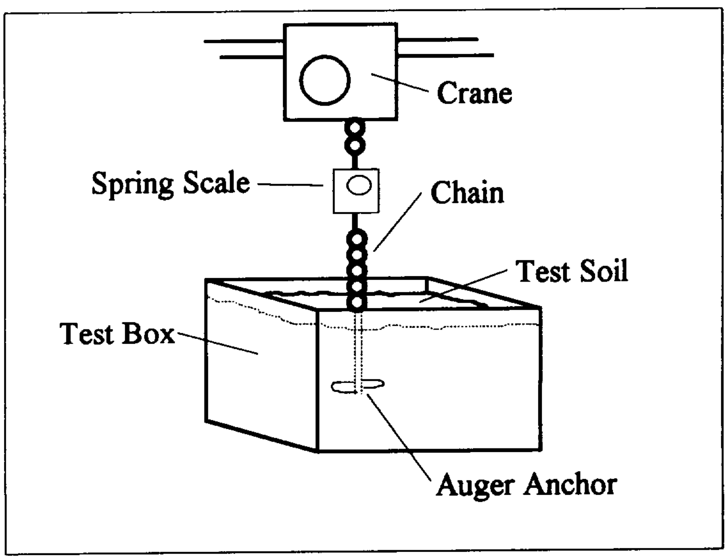


Figure 18. Test Box and Crane Assembly

4.4 Procedure

The soil was first packed by team members stomping on it, and leveling it out with a piece of wood. Preliminary tests were done in this "loosely-packed" soil. The rest of the tests were done in "extremely tamped" soil, which meant the soil had been tamped with steel rods, leveled and stomped on. A nuclear densimeter was used to test the compaction of the soil. The moisture weight was at approximately fourteen percent. This meant that the soil was at eight-two percent of the optimum moisture level for compaction since seventeen percent was considered optimal. The density of the compacted soil was 1883 kg/m^3, compared to the lunar soil density of 1200 kg/m^3. This would cause the anchors to hold more in the test box than they actually would in lunar soil.

An auger was placed at the surface of the soil and circular weights were placed through the top the auger and rested on a pin sticking out the side of the auger. The weights were used to apply a downward force on the auger. A torque wrench was connected to the hexagonal top of the auger and was used to "screw" the auger into the soil. The number of revolutions the auger required before it began to dig itself into the soil was recorded. The changing torque and the total number of revolutions to emplace the auger to the desired depth was also noted. This data can be referred to in Appendix D. Once emplaced, the height and width of the circular soil dug up from the auger was measured, as well as the depth of the auger. The limiting depth an auger had to be emplaced to hold a force greater than or equal to 334 N (75 lb) was determined for each auger.

A pulley/crane system was used to pull the augers out at 90, 45, and 0 degree angles with respect to the horizontal. At the end of the crane there was a hook, and a rope connected a spring scale to it. The spring scale was then connected to the auger and was used to measure the applied force. A chalk mark was made on the side of the anchor before any force was applied. This was used as a reference point to measure how much the auger moved when a pullout force was applied. A range of forces from 71 N to 712 N were applied to the auger. The changes in the movement, or auger depth, was recorded at each increment of increased applied force. The maximum force at pull-out or failure was also noted. A sample data sheet used for the different auger tests is in Appendix C.

4.5 Testing Results

Early test results showed the first few, of the eight augers that were tested were too large. The forces they were holding were well beyond expectations. Smaller augers were tried and were found to hold well. They went into the soil with less energy.

Different tapers on the bottom of the augers were tested. Instead of a wedge shape, some of the augers were modified to taper out to a point at the tip similar to a wood screw. Eventually it was found that the tapered end worked better for the multiple helix augers, but the best results came from using small augers with a single helix and no taper. These augers went into the soil far easier than the double or multiple helix anchors, and they held better.

The most surprising result was that smaller diameter single blade augers were holding better than the larger diameter single blade augers for the same depth. At first this was disturbing because, since the blades are cutting into the regolith and not disturbing it, one would expect a larger diameter blade to be held by a larger volume and mass of soil and therefore hold more force. However, After realizing that our mathematical model of helical anchors (described in Math Model Section of report) predicted that a deep anchor condition would explain this, it made sense. The anchor's ability to hold was greatly increased if it could be considered deep enough to avoid the tendency to come back out of the hole it was placed in (refer to Figure 14). This deep anchor condition resulted with increasing ratios of depth divided by diameter[49]. This explained why the smallest diameter anchor was holding better.

Experimentation with different blade pitches proved that this was critical to the auger's ability to pull itself into the soil with a minimum of downward force. The consistency of the blade's pitch was very important at getting the anchor to go into the soil with less energy and low downward force. This factor came by chance since the team fabricated some of the augers. The blades for the anchor were cut out of plate, and welded to a shaft similar to an auger that was purchased. The method of building these prototypes was not as accurate as the purchased augers, and this showed up in our test results.

The results from these tests showed that the dimensions and style of an auger was critical to their ability to hold in the soil. Quality was also a concern since this affected the path of the helix through the soil and thus, the soil disturbance. Single bladed, small diameter augers proved to hold more force than both the larger diameter multi-helix augers and the larger diameter single helix anchors. The test data can be referred to in Appendix C.

5.0 PROTOTYPE TESTING

After evaluating the different effects of the various auger styles, we specified the design of a prototype anchor to be built. We tested this prototype in a similar manner as the first experimental anchors. A description and evaluation of this prototype and the testing follows. A detailed drawing of the prototype anchor appears in Appendix F.

5.1 Prototype Description

Dimensions for the prototype were generated based on the numerous tests, mathematical models, and research mentioned previously. A prototype anchor was designed and produced. The materials used for the prototype were Stainless Steel 303 and 304. This materials were chosen for the ease of machining, corrosive resistance, and strength. The Stainless Steels 303 and 304 are not the intended materials for the actual production of the augers due to weight constraints. The auger dimensions were determined from math models, experimental testing, and researched data.

A few key aspects of the prototype design are the pilot (tip), auger blade, shaft (stem), emplacement head, and connection mate. The pilot is the most important aspect of the anchor design. It enables the auger blade to stabilize and begin cutting into the soil. Without this component, the blade would just "walk" across the surface. The pilot used for the prototype was a piece of .9525 cm. diameter drill bit 2.5 cm. long. It was recessed into the shaft of the anchor and welded into place. The length of the pilot was proven to be sufficient from preliminary auger tests. If the pilot were too long, it would prevent the auger blade from reaching the soil and extra downward force would be needed to get the blade cutting into the soil.

Another important aspect of the anchor is the auger blade. The blade dimensions greatly determine the quantity of energy needed to emplace the anchor and how much holding force the anchor will have. Three dimensions associated with the blade are the diameter, pitch, and thickness. The prototype anchor had a blade pitch is 2.5 cm, diameter is 3.8 cm, and thickness of 0.158 cm. The helical blade was welded to the stem immediately after the pilot. Testing proved that if the pitch and diameter were too large, the amount of force and energy to emplace the anchor was too large. If these dimensions were too small, the anchor would have minimum holding force. Also, the thicker the blade, the greater the emplacement energy.

Another key factor is the stem. This determines the maximum auger blade depth, and how much lateral and bending stress the anchor can withstand. The stem length is the measurement from the top of the auger blade to the connection mate. The chosen length and diameter for the stem is 30.5 cm. and 1.25 cm. The overall length of the structural shaft is 43.8 cm. The stem length has proven to be an important factor in correlation to the auger blade diameter. As mentioned in the section 3.1, a proper depth must be reached to produce a corresponding cylinder that does not extend to the soil's surface. This enables the anchor to produce a greater holding force, thus keeping it into the ground.

The last important component of the anchor is the mating connection. This connection is comprised of two 19 mm. washers which are welded to a turned portion of the emplacement head. A 3.8 cm. spacing exists between them enabling a variety of connection methods. This design insures that connected line can freely rotate 360 degrees and allow pullout forces at angles between 0 and 90 degrees. It also insures that there is no vertical sliding at the connection.

The dimensions for the emplacement head are not as critical. The head has to be easily connectable for testing and there should be enough length to be able to apply weights. The diameter of the head should also be relatively similar to that of the shaft. The chosen dimension was 19 mm of hexagonal stock which is 7.6 cm in length. The emplacement head was then welded to the top of the shaft to secure it from spinning.

5.2 Experimental Equipment

The experimental test setup was the same as the one used with the eight different augers. The only difference was that we used a load cell to determine the forces instead of the springs scales, as used before. The load cell shown in Figure 19 was designed by the group, and was of a C-shaped geometry made out of Aluminum 6061. Strain gauges were secured to the load cell and connected to a strain indicator to measure holding forces.

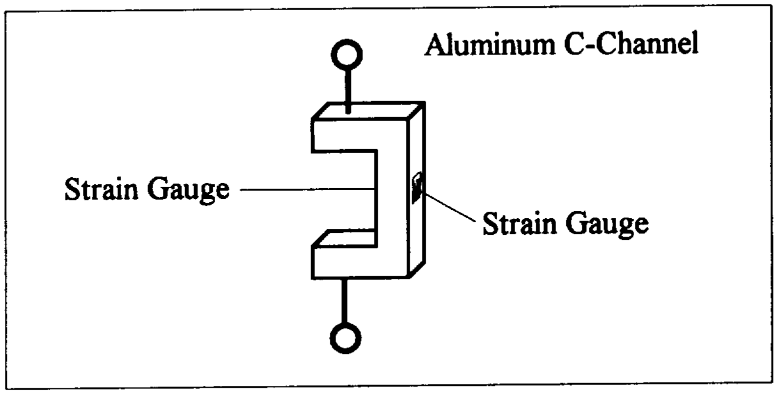


Figure 19. Load Cell

A torque wrench and 19 mm socket were used to drive the anchor into the soil while measuring the amount of torque. A mass of 4.5 kg was placed at the top of the anchor to aid in emplacement. A ruler was used to measure the depth of the anchor in the soil. A protractor measured the angle at which the crane was pulling on the anchor.

5.3 Experimental Procedure

The standard test procedure consisted of inserting the anchor to a specified depth and pulling it out at various angles to calculate holding force values. The test box was initially tamped with 10 kg. rods to ensure an even compaction throughout the test bed. The strain indicators on the load cell were balanced to zero while attached to the overhead crane.

The anchor was emplaced in the test bed so as to disrupt a minimum amount of soil so as not to influence the pull out test. A mass of 4.5 kg was applied to the top of the anchor to simulate the downward force to be supplied by the emplacement system. A 19 mm socket was attached to the torque wrench which was used to drive the anchor into the soil. As the anchor was being wrenched into the soil, the number of revolutions and the changing torque were periodically recorded. Once the testing depth was reached, this depth was measured and the data was recorded. A sample data sheet for the prototype is in Appendix C.

The load cell was then connected to the mating connection with a piece of chain. The load cell was connected in series to a crane hook with a piece of chain. This set up can be seen in Figure 20. The crane was then positioned for the necessary pull out angle. Without any tension in the chain, the strain indicator was balanced one more time. The pull out could now begin.

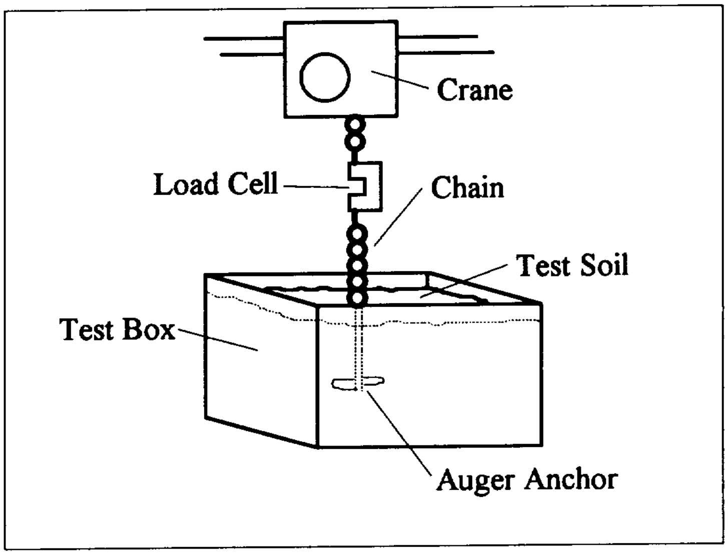


Figure 20. Test Setup with Load Cell

The hook was slowly raised while the strain indicator and anchor were watched to determine the point of failure or the peak holding force before the anchor began to pull out of the test bed. The peak holding force values were recorded and the anchor was removed from the bed which was then prepared for another test. After each test, the soil simulant was tamped to approximately the same compaction. Compaction testing was not performed between each individual test.

5.4 Results of Prototype Testing

The results from the prototype testing proved that the single helix anchor meets the design requirements. After evaluating the pullout force results, there was a possibility of overdesign. However, variability of the lunar regolith and the test soil necessitates the overdesign. NASA contact, Butler Hine, said, "... the holding force required is so highly task dependent, that you can't say any value is over designed."

As hypothesized, as the depth increased, so did the holding capabilities of the anchor. Figure 21 illustrates that the maximum value for holding force occurred at the maximum depth of insertion. The maximum holding force was tested at depths of 15, 20, 25, and 30 cm. The approximate energy required to insert the anchor was 6 to 13 Nm depending on how deep they were placed.

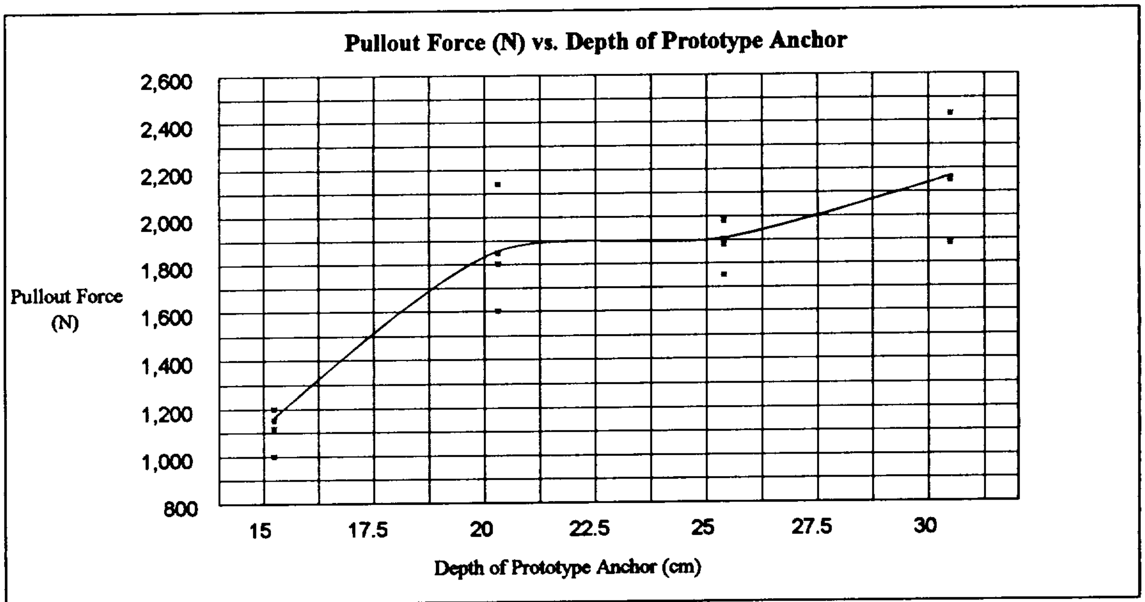


Figure 21. Pullout Force versus Depth

Figure 22 illustrates the holding force as a function of the pullout angle. The curve in Figure 22 was generated from pullouts at 10 degree intervals. The maximum holding force was at 60 degrees and a minimum was located at 40 degrees. The tests were repeated, with all at a depth of 30.5 cm. The energy required to insert the anchor was again approximately 6 to 13 Nm.

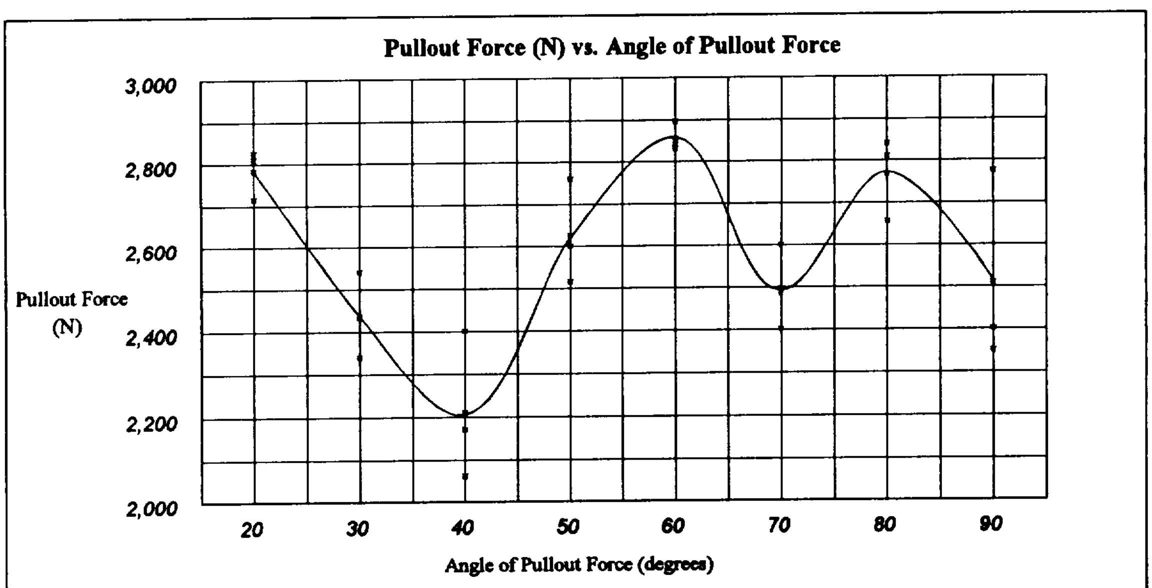


Figure 22. Pullout Force versus Pullout Angle

The graphed results showed inconsistencies at 40 and 70 degrees. Unable to interpret the data at these points, we contacted Jim Hardcastle, a professor in Soil Mechanics at the University of Idaho. His explanation for the data points was that the auger was modeling two separate soil mechanics theories, a pile and a footing. The stem of the anchor was acting as a pile and the auger blade as a footing. When applying loads to the anchor, the two theories were superimposing on one another. At the angles of 40 and 70 degrees, the superposition of the models produced a points of failure. Professor Hardcastle also mentioned that there have not been any studies proposing a solution to the problem. Therefore, it is recommended not to load the anchor at these angles. These results may vary with different anchor sizes and depths.

Any error in the numerical results is attributed to several things. The soil in the testing box varies in compaction due to the tamping methods. This directly effects holding force capabilities of the anchor. The more compact the soil, the more force the anchor holds. However, revolutions to insert the anchor also increase with compaction of soil. In regards to the accuracy of pullout force versus angle of pullout, the angle was measured by using a level and protractor. This method of measuring the angle was sufficient but not perfect. Keeping a stationary position of the overhead crane during pullout was difficult. Also, error may have been induced by the load cell. Even though it was calibrated on an hydraulic testing machine, temperature changes in the load cell due to variation of the ambient temperature may have caused some error in the pullout force readings. Also, possibilities of residual stresses remaining in the load cell caused by previous pullouts could have altered the strain indicator readings.

The performance of the prototype has gone beyond expectations. Comparing its results to previous models tested, it requires less emplacement energy, supplies higher holding force, and requires less revolutions for emplacement.

6.0 Conceptual Emplacement System

The emplacement system which was designed is a conceptual design. Unlike the anchor itself, the emplacement system was not built, although the concepts were tested. the emplacement system needs to provide the necessary energy to emplace the anchor and it needs to be autonomous. The emplacement system would be expected to perform in the extreme lunar environments and it would need to require as little energy as possible.

6.1 Description

An emplacement system needs to automatically provide the energy and means for placing the anchor once a location is specified. Power requirements for the emplacement system must be low since the common sources of energy used in lunar missions produce low power rates. Since there will not be sufficient torque to place an auger anchor directly in the soil with an electric motor, a reduction gear system, or an energy storage method is needed. Energy requirements from the test data were used to evaluate the needs for the emplacement system. The energy needed for auger emplacement can be seen in Appendix D. A gear system could supply the necessary energy but lubrication needs and reliability would be a problem. An idea to use a flywheel as an energy storage device matched well with the torque needed for auger emplacement. An analysis was performed on the feasibility of both these systems in Appendix E.

A flywheel system was chosen as the final emplacement system concept. The detailed drawings of the emplacement system appear in Appendix F. It contains four main features: the insertion mechanism, the lifting and latching device, the release chuck, and a frame/stand which can be used to make the emplacement system free standing or attached to a rover.

The insertion mechanism consists of a flywheel and an electric motor to spin the flywheel. The motor transfers kinetic energy to the flywheel in order to place the anchor to its proper depth within the regolith. Using the Flywheel as assumed in Appendix E The approximate angular velocity needed to emplace an anchor is 1000 revolutions per minute, which was calculated with mathematical equations. The concept of using high speed emplacement was tested by using a hand drill and letting an auger anchor emplace itself at 1200 RPM. Encasing these two components is a containment box. Its sole purpose is to keep particles from entering the electrical motor housing and to keep the flywheel and shaft aligned vertically.

The device that raises and lowers the insertion mechanism incorporates a gear crank at the top for resetting the emplacement system. A small motor could be used for full autonomous operation. Connected to the system at the top of the frame is a simple latching device which holds the insertion mechanism in place while the flywheel is accelerated to the required angular velocity. In order to enable the insertion mechanism to lower, the lever will have to be disengaged by mechanical means. The insertion mechanism slides up and down on two shafts which are protected by dust boots. These guide the insertion box and keep it from twisting.

On the end of the driving shaft is a chucking device. This device uses internal levers and springs to grasp the anchor for insertion. Once the bottom of the chuck touches the ground, it pushes upwards on the grasping latches, forcing the chuck in half releasing the anchor. This mechanism is intended to allow the flywheel to spin freely after the anchor is placed. If there is excess energy stored in the flywheel, it will not spin the auger after it is fully inserted. This will keep the auger from disrupting the soil which will decrease its holding ability. When the insertion box is locked into its initial position, another anchor can be inserted and the chuck can be closed and locked.

The emplacement system frame/stand consists of four telescopic legs and a frame to connect to the lifting device. These legs enable the anchor to be emplaced at slight angles relative to the soil and keep the critical height (dimension between the regolith and chuck) at the proper level. There is also an additional stand which can allow the emplacement system to be attached to a rover.

The main goal of this design was to create a reactionless emplacement system and to make it easily automated. The flywheel system was chosen on the basis that it uses momentum and low levels of power to provide a means for conveying work. A 1/4 scale working model was built to show that this system can work.

6.2 Operation

When an anchor is to be emplaced, the insertion mechanism will initially be raised to the top of the lifting device and latched properly. The motor then begins to spin the flywheel up to the appropriate speed. Once the flywheel has reached approximately 1000 rpm, the lever will be tripped, and the box will begin to descend downward toward the regolith. After the anchor touches the regolith, it will begin screwing itself into the soil. The additional weight of the flywheel is applied to the anchor for emplacement purposes. After the anchor reaches the appropriate depth, the chuck will rub against the ground and disengage the grip on the anchor. Now the insertion mechanism can be raised to the proper position, via the gear crank or electric motor, and latched. The system is now ready for another anchor.

7.0 CONCLUSIONS

Finding a system which can successfully anchor into the regolith is not an easy task. Uncertainties relating to the soil properties, and the effects of reduced gravity are hard to account for when testing systems on Earth. Although there are uncertainties about the exact emplacement design, this system meets it overall design requirements. Further development would best be focused on making the system lightweight, and smaller. A need for fine tuning and more experimentation also exists.

7.1 Design Summary

The final design concept for the anchor and emplacement system includes a single helix auger anchor and an autonomous emplacement system. This system was chosen for its minimal emplacement energy requirements, its simplicity and reliability, and because it can be easily automated. The emplacement system operates by using a flywheel to store the energy needed to emplace the auger. This system allows the power requirements of the system to be very low. Since the system is autonomous, the time required to get the flywheel up to speed is not critical.

Consideration of a human placed auger anchor would be useful for situations where automation is not required. A small emplacement tool could be used, and the auger could be manually inserted into the soil. The downward force needed for emplacement is minimum so there would be no problem with an astronauts reduced weight due to the low gravity.

7.2 Design Concerns

An important design feature of the anchor and emplacement system is that it needs to be lightweight. Having a system that includes a flywheel to store energy will need to be massive. Possibilities are to use a hollow flywheel assembly and fill it with regolith to provide the necessary mass. This may also cause balance problems, as the system spins with high rotational velocities. Due to the high rotational velocity of both the flywheel and the auger anchor, these components must be precisely balanced. Momentum plays a dominating role in reduced gravity situations, which compounds the problem of balance.

Any unbalance in the system will create movement of the system and momentum could cause the emplacement system to tip over.

This anchor emplacement concept can be scaled for specific tasks, or requirements. To precisely design the parameters for a different scale auger-type anchor, several things must be evaluated. The expected loading, the depth needed, the diameter of the auger blade, and the pitch, or helix angle must all be determined. As discussed in the math model section 3.0, a deep anchor condition should be sought by keeping the depth (H) divided be the blade diameter (D) at least above 5, depending on the soil properties.

Design of the pitch of the blade (helix angle) would allow the spinning auger to pull itself into the soil smoothly. A pitch that is too shallow will not go into the regolith soon enough, causing the emplacement system to be unstable. More energy for emplacement would also be needed because the auger would have to spin more revolutions in the regolith to reach a required depth. A pitch that is too steep will pull the emplacement system into the soil too quickly. This will waste energy by changing the momentum of the free falling emplacement system.

Connection of the anchor to cables or attachments was not thoroughly investigated. Due to the uncertainty of what type of connection will be needed, a simple connection suitable for D-ring placement at any angle was designed. Performance of the auger anchor at various angles of applied force is not well understood. As discussed in the prototype results, a decreased holding power was found at certain angles of pullout force. This may be caused by failure planes in the soil. These effects may change with different size anchors, different depths, etc.

Another foreseen problem with the anchor system will be its performance with constant load over time. It is not known if the lunar soil will allow the anchor to creep, and give out under extended loading. The reaction of the anchor to many cycles of loading and unloading, possibly at various angles was also not studied.

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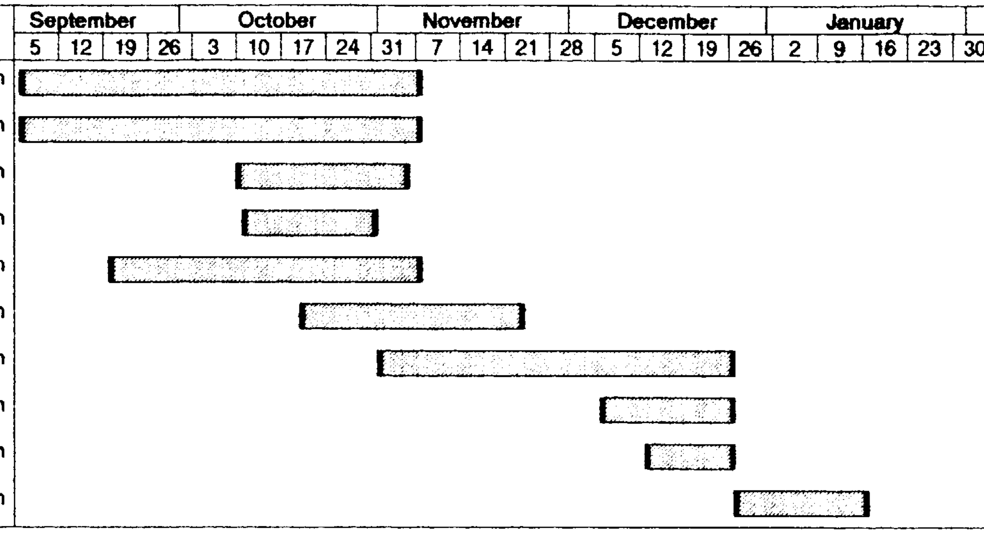
APPENDIX A

Gantt Chart

NASA Anchor Emplacement Design Team

ID	Name	Duration	Scheduled Start	Scheduled Finish
1	Customer Requirements	9w	9/6/93 8:00am	11/7/93 5:00pm
2	Research	9w	9/6/93 8:00am	11/7/93 5:00pm
3	QFD	4w	10/10/93 8:00am	11/5/93 5:00pm
4	Function Structure	3w	10/11/93 8:00am	10/31/93 5:00pm
5	Generate Concepts	7w	9/20/93 8:00am	11/7/93 5:00pm
6	Concept Testing	25d	10/20/93 8:00am	11/23/93 5:00pm
7	Concept Evaluation	8w	11/1/93 8:00am	12/26/93 5:00pm
8	Building of Test Bed	15d	12/6/93 8:00am	12/26/93 5:00pm
9	Design Review	10d	12/13/93 8:00am	12/26/93 5:00pm
10	Winter Recess	15d	12/27/93 8:00am	1/16/94 5:00pm

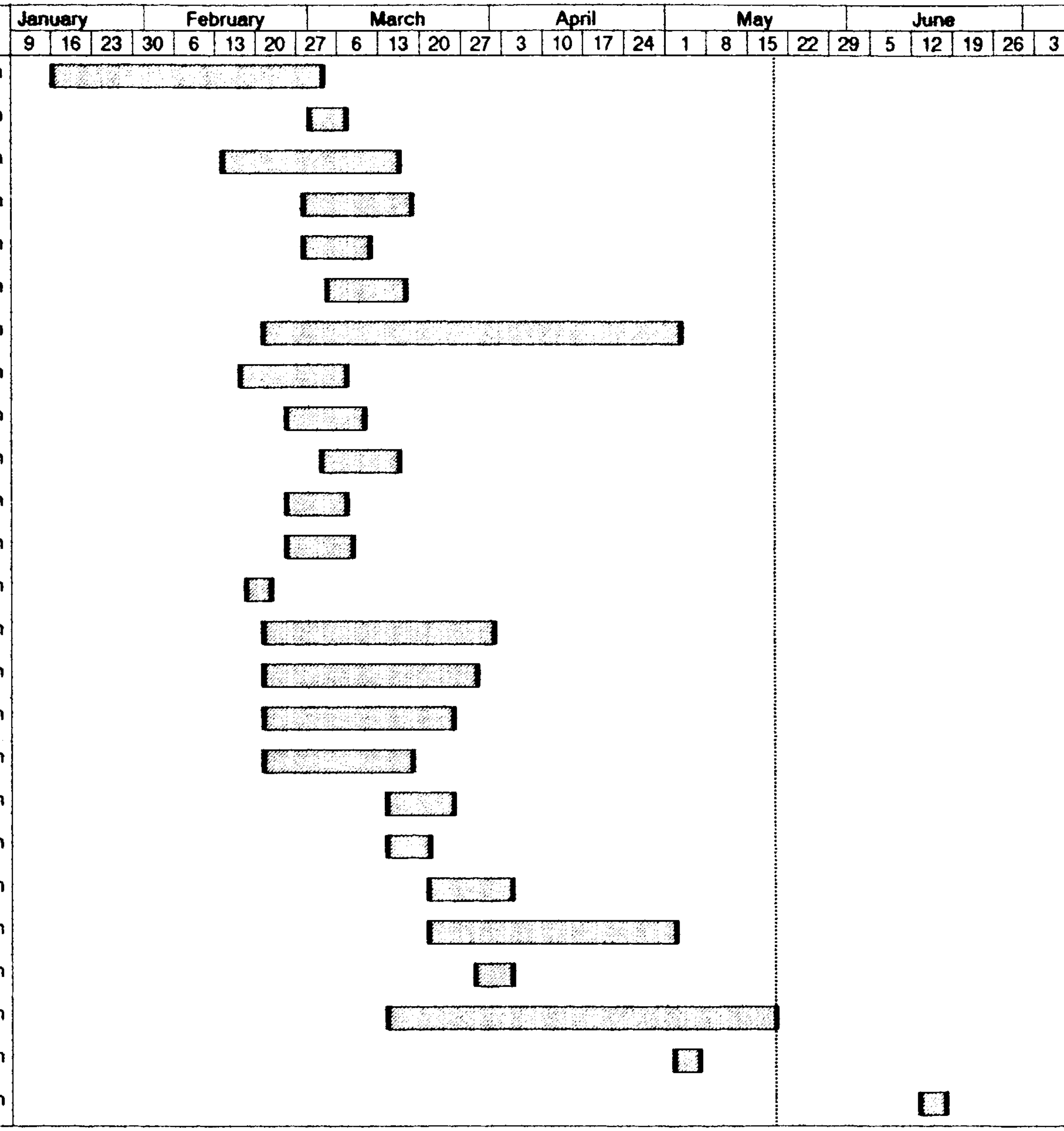


Project:
Date: 5/19/94

Progress

NASA Anchor Emplacement Design Team

ID	Name	Duration	Scheduled Start
1	Testing of Augers	6.8w	1/16/94 8:00am
2	Generate Auger Dimensions	1w	3/1/94 8:00am
3	Design Emplacement System	4.6w	2/14/94 8:00am
4	Evaluate Testing (Graphs)	15d	2/28/94 8:00am
5	Generate Math Model for Aug	10d	2/28/94 8:00am
6	Final Design for Auger	10d	3/4/94 8:00am
7	Figures for Report	10.4w	2/21/94 8:00am
8	Refine Proposal (Flywheel)	2.6w	2/17/94 8:00am
9	Refine Proposal (Gear Sys.)	2w	2/25/94 8:00am
10	Finalize Emplacement	2w	3/3/94 8:00am
11	** Flywheel	1.4w	2/25/94 8:00am
12	** Main System	1.6w	2/25/94 8:00am
13	Decision of Types of Drawing	3d	2/18/94 8:00am
14	Produce Drawings	6w	2/21/94 8:00am
15	** Anchor	5.4w	2/21/94 8:00am
16	** Release Chuck	5w	2/21/94 8:00am
17	** System	4w	2/21/94 8:00am
18	Build Anchor	2w	3/14/94 8:00am
19	SPRING BREAK	1.2w	3/14/94 8:00am
20	Abstract	2.2w	3/21/94 8:00am
21	Test Prototype	6.2w	3/21/94 8:00am
22	Final Report (Breakdown)	1w	3/29/94 8:00am
23	Document Project	9.8w	3/14/94 8:00am
24	Design Fair	1w	5/2/94 8:00am
25	NASA Conference	5d	6/13/94 8:00am



Project:
Date: 5/19/94

Progress

APPENDIX B

Maple Equations

Prototype of Helical Anchor on the Lunar Surface

Shallow Anchor Condition
Diameter of Single Helix = 2.5 inches
Depth of Anchor = 12.0 inches

Qp is the bearing resistance (lb).

```
> Qp :=(pi/4)*F*g*D^2*H;
```

$$Qp := \frac{1}{4}\pi F g D^2 H$$

g is the unit weight of the soil (lb/ft^3)

```
> g :=15.606864;
```

$$g := 15.606864$$

D is the diameter of helix (ft)

```
> D :=0.208333;
```

$$D := .208333$$

H is the depth of the anchor (ft)

```
> H :=1.0;
```

$$H := 1.0$$

```
> pi :=3.14159;
```

$$\pi := 3.14159$$

F is the breakout factor

```
> F :=80.06;
```

$$F := 80.06$$

phi is the soil friction angle (degrees)

```
> phi :=45;
```

$$\phi := 45$$

```
> tan(45) :=1;
```

$$\tan(45) := 1$$

Qf is the cylindrical frictional resistance (lb)

```
> Qf :=0;
```

$$Qf := 0$$

Qu is the ultimate uplift capacity (lbs)

```
> Qu :=Qp +Qf;
```

$$Qu := 42.59286775$$

```
>
```

Prototype of Helical Anchor on the Earth's Surface

Shallow Anchor Condition
Diameter of Single Helix = 2.5 inches
Depth of Anchor = 12.0 inches

Qp is the bearing resistance (lb).

```
> Qp :=(pi/4)*F*g*D^2*H;
```

$$Qp := \frac{1}{4} \pi F g D^2 H$$

g is the unit weight of the soil (lb/ft^3)

```
> g :=93.642;
```

$$g := 93.642$$

D is the diameter of helix (ft)

```
> D :=0.208333;
```

$$D := .208333$$

H is the depth of the anchor (ft)

```
> H :=1.0;
```

$$H := 1.0$$

```
> pi :=3.14159;
```

$$\pi := 3.14159$$

F is the breakout factor

```
> F :=80.06;
```

$$F := 80.06$$

phi is the soil friction angle (degrees)

```
> phi :=45;
```

$$\phi := 45$$

```
> tan(45) :=1;
```

$$\tan(45) := 1$$

Qf is the cylindrical frictional resistance (lb)

```
> Qf :=0;
```

$$Qf := 0$$

Qu is the ultimate uplift capacity (lbs)

```
> Qu :=Qp +Qf;
```

$$Qu := 255.5594333$$

```
>
```

```
>
>      for D from 0.1 by .015 to .4
>           do
>
> phi :=45;
> pi :=3.14159;
> g :=(1500)*(1/6)*(1/1000)*(0.036127/1)*(1728/1);
> H :=.75;
> G :=H/D;
> K :=3.2;
> F :=4*G^2*K*(tan (phi))*((cos (phi/2))^2)*(0.5/G+0.333*tan
> (phi/2))+4+5.33*G^2*(tan(phi/2))^2+8*G*tan(phi/2);

> Qp :=(pi/4)*F*g*D^2*H;

> Qf :=0;
> Qu :=Qp;
> tan(45) :=1;
> cos(45/2) :=0.9239;
> tan(45/2) :=0.4142;
>
>
>         od;
                              phi := 45

                           pi := 3.14159

                         g := 15.60686400

                              H := .75

                         G := 7.500000000

                              K := 3.2

                         F := 206.0296435
```

```
>
>     for H from 0.4167 by .029165 to 1
>         do
>
> phi :=45;
> pi :=3.14159;
> g :=(1500)*(1/6)*(1/1000)*(0.036127/1)*(1728/1);
>
> D :=.3;
> G :=H/D;
> K :=3.2;
> F :=4*G^2*K*(tan (phi))*((cos (phi/2))^2)*(0.5/G+0.333*tan
> (phi/2))+4+5.33*G^2*(tan(phi/2))^2+8*G*tan(phi/2);

> Qp :=(pi/4)*F*g*D^2*H;

> Qf :=0;
> Qu :=Qp;
> tan(45) :=1;
> cos(45/2) :=0.9239;
> tan(45/2) :=0.4142;
>
>
>       od;
                                phi := 45

                              pi := 3.14159

                            g := 15.60686400

                                D := .3

                            G := 1.389000000

                                K := 3.2
```

APPENDIX C

Test Data With Specifications & Tolerances
(Also includes sample data sheets)

AUGER TESTING RESULTS

LOCATION: Gauss Engineering Lab; University of Idaho
TEMPERATURE: 27°C
PRESSURE: Ambient

PHYSICAL AUGER DESCRIPTIONS:

1) Auger #1: Seven revolutions, hollow tube, 4.5 in. hex. rod welded to top.

2) Auger #2: Two revolutions at bottom, solid tube, 5 in. hex. rod welded to top, blunt, angled tip.

3) Auger #3: Four revolutions, tapered bottom, solid tube, 4.5 in. hex. rod welded to top, blunt tip welded on bottom.

4) Auger #4: One revolution at bottom, solid tube, hex. rod welded to top.

5) Auger #5: Two revolutions at bottom, solid tube, hex. rod welded to top, blunt tiop welded on bottom.

6) Auger #6: One revolution at bottom, solid tube, hex. rod welded to top.

7) Auger #7: One revolution at bottom, solid tube, hex. rod welded to top.

MATERIALS:

1) Vernier Caliper: ±0.001 in.
2) Tape Measure: Starrett/SKP16/63832/ 16'3/4" wide blade
3) Rope
4) Pulley/Crane
5) Testing Box: 4x4x3 ft.
6) Decomposed Granite: Moist, easily packed.
7) Spring scale #1: Landers Improved/ 125 lb. limit
8) Spring scale #2: Hanson/8916/160 lb. limit
9) Torque Wrench
10) Electronic Scale: Fortec
11) Steel Ruler/Plastic Ruler: ±0.01 in.
12) Block of Wood: 16 in. long, 1'12 oz.

PACKING METHOD:

1) <u>"loosely-packed":</u> Reworked and mixed soil with long stocks of steel, occasionally added water, leveled soil with block of wood, then continuously stomped on by team member.

2) <u>"extremely-tamped":</u> Reworked, mixed soil, and tamped excessively with long stocks of steel, occasionally added water, leveled soil with block of wood, then continuously stomped on by team member.

STANDARD MEASUREMENTS OF AUGERS

Auger #	Mass (oz)	Total Length (in)	Total Diameter (in)	Outside Rod Diam. (in)	Inside Rod Diam. (in)	Blade Pitch (in)	Blade Taper (deg)	Blade Thickness (in)	Total Revol. (#)	Tip Length (in)
1	2'5.4	29	3.35	0.62	0.5	3.2	20	0.05	7	0
2	4'9.75	31	3.75	0.7	-	2.1	10	0.14	2*	2.1
3	2'9.4	29	3.35	0.62	0.5	3.2	20	0.05	4	2.25
4	14.2	15	3	0.4	-	1.1	15	0.05	1	1.1
5	13.2	14.2	2.7	0.37	-	0.7	5	0.06	2**	1.75
6	11	13.8	2.82	0.37	-	0.7	12	0.06	1	1.25
7	7.5	14	1.75	0.31	-	0.5	4	0.06	1	0.85

* There is a distance of 6.20 in. between the two revolutions.

** There is a distance of 4.62 in. between the two revolutions.

AUGER #1 TESTING DATA

SOIL: "LOOSELY-PACKED"
WEIGHT ADDED: 3 LBS.

Trial #	# Rev. to Grab	Total # Rev. to Emplace	Soil Height (in)	Soil Diameter (in)	Auger Depth (in)
1	20.5	24	1.75	8	16.62
2	28	30	1.75	8	11.5
3	21	25	1.5	7	18

NOTE: A 3 lb. weight was dropped 4.5 in. four times to press down in soil before revolutions were performed.

Inches Moved at Pull Out Forces of 90°								
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.
1	0	0	0.06	0	0	0	0.06	0
2	0	0	0	0.06	0.06	0.25*	-	-
3	0	0	0	0.06	0	0	0	0.5**

* Limiting force applied. Can watch come out, and slips 2 lbs. in 15 sec.
** After 1 min., slipped and lost 3 lbs. After 2 additional min., lost 0 lbs.

AUGER #2 TESTING DATA

SOIL: "LOOSELY-PACKED"
WEIGHT ADDED: 1'12 oz.

Trial #	# Rev. to Grab	Total # Rev. to Emplace	Soil Height (in)	Soil Diameter (in)	Auger Depth (in)
1	17.5	21.5	1	8	11.63
2	13.5	18	1	8.25	11.25
3	25	34	1.5	8	11.5
4	16.5	25	1.5	8.75	18

Inches Moved at Pull Out Forces of 0°					
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	125 lbs.
1	1	1	1.5	3.0*	-
2	1	1	1	3.0**	-
3	0.5	1	0.5	1.5	2.5***
4	0.12	0.12	1	1	3.25****

* Anchor gave and had to re-emplace.

** At 113 lbs., anchor pulled out. The soil cracked and disrupted soil measured 18 in. wide and 24 in. long.

*** Soil cracked a length of 1 ft. from the hole, opposite the direction of force.

**** If 125 lb. force would have been held for a period of time, the anchor would have pulled out. The soil displaced 13 in. long and 9in. wide.

Inches Moved at Pull Out Force of 90°						
Trial #	65 lbs.	75 lbs.	80 lbs.	100 lbs.	112 lbs.	125 lbs.
5	0.04	0.04	0.04	Max.*	-**	-***

* Started to slip. Lost 1 lb.

** Started to come out.

*** Slipped and lost 2-3 lbs. in 1 min., another 0.5 lbs. in 1 min., and 1.5 lbs. in 5 min. more.

MAX. EMPLACEMENT TORQUE: **10 ft-lbs.**

AUGER #2 TESTING DATA

SOIL: "EXTREMELY TAMPED"
WEIGHT ADDED: 13 LBS.

Trial #	# Rev. to Grab	Total # Rev. to Emplace	Soil Height (in.)	Soil Diameter (in.)	Auger Depth (in.)
1	43	47	1.8	9	10.25
2	25	29	1.5	8.5	15.5

Inches Moved at Pull Out Forces of 90°								
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.
1	0	0	0	0	0	0	0.06	0
2	0	0	0	0	0	0	0.06	0

Inches Moved at Pull Out Forces of 0°								
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.
1	0.06	0.75	0.56	1.88	1.56	2	-	-
2	0.12	0.31	0.44	0.87	1.25	1.75	1.69	1.94

MAX. EMPLACEMENT TORQUE: 20 ft-lbs.

AUGER #1 VS. AUGER #3 TESTING RESULTS

SOIL: "LOOSELY-PACKED"

WEIGHT ADDED:
TRIAL 1 = 16 LBS.
TRIAL 2 = 8 LBS.
TRIAL 3 = 5 LBS.

Comparison of Emplacement With Different Weights Added		
Trial #	Auger #1 Rev. to Grab	Auger #3 Rev. to Grab
1	4.5	8.5
1	6.5	2.75
1	4.75	3.2
1	3.8	2.5
2	20	15
2	14.75	10
2	15.5	17
3	26	23
3	31.5	21.5
3	20	15

AUGER #3 TESTING DATA

SOIL: "LOOSELY-PACKED" VS.
"EXTREMELY TAMPED"
WEIGHT ADDED:
TRIALS #1 & #2 = 8 LBS.
TRIAL #3 = 16 LBS.

"Loosely-packed" Soil					
Trial #	# Rev. to Grab	Total # Rev. to Emplace	Soil Height (in)	Soil Diameter (in)	Auger Depth (in)
1	-	30	1.5	8	18.25
"Extremely-tamped" Soil					
2	35	45	1.5	8	14.5
3	27.5	30	2.5	8.5	4.5

Inches Moved at Pull Out Forces of 45°								
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.
1	0	0	0	0.06	0	0.06	0	1.4
2*	0	0	0	0	0	0	0	0.06
3	0	-**	-	-	-	-	-	-

* Torque to get out of soil was 1 ft. lb.

** Pulled out at 16 lbs.

Inches Moved at Pull Out Forces of 90°		
Trial #	16 lbs.	32 lbs.
3	Max.	-

AUGER #4 TESTING DATA

SOIL CONDITIONS: "EXTREMELY TAMPED"
WEIGHT ADDED: 10 LBS.

Trial #	# Rev. to Grab	Total # Rev. to Emplace	Soil Height (in.)	Soil Diameter (in.)	Auger Depth (in.)
1	36.5	43	1	7	9.3
2	20.5	24.5	1.5	6	9.5
3	31.5	34.5	2	5.5	7
4	23.5	27.5	1.7	5.5	7.2
5	15.5	19	1.5	6	8
6	35.25	41.5	1.2	5.5	7.2

Inches Moved at Pull Out Forces of 90°											
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.	140 lbs.	150 lbs.	160 lbs.
1	0	0	0	0	0	0	0	0.06	0	0	0
2	0	0	0	0	0.06	0	0	0	0.06	0	0
3	0	0.06	0.06*	-	-	-	-	-	-	-	-
4	0.03	0	0.03**	-	-	-	-	-	-	-	-
5	0	0	0	0.44#	-	-	-	-	-	-	-

* Max. force was 70 lbs.
** Max. force was 50 lbs.
\# Max. force was 80 lbs.

Inches Moved at Pull Out Force at 0°								
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.
6	0.27	0.3	0.6	0.9	1.3	1.72	2.3	-

MAX. EMPLACEMENT TORQUE: 10 ft-lbs.

AUGER #5 TESTING DATA

SOIL CONDITIONS: "EXTREMELY TAMPED"

WEIGHT ADDED:

TRIAL #1 = 10 LBS.

TRIALS #2 & #3 = 15 LBS.

Trial #	# Rev. to Grab	Total # Rev. to Emplace	Soil Height (in.)	Soil Diameter (in.)	Auger Depth (in.)
1	44	56	-	-	11.25
2	-	-	-	-	7.88
3	-	-	-	-	5.88
4	-	65	1.75	4	6.88
5	36	50	1	3	8.63

Inches Moved at Pull Out Forces of 90°											
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.	130 lbs.	140 lbs.	160 lbs.
1	0	0	0	0	0	0	0	0	0	0	0.12
2	0	0	0	0	0	0	0	0	0	0	0.12
3	0	0	0	Max.	-	-	-	-	-	-	-
4	0	0	0	0	0	0	0	0	0	0	0
5	0.12	0.12	0	0	Max.	-	-	-	-	-	-

MAX. EMPLACEMENT TORQUE: 7 ft-lbs.

AUGER #6 TESTING DATA

SOIL CONDITIONS: "EXTREMELY TAMPED"
WEIGHT ADDED: 10 LBS.

Trial #	# Rev. to Grab	Total # Rev. to Emplace	Soil Height (in.)	Soil Diameter (in.)	Auger Depth (in.)
1	56.75	62	1.5	5.5	6.12
2	36	47	1.75	5.5	6.87
3	39	46	1.75	5	6.62
4	50.5	63	2	6	7.37
5	49.5	63.75	1.5	5	7.12

Inches Moved at Pull Out Forces of 90°											
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.	130 lbs.	140 lbs.	160 lbs.
1	0	0.06	0.06	Max.	-	-	-	-	-	-	-
2	0	0	0.03	0.03	0	0.03	0.03	0.06	Max.	-	-
3	0	0	0	0	0	0	0.06	0.06	0	0.06	Max.*

* Actual pull-out was at 155 lbs.

Inches Moved at Pull Out Forces of 0°								
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	114 lbs.	125 lbs.
4	0.56	1.17	1.82	2.8	0	0	3.62*	-
5	0.4	0.8	1.32	2	2.44	2.9	0	Max.

* The last measurement is the total movement for trials 4 & 5.

MAX. EMPLACEMENT TORQUE: 8 ft-lbs.

AUGER #7 TESTING DATA

SOIL: "EXTREMELY TAMPED"

WEIGHT ADDED: MUCH GREATER THAN 10 LBS.

Trial #	# Rev. to Grab	Total # Rev. to Emplace	Soil Height (in.)	Soil Diameter (in.)	Auger Depth (in.)
1	-	55	-	-	11.05
2	-	-	-	-	8.8
3	-	-	-	-	6.55
4	-	75	1.25	4	6.05
5	105	120	1	4.5	6

Inches Moved at Pull Out Forces of 90°											
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.	100 lbs.	112 lbs.	125 lbs.	130 lbs.	140 lbs.	160 lbs.
1	0	0	0.12	0	0	0.12	0	0	0	0	0
2	0	0	0	0	0.12	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	Max.	-
4	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0.03	0	0	0

Inches Moved at Pull Out Force of 0°					
Trial #	16 lbs.	32 lbs.	48 lbs.	72 lbs.	88 lbs.
5	0.35	0.68	1.1	2.25	-

Note: The inches at 72 lbs. is the total movement.

MAX. EMPLACEMENT TORQUE: 7 ft-lbs.

Sample Data Sheet

AUGER TESTING

DATE:

NAMES:

SOIL CONDITIONS:

AUGER #:

WEIGHT ADDED:

---

1) # REV. TO GRAB:

TORQUE MEASUREMENTS:

<u>ft-lbs</u> <u>at # of rev.</u>

2) TOTAL # OF REV. TO EMPLACE:
3) SOIL HEIGHT:
4) SOIL DIAMETER:
5) AUGER HEIGHT FROM SOIL:

6) DEGREE OF PULL-OUT FORCES:

7) AT 16lbs. MOVED _______ in.
AT 32lbs. MOVED _______ in.
AT 48lbs. MOVED _______ in.
AT 72lbs. MOVED _______ in.
AT 88lbs. MOVED _______ in.
AT 100lbs. MOVED _______ in.
AT 112lbs. MOVED _______ in.
AT 125lbs. MOVED _______ in.

MAX. AT PULL-OUT _______ lbs.

Sample Data Sheet

TESTING OF PROTOTYPE #1

DATE: **TEST #:**

NAMES:

SOIL CONDITIONS: Extremely Tamped

WEIGHT ADDED: 10 lbs.

---

1) # REV. TO GRAB:

TORQUE MEASUREMENTS:

ft-lbs at # of rev.

2) TOTAL # OF REV. TO EMPLACE:

3) SOIL HEIGHT:

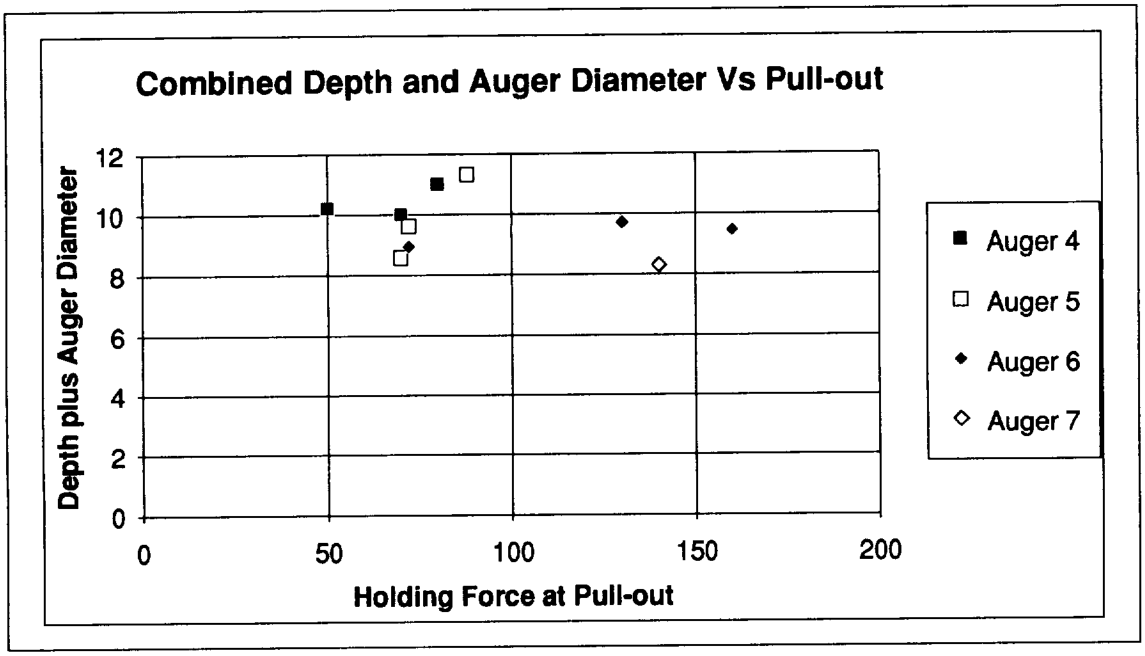
4) SOIL DIAMETER:

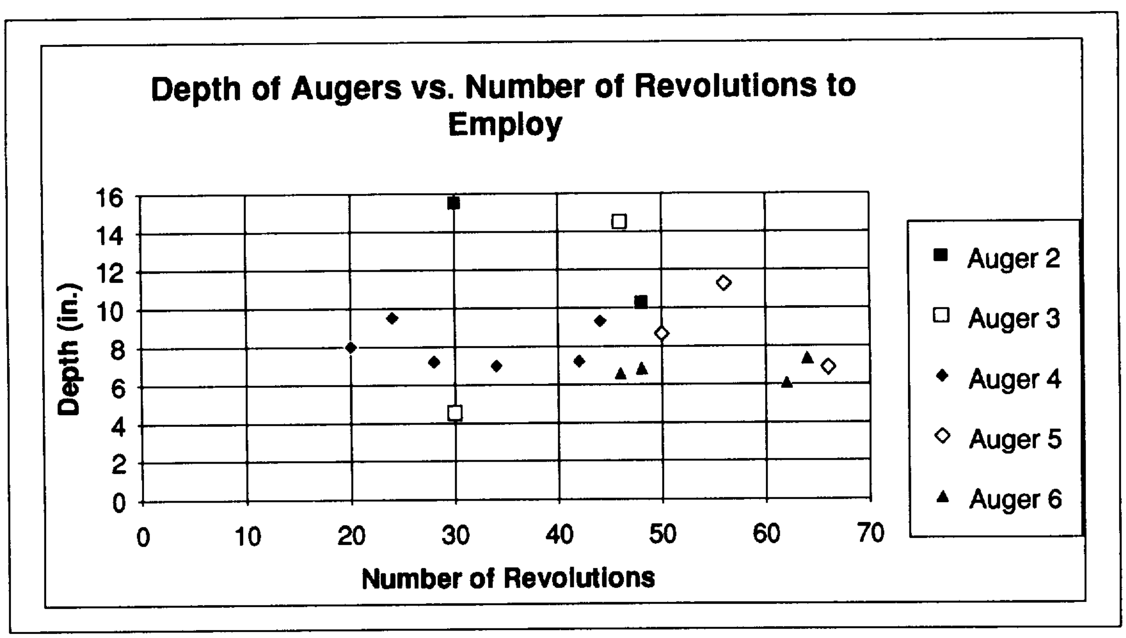
5) AUGER HEIGHT FROM SOIL:

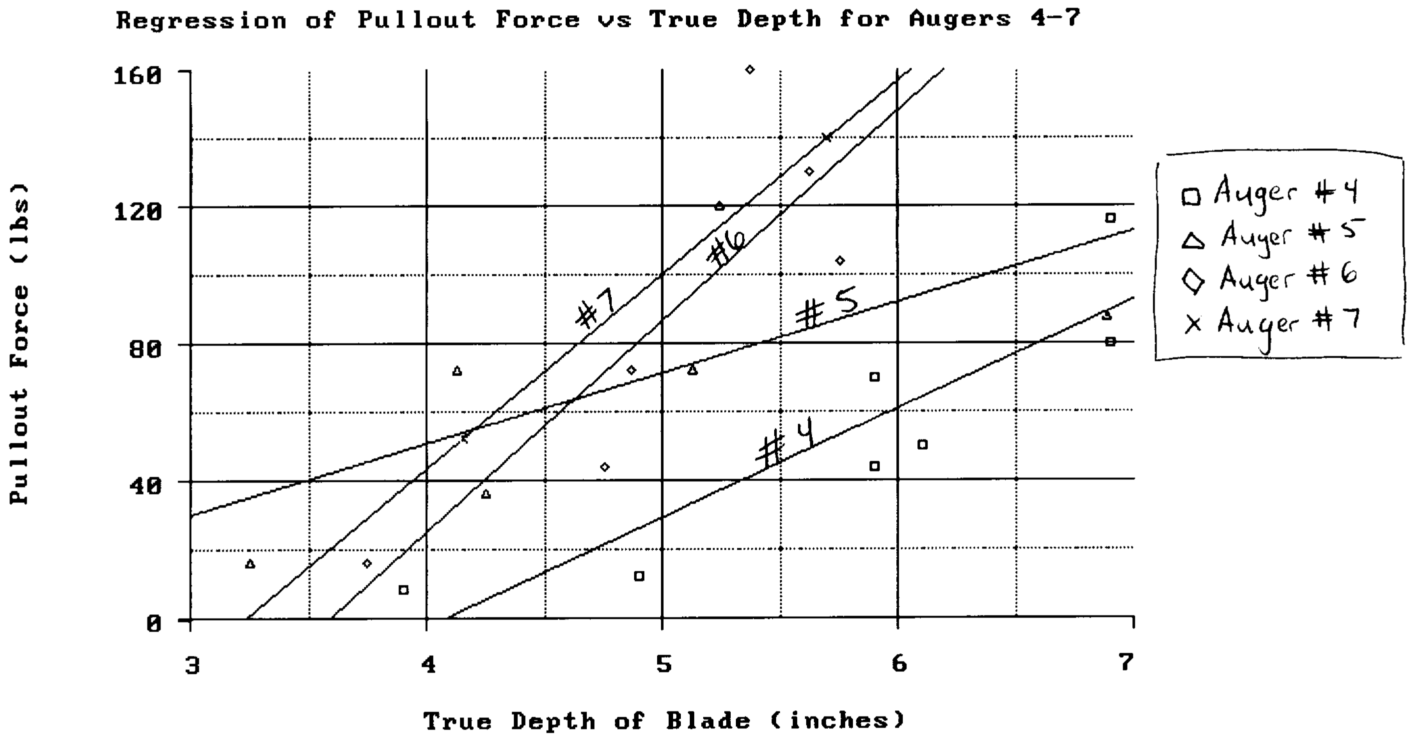
6) DEGREE OF PULL-OUT FORCES (circle one): 90 45 0

7) MAX. PULL-OUT _______ lbs.

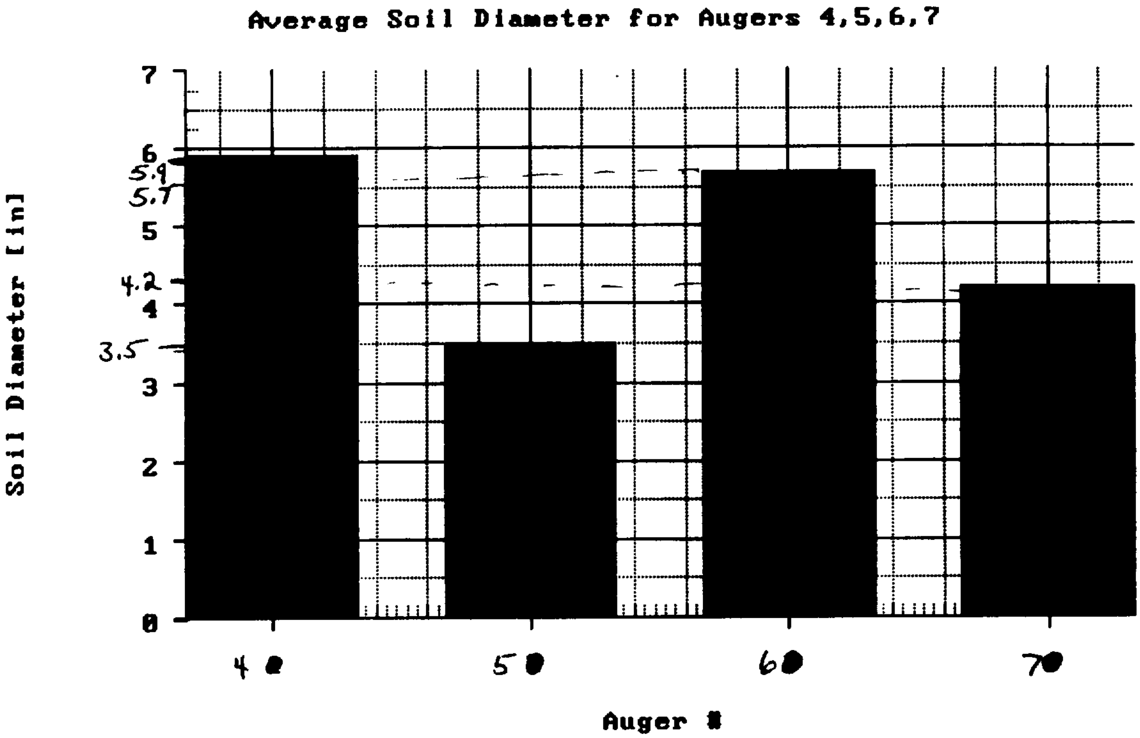
Auger Testing Results

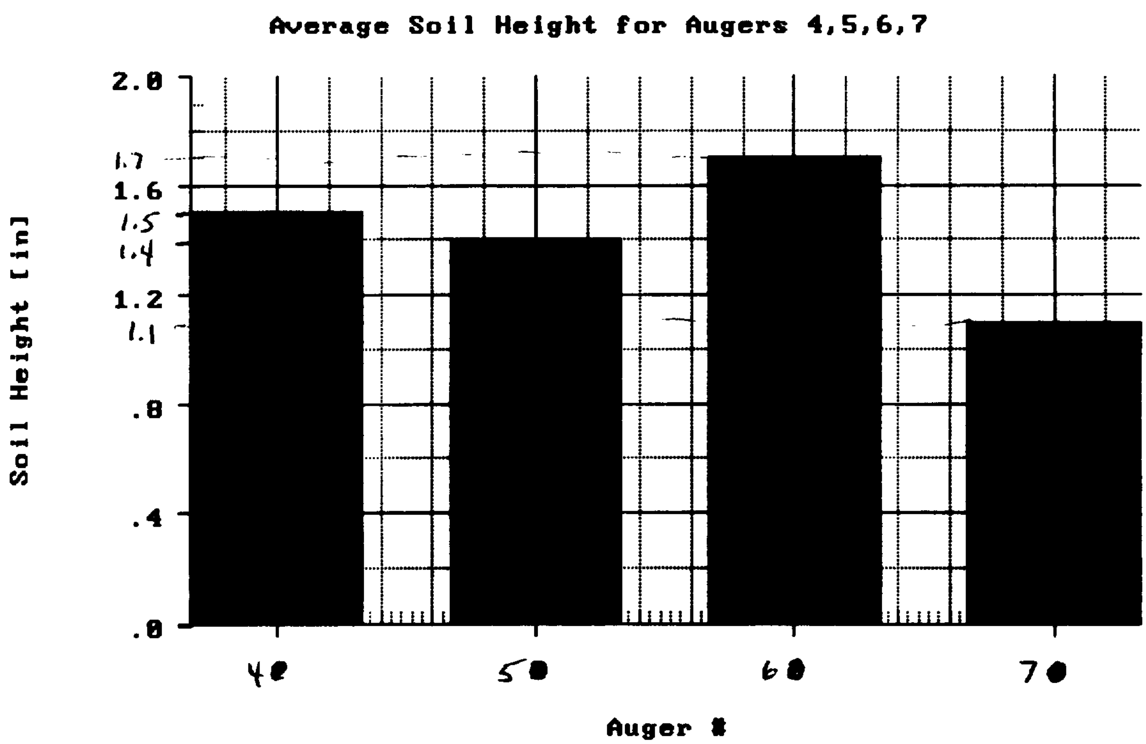






Note: The true depth of the blade was calculated as the depth of the auger minus the tip length. I felt this would be a better way of expressing the depth of the auger.





9

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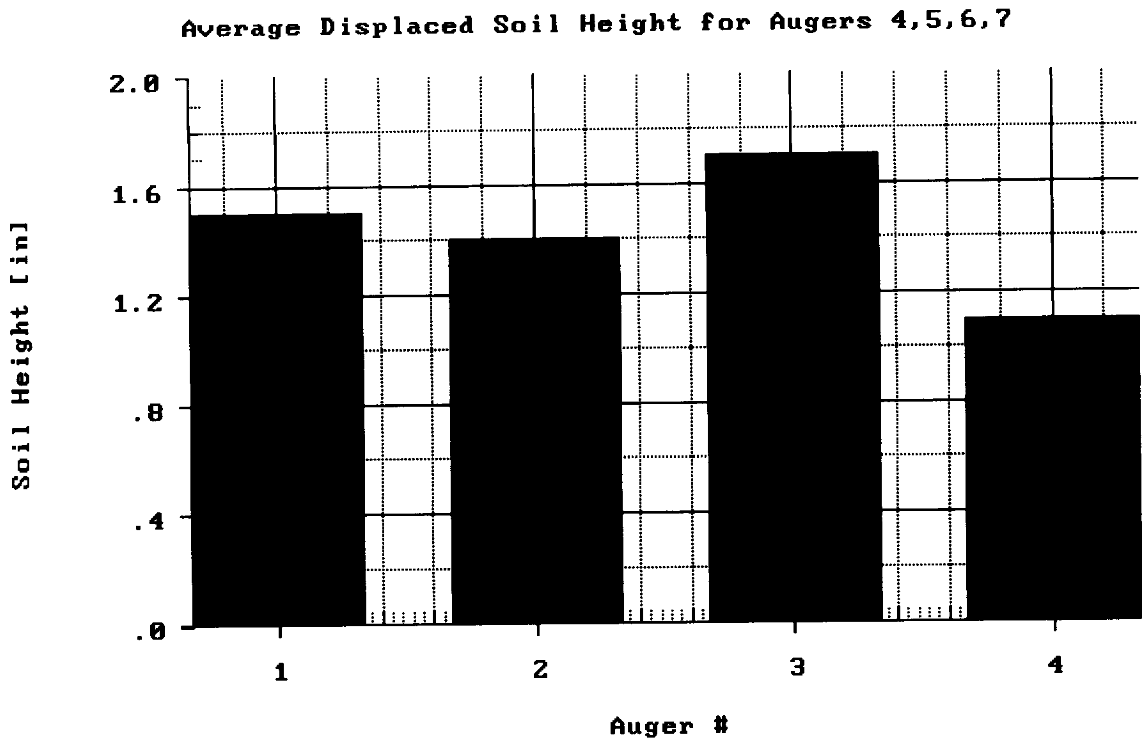
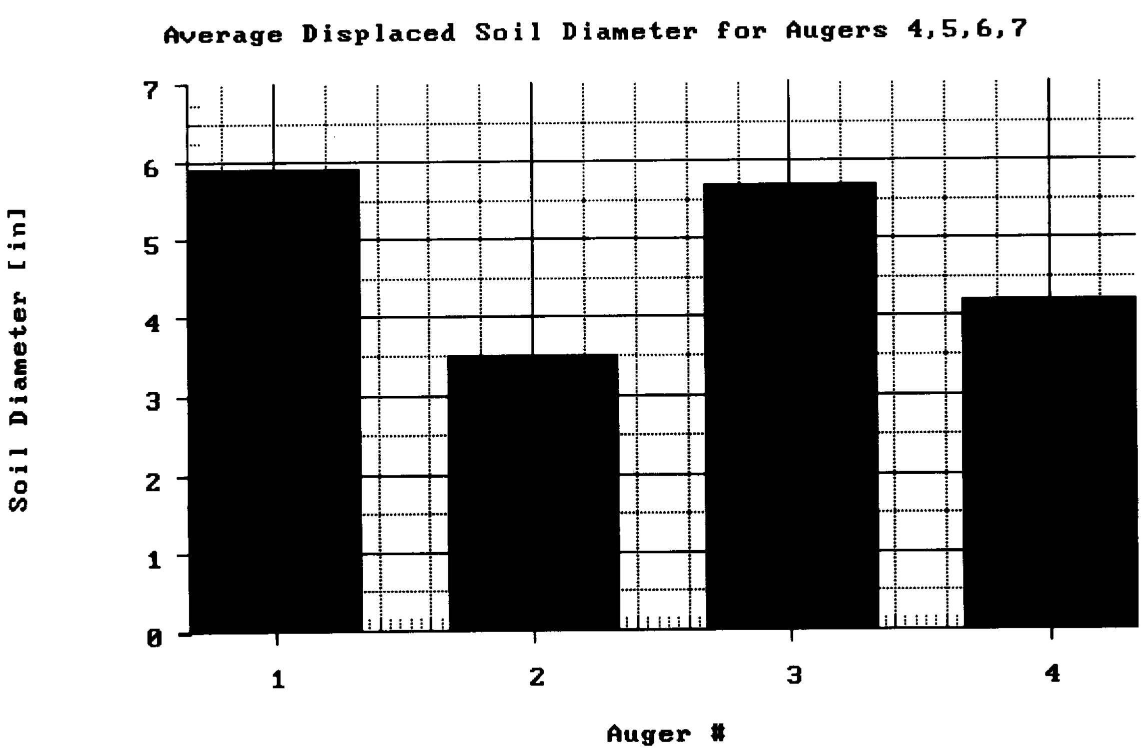
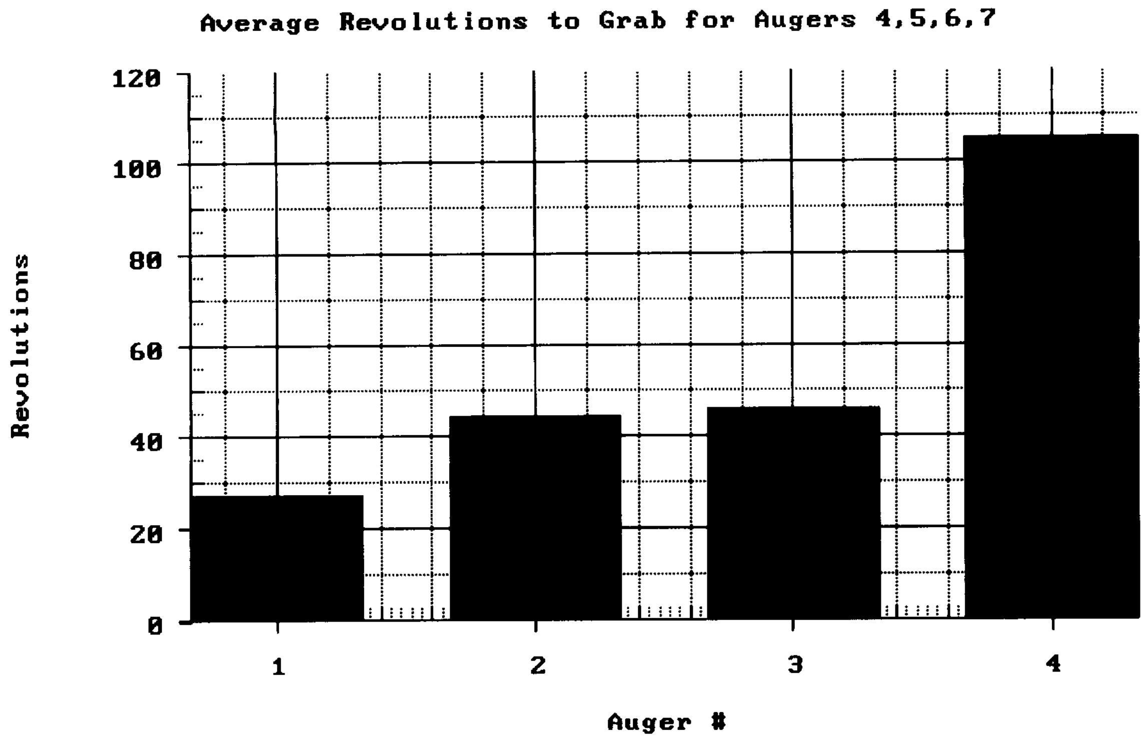
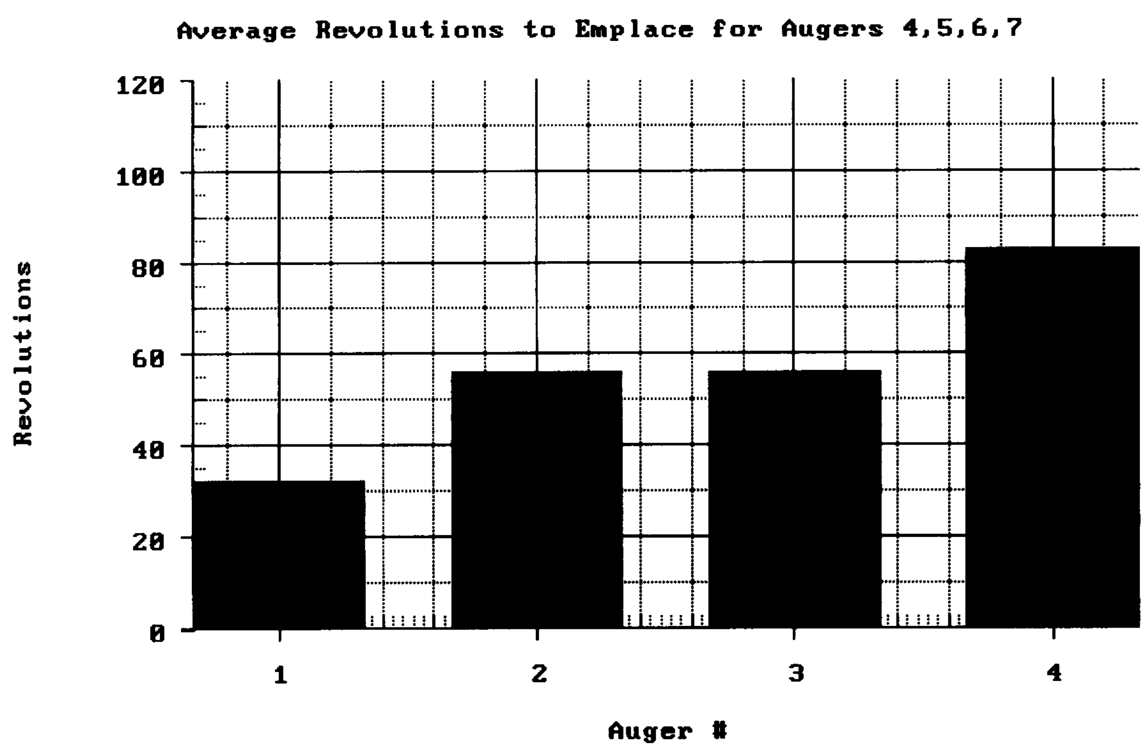
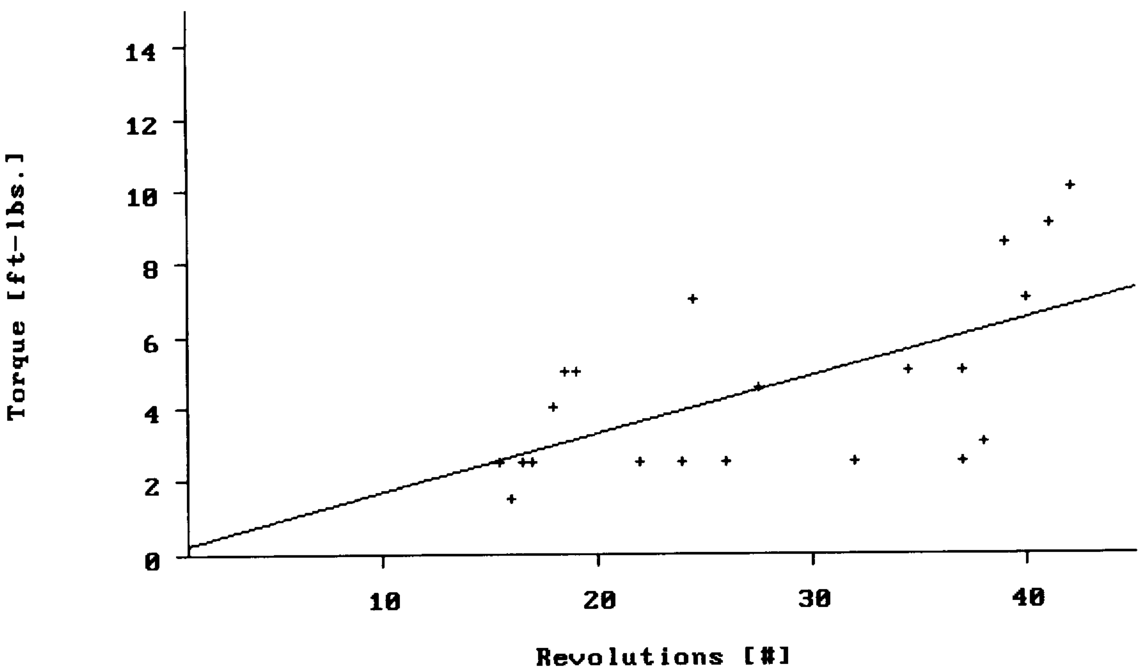

Average Displaced Soil Height for Augers 4,5,6,7
2.0
1.6
1.2
.8
.4
.0
Soil Height [in]
1
2
3
4
Auger #


Average Displaced Soil Diameter for Augers 4,5,6,7
7
6
5
4
3
2
1
0
Soil Diameter [in]
1
2
3
4
Auger #

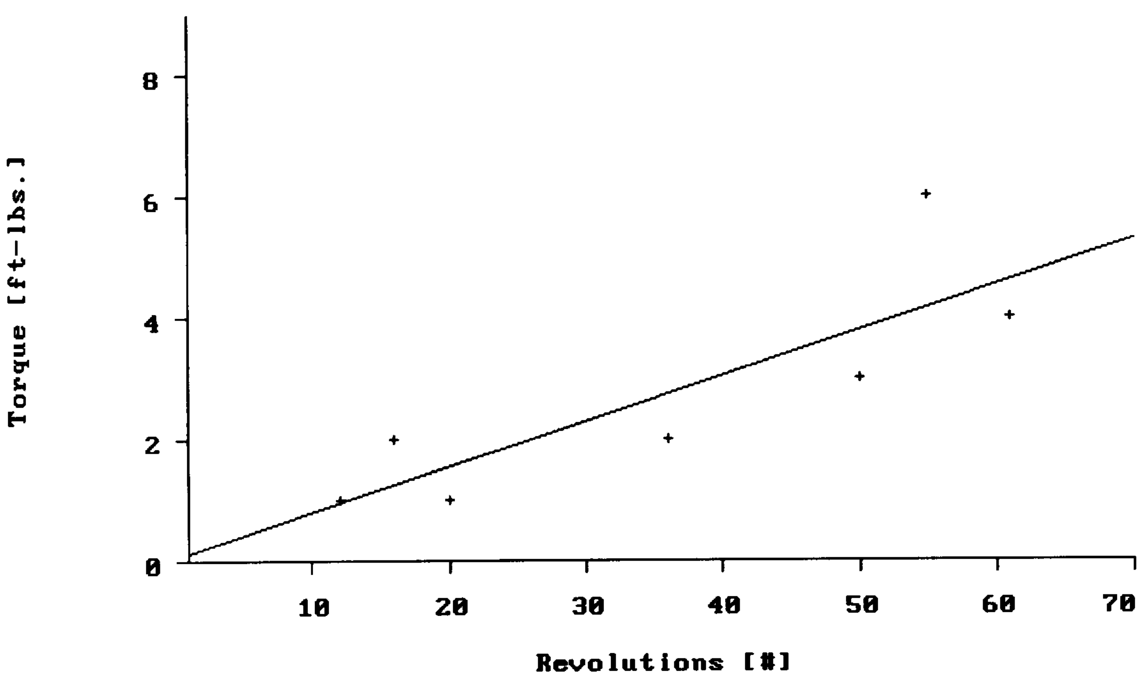

Average Revolutions to Grab for Augers 4,5,6,7
120
100
80
60
40
20
0
Revolutions
1
2
3
4
Auger #


Average Revolutions to Emplace for Augers 4,5,6,7
120
100
80
60
40
20
0
Revolutions
1
2
3
4
Auger #

Auger #4: Torque vs. Revolutions at 10 lbs.



Auger #5: Torque vs. Revolutions at 15 lbs.



PROTOTYPE RESULTS

Table contains depth with corresponding holding force

Depth and Revolutions	30.48	revs.	25.4	revs.	20.32	revs.	15.24	revs.
First	1880	25	1750	23	1600	20	1000	18
Second	2150	29	1900	25	1800	22	1150	20
Third	2430	35	1980	25	2140	30	1200	21

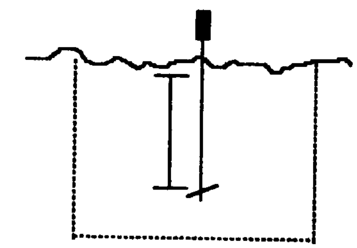
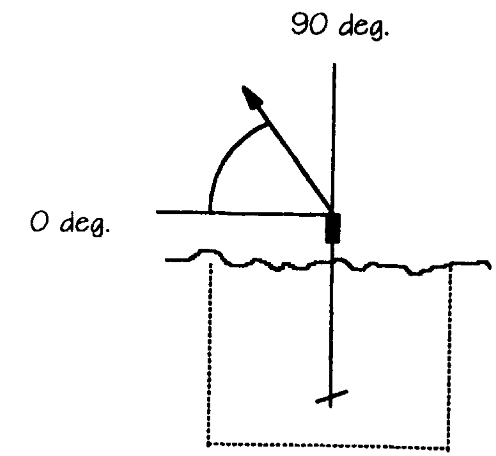


Table contains angle with corresponding holding force

Angle (degrees)	90	80	70	60	50	40	30	20
First	2350	2655	2400	2830	2515	2060	2340	2715
Second	2400	2810	2485	2840	2600	2170	2430	2810
Third	2775	2840	2600	2895	2760	2400	2540	2825



During all tests the Torque measurements were approximately 6 to 13 Nm.

Prototype

$\mathbf{L} := .3302 \quad \mathbf{F} := 2200 \quad \mathbf{D} := .0127$

$\mathbf{UTS} := 601000000$

$\mathbf{Yeild} := 241000000$

Bending Stress **Shear Stress**

$$\mathbf{Sigma1} := \frac{\mathbf{F}\cdot\mathbf{L}\cdot\left(\frac{\mathbf{D}}{2}\right)}{\left(\frac{\pi\cdot\mathbf{D}^4}{64}\right)} \qquad \mathbf{Sigma2} := \frac{\mathbf{F}}{\left(\frac{\pi\cdot\mathbf{D}^2}{4}\right)}$$

$$\mathbf{Sigma1} = 3.612\cdot10^{9} \qquad \mathbf{Sigma2} = 1.737\cdot10^{7}$$

Optimum

Bending Stress **Shear Stress**

$$\mathbf{d1} := \left(\frac{2\cdot\mathbf{Yeild}\cdot\pi}{64\cdot\mathbf{F}\cdot\mathbf{L}}\right)^{-\frac{1}{3}} \qquad \mathbf{d2} := \left(\frac{\mathbf{Yeild}\cdot\pi}{\mathbf{F}\cdot4}\right)^{-\frac{1}{2}}$$

$$\mathbf{d1} = 0.031 \qquad \mathbf{d2} = 0.003$$

APPENDIX D

Emplacement Energy Analysis

ME 426 NASA Anchor Emplacement Team — Sunday, February 27, 1994

Spreadsheet For Calculating Energy

Method: Integrate the torque over the range of revolutions to come up with the energy to place the auger

Note: This method is consevative because I assumed that the torque acted all the way from the last torque measurement untill the new measure

Auger # 2

6.28319 (2 Pi)	Torque (ft-lb)	# of Revs	Energy (in-lb)		
6.28319	15	62	70120		
6.28319	45	75	44108	Av. Torque:	20 ft lbs
6.28319			114228 **Total Energy (in-lbs)**		
6.28319					
6.28319	Torque (ft-lb)	# of Revs	Energy (in-lb)		
6.28319	5	34	12818		
6.28319	7.5	40	3393		
6.28319	10	41	754		
6.28319	10	43	1508		
6.28319	11.5	45	1734		
6.28319	15	45.75	848		
6.28319	20	47	1885	Av. Torque:	6 ft lbs
6.28319			22940 **Total Energy (in-lbs)**		
6.28319					
6.28319	Torque (ft-lb)	# of Revs	Energy (in-lb)		
6.28319	5	23	8671		
6.28319	10	25	1508		
6.28319	12.5	26	942		
6.28319	15	27	1131		
6.28319	20	29	3016	Av. Torque:	7 ft lbs
6.28319			15268 **Total Energy (in-lbs)**		

Auger # 4

Torque (ft-lb)	# of Revs	Energy (in-lb)		
1.5	16	1810		
2.5	37	3958		
3	38	226		
8.5	39	641		
10	43	3016	Av. Torque:	3 ft lbs
		9651 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
Pull out	2.5	32	6032		
70 lbs	5	34.5	942	Av. Torque:	3 ft lbs
			6974 **Total Energy (in-lbs)**		

Torque (ft-lb)	# of Revs	Energy (in-lb)		
2.5	22	4147		
7	24.5	1319	Av. Torque:	3 ft lbs
		5466 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
Pull out	2.5	24	4524		
50 lbs	2.5	26	377		
	4.5	27.5	509	Av. Torque:	3 ft lbs
			5410 **Total Energy (in-lbs)**		

Torque (ft-lb)	# of Revs	Energy (in-lb)		
5	37	13949		
7	40	1583		
9	41	679	Av. Torque:	5 ft lbs
		16211 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
	2.5	15.5	2922		
Pull out	2.5	16.5	188		
90 lbs	2.5	17	94		
	4	18	302		
	5	18.5	188		
	5	19	188	Av. Torque:	3 ft lbs
			3883 **Total Energy (in-lbs)**		

Auger # 7

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
Pull out	1	10	754		
140 lbs	7	55	23750	Av. Torque:	6 ft lbs
			24504 **Total Energy (in-lbs)**		

Auger # 5

Torque (ft-lb)	# of Revs	Energy (in-lb)		
7	44	23223		
4	56	3619	Av. Torque:	6 ft lbs
		26842 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
	1	12	905		
	1	20	603		
	6	55	15834		
	4	61	1810	Av. Torque:	4 ft lbs
			19151 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
	2	16	2413		
Pull out	2	36	3016		
88 lbs	3	50	3167	Av. Torque:	2 ft lbs
			8595 **Total Energy (in-lbs)**		

Auger # 6

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
Pull out	5	58	21865		
72 lbs	5	59	377		
	5	61	754		
	5.5	62	415	Av. Torque:	5 ft lbs
			23411 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
	4.5	39	13232		
Pull out	5	42	1131		
135 lbs	6	44	905		
	7	46	1056		
	7	47	528	Av. Torque:	5 ft lbs
			16852 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
Pull out	5	41	15457		
155 lbs	6	43	905		
	6	45	905		
	7.5	46	565	Av. Torque:	5 ft lbs
			17832 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
	5	57	21488		
	6	60	1357		
	8	62	1206		
	8	63	603	Av. Torque:	5 ft lbs
			24655 **Total Energy (in-lbs)**		

	Torque (ft-lb)	# of Revs	Energy (in-lb)		
Pull out	6	56	25334		
125 lbs	6	58	905		
(0 degrees)	7	60	1056		
	8	63	1810	Av. Torque:	6 ft lbs
			29104 **Total Energy (in-lbs)**		

APPENDIX E

Emplacement Method
Flywheel and Gear Analysis

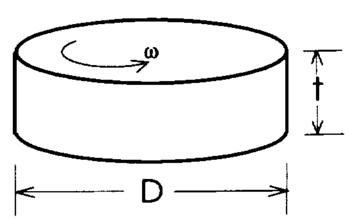
Flywheel Analysis

Concept:
This analysis is a work-energy approach. The goal is to use a flywheel to provide energy to employ the auger. This system takes advantage of the flywheel's ability to store energy which can be supplied at a low rate. After sufficient energy has been stored, the flywheel can be used to supply high power to employ the auger.

Definition of Variables:

E	Energy to Employ an Anchor (in-lb)
KE	Rotational Kinetic Energy of Flywheel (in-lb)
t	Thickness of Flywheel (in.)
D	Diameter of Flywheel (in.)
r	Radius of Flywheel (in.)
ρ	Density of Flywheel Material (lbm/ft^3)
m	Mass of Flywheel (slugs)
ω	Rotational Velocity of Flywheel (Rad/sec)
I	Mass Moment of Inertia for the Flywheel ($lb \cdot sec^2 \cdot in$)

Density of Flywheel Material = ρ



Rotational Kinetic Energy of Flywheel = $1/2\ I\ \omega^2$

Figure Flywheel Geometry

Assumptions:

1) The flywheel geometry will be assumed for this analysis (The actual geometry will most likely be a flywheel with spokes or a web, since it will have a better mass moment of inertia for the same weight).
2) Friction losses will be neglected for this analysis.
3) The energy to employ an auger will be assumed.
4) The flywheel material will be steel (ρ = 489 lbm/ft^3).

Governing Equations:

1) Mass Moment of Inertia for the flywheel (I) = $1/2\ mr^2$
2) Rotational Kinetic Energy of flywheel (KE) = $1/2\ I\ \omega^2$
3) Rotational Energy of flywheel (KE) = Energy to Employ the Anchor (E)

Analysis:

Find RPM of flywheel given these conditions:

Energy to employ an auger:	E = 25000 in-lb (This was typical in testing)
Flywheel Diameter	D = 12 in.
Flywheel Thickness	t = 3 in.

(These values are arbitrary, and will be different for specific systems)

Solution:

Volume of Flywheel $= \pi(D/2)^2(t) = \pi(6\text{in})^2(3\text{in}) = 339\ \text{in}^3$

Mass of Flywheel (m) = Volume(ρ)(slug/32.174 lbm)

$= 339\ \text{in}^3(489\ \text{lbm/ft}^3)(\text{ft}^3/12^3\ \text{in}^3)(\text{slug}/32.174\ \text{lbm})$

$= 2.98$ slug (units = lb s^2/ft)

Mass Moment of Inertia = $1/2\ mr^2$ = (I)

$= 1/2(2.98\ \text{lb s}^2/\text{ft})(6\text{in})^2(\text{ft}/12\ \text{in})$

$= 4.47\ \text{lb}\cdot\text{s}^2\cdot\text{in}$

Kinetic Energy (KE) $= 1/2\ (\ I\ )\ \omega^2$

$= 1/2(\ 4.47\ \text{lb s}^2\ \text{in})\ \omega^2$

Solve for Rotational Velocity (ω):

Kinetic Energy (KE) = Energy to Employ Anchor (E)

$1/2(\ 4.47\ \text{lb s}^2\ \text{in})\ \omega^2 = 25000$ in-lb

$\omega^2 = (25000\ \text{in-lb}) \div (1/2(\ 4.47\ \text{lb s}^2\ \text{in}))$

$\omega = [(25000\ \text{in-lb}) \div (1/2(\ 4.47\ \text{lb s}^2\ \text{in}))]^{1/2}$

$\omega = 106$ Radians /sec

(106 Radians /sec)(Rev/2πRad)(60sec/min) = 1012 RPM

Total angular velocity for this system = 1012 RPM

Gear Analysis

Concept:

This analysis is based on an angular velocity approach. The goal is to asses the feasibility of using a gear based system to employ an auger type anchor on the moon or Mars. This system takes advantage of the high efficiency that gears provide, and the extreme torque transformations only gears can provide. A gear system can in theory provide a high torque output for a low torque input.

Analysis:

From a strictly equation based analysis of an existing system. The following is derived.

Definitions of Variables:

- ω The angular velocity of subscripted component (rev/sec)
- N The number of teeth of subscripted component
- P The power inputted into the system (ft-lbf/sec)
- τ The torque at the subscripted component (ft-lbf)

Assumptions:

1) The tooth forces do not shear off the teeth.
2) Fiction losses are negligible.

Governing Equations:

$$\frac{\omega_2 - \omega_{arm}}{\omega_1 - \omega_{arm}} = \frac{-N_2}{N_1} \quad \textbf{(eqn. 1)}$$

$$P = \tau\omega \quad \textbf{(eqn. 2)}$$

Analysis:

Solve the system of equations for a existing gearing system. Leaving the variables open for change.

Solution:

Final Equation:

$$\omega_{out} = \omega_{in}(\frac{N_{in}}{N_C + N_{in}})(\frac{-N_D N_C}{N_E N_B} + 1)(\frac{N_F}{N_H + N_F})(\frac{-N_I N_H}{N_J N_G} + 1) \quad \text{(eqn. 3)}$$

by equations 2 equation 3 becomes:

$$\tau_{out} = \tau_{in}(\frac{N_{in}}{N_C + N_{in}})(\frac{-N_D N_C}{N_E N_B} + 1)(\frac{N_F}{N_H + N_F})(\frac{-N_I N_H}{N_J N_G} + 1) \quad \text{(eqn. 4)}$$

Solving using values from a real world application:

$\tau_{out} = 45(ft - lbf)$ with $\tau_{in} = .005985(ft - lbf)$

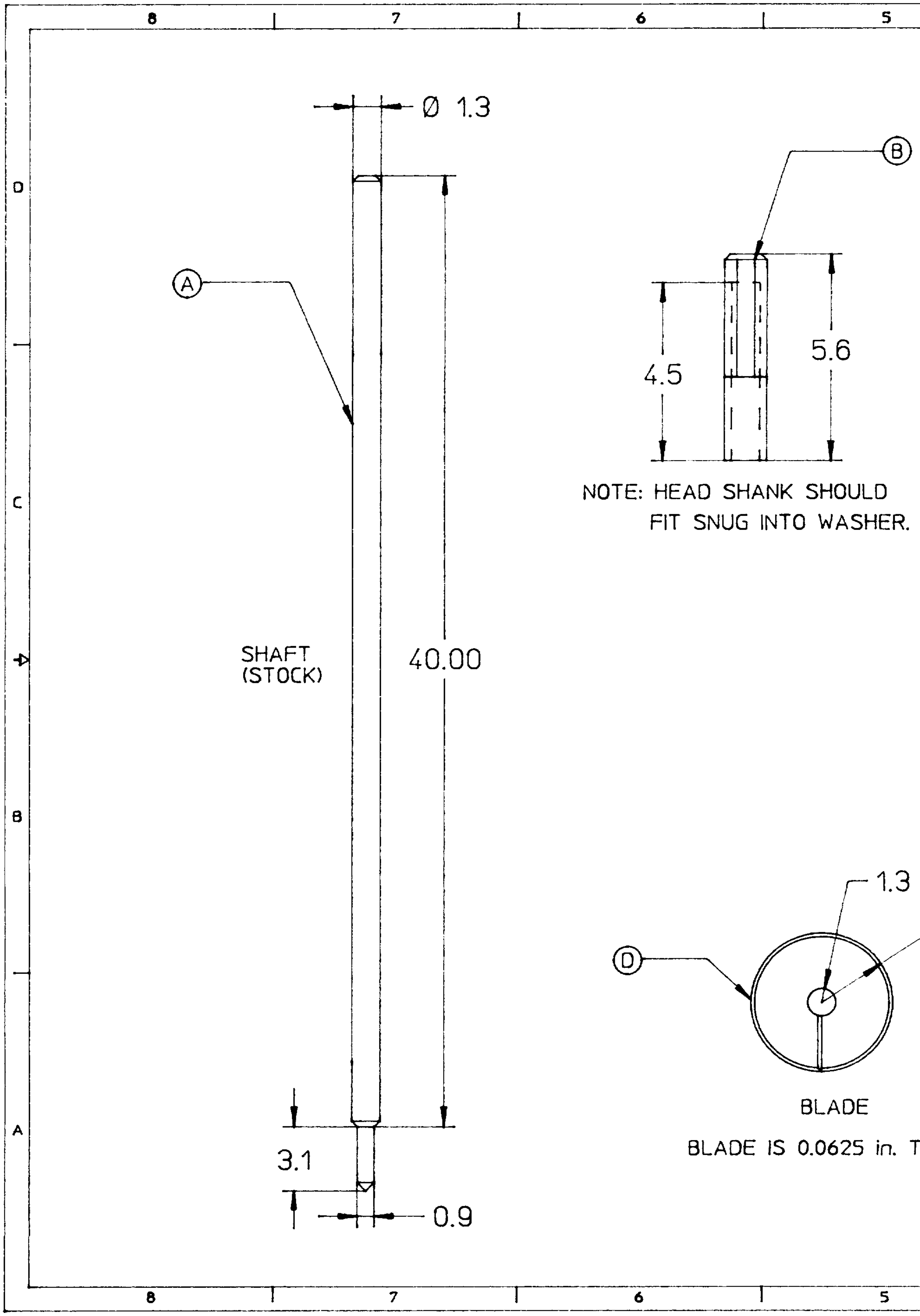
Conclusion:

While the gear based system provides extreme torque advantages the it also provides some problems. From our research and group discussions, we have discovered some problems with a gear type system. First of all the tooth stress under loading conditions may cause the shearing of gear teeth under high torque conditions. Secondly, a special lubricant would have to be developed to with stand the temperature swings associated with the moon and Mars. Thirdly, sever thermal stresses in the gears themselves would have to be over come so that they would not stress fracture. And finally, the extreme cool and hot temperatures of the moon would cause thermal fatigue in the gears.

APPENDIX F

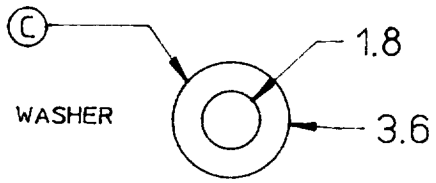
Detailed Drawings of Anchor and Anchor Emplacement System

FOLDOUT FRAME 1.



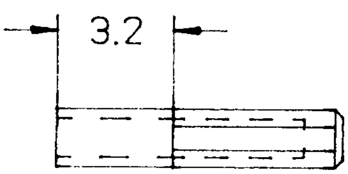
FOLDOUT FRAME 2

WASHER IS 0.3175 THICK



NOTE: WASHER SHOULD BE
PURCHASED INSTEAD
OF MANUFACTURED.

NOTE: ALL DIMENSIONS
ARE IN CENTIMETERS.



NOTE: ALL PARTS ARE TO BE
MADE OUT OF STAINLESS
STEEL 303.

NOTE: THIS HOLE NEEDS TO
FIT SNUG AROUND THE
SHAFT.

6.4

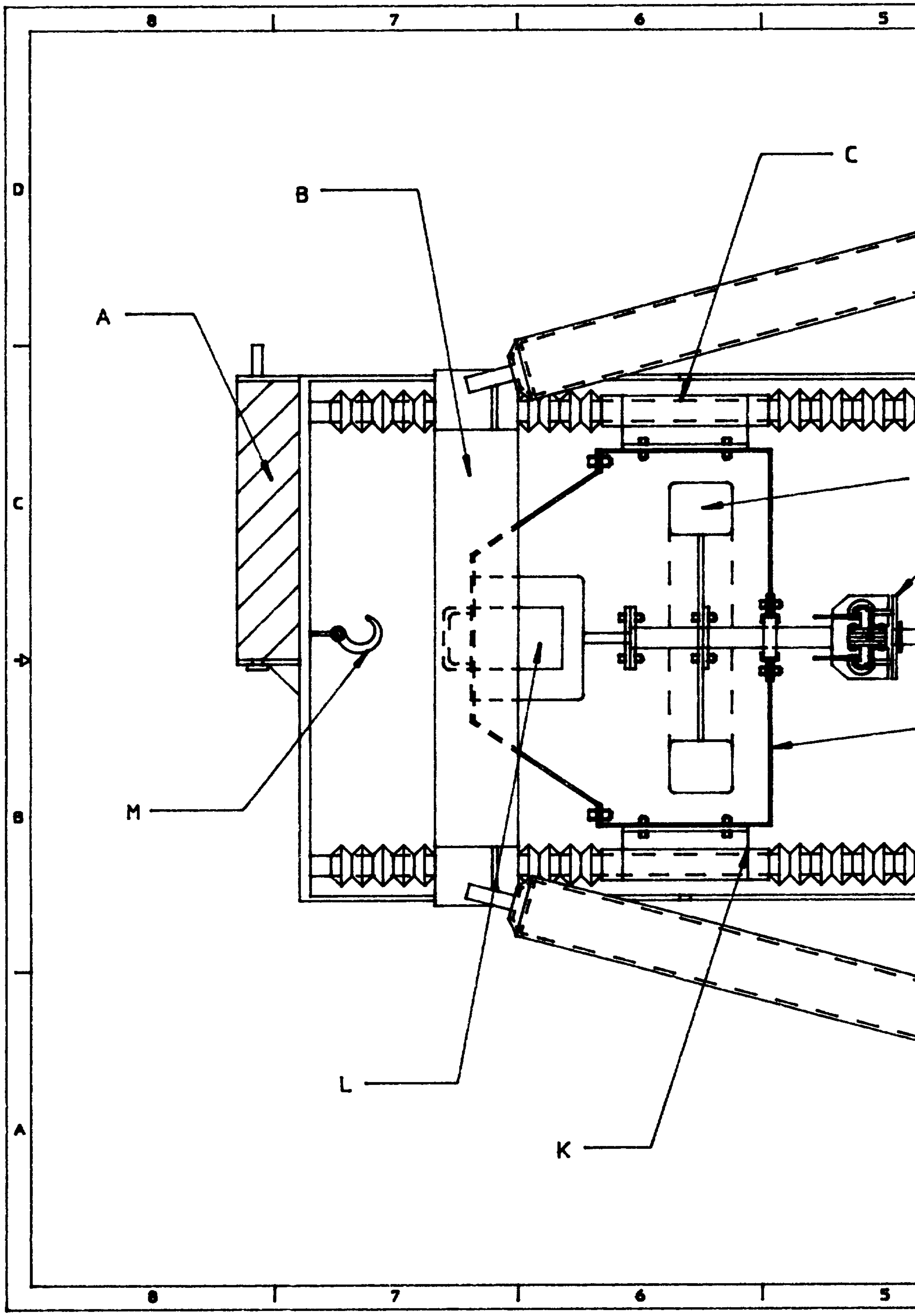
OTE: THE CENTER HOLE
NEEDS TO FIT
SNUG AROUND THE
SHAFT.

K

A	1	0.5 in. ROUND STOCK
B	1	0.75 in. HEXAGONAL STOCK
C	2	WASHERS
D	1	AUGER BLADE

A.B. HOLT	5/20/94	ANCHOR PARTS	Conceptual Design
		ME30 5.02	-00000-00000-1

FOLDOUT FRAME 1



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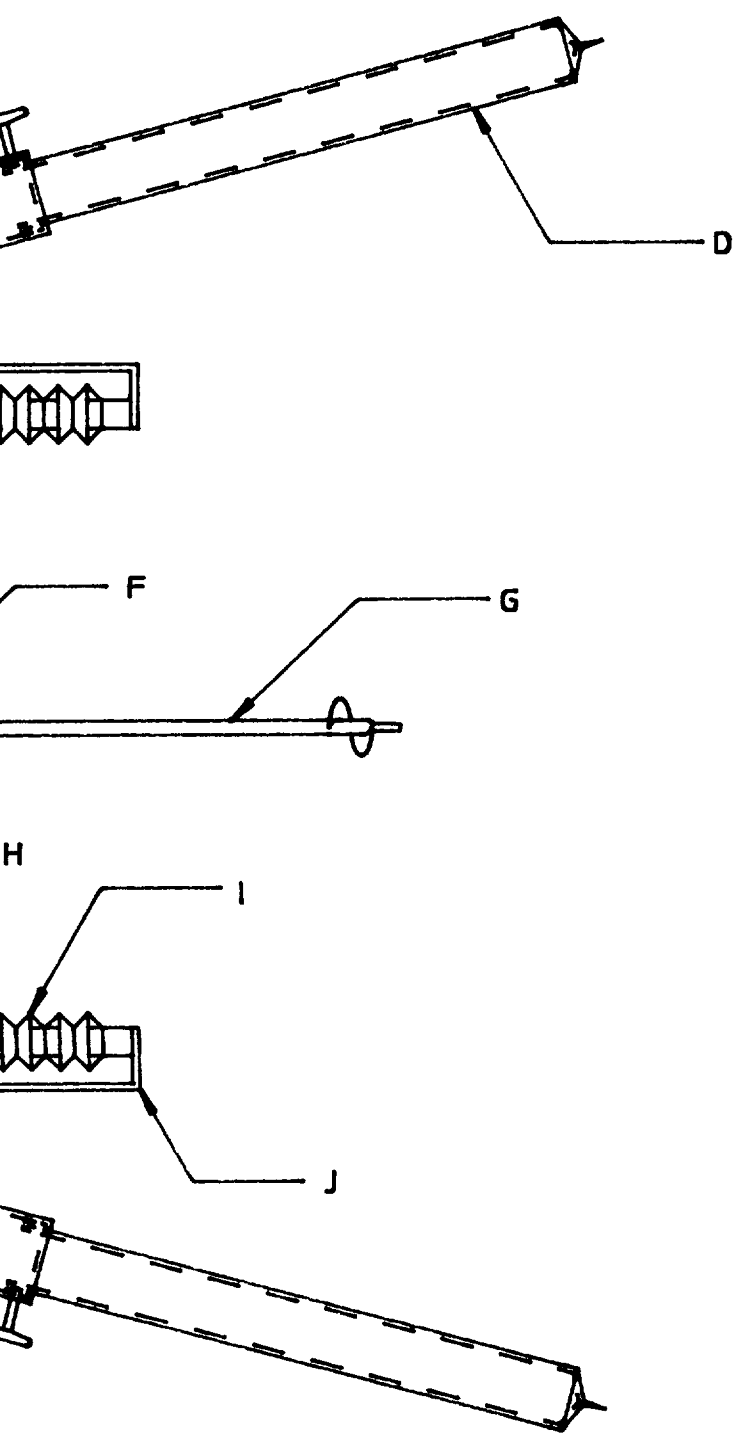
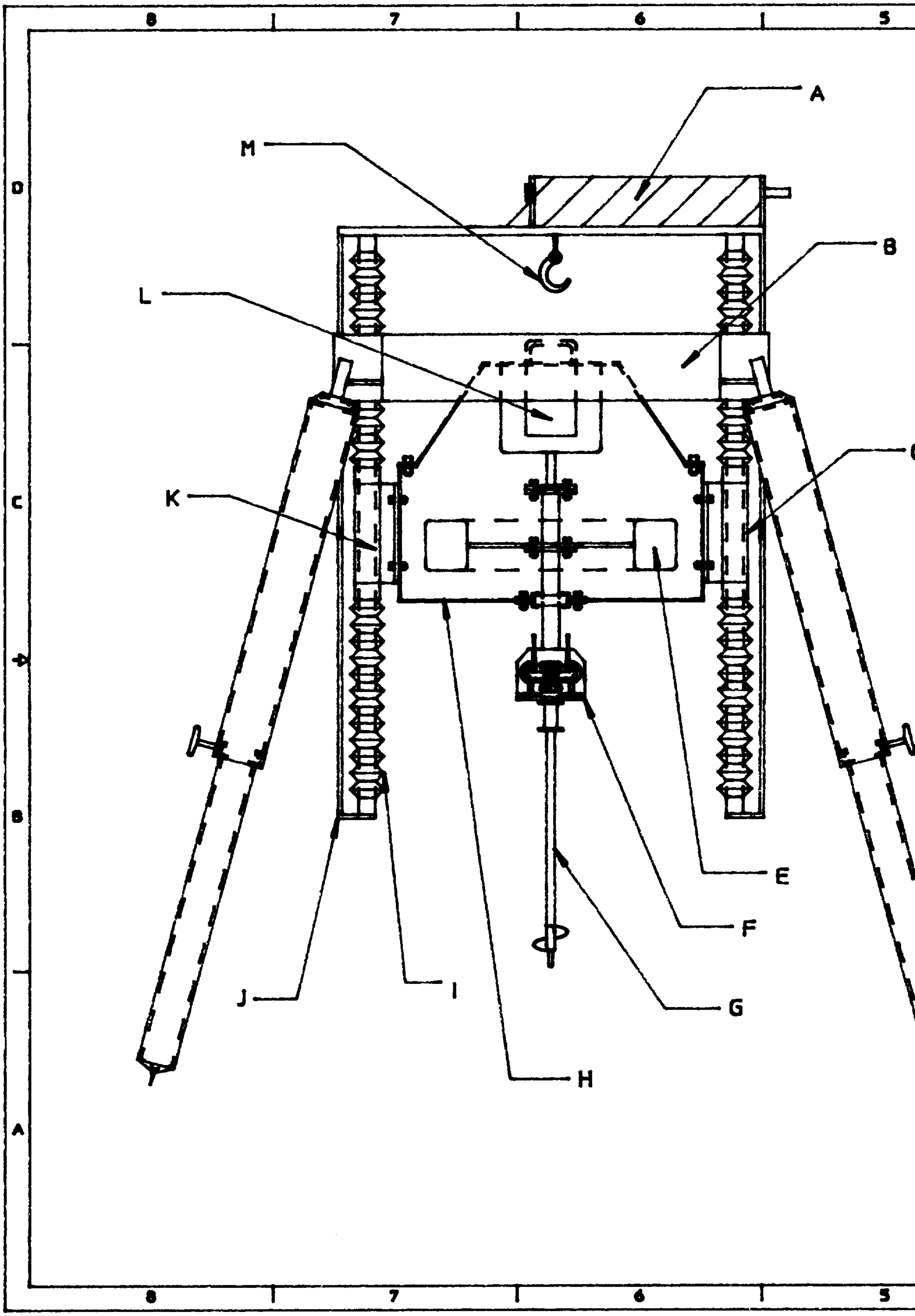


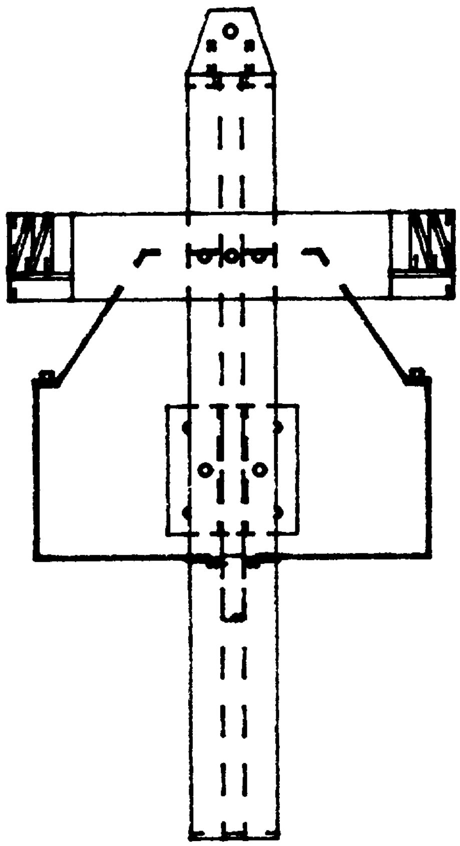
A	1	RAISING MECHANISM
B	1	STANDING FRAME
C	2	HOUSING GUIDES
D	4	TELESCOPIC LEGS
E	1	FLYWHEEL
F	1	RELEASE CHUCK
G	1	ANCHOR
H	1	HOUSING
I	2	DUST COVERS
J	1	EMPLACEMENT FRAME
K	2	GUIDE SHAFTS
L	1	ELECTRIC MOTOR
M	1	RAISING HOOK

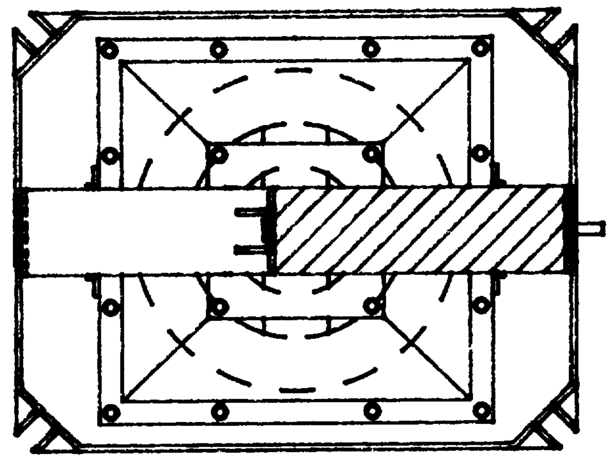
A.B. HOLT	5/20/94	1D-SYSTEM	Conceptual Design
			-00000-00000-1

FOLDOUT FRAME



FOLDOUT FRAME 2





A	1	RAISING MECHANISM
B	1	STANDING FRAME
C	2	HOUSING GUIDES
D	4	TELESCOPIC LEGS
E	1	FLYWHEEL
F	1	RELEASE CHUCK
G	1	ANCHOR
H	1	HOUSING
I	2	DUST COVERS
J	1	EMPLACEMENT FRAME
K	2	GUIDE SHAFTS
L	1	ELECTRIC MOTOR
M	1	RAISING HOOK

A.J. HOLT	5/20/94	3-VEIW SYSTEM	Conceptual Design
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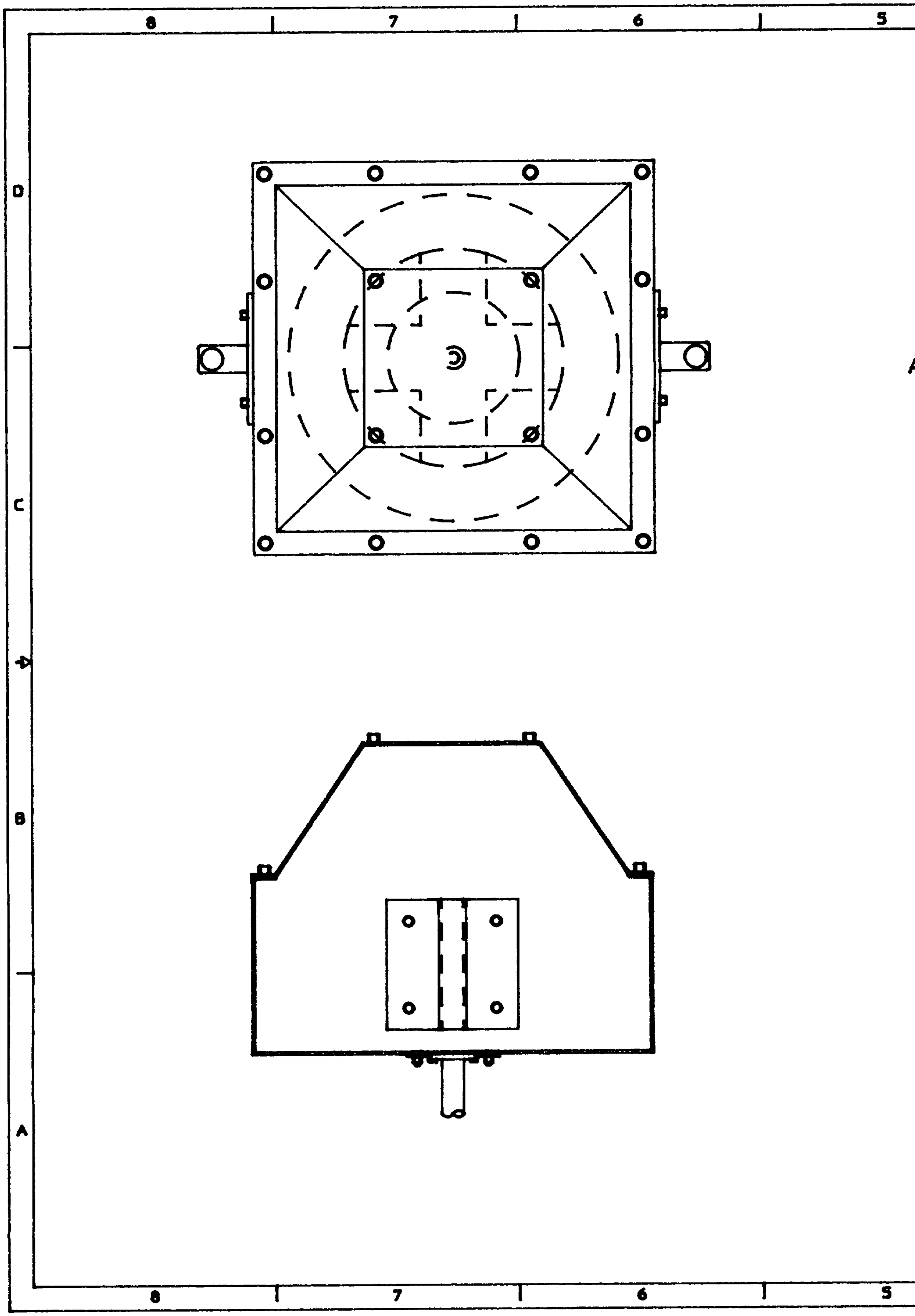
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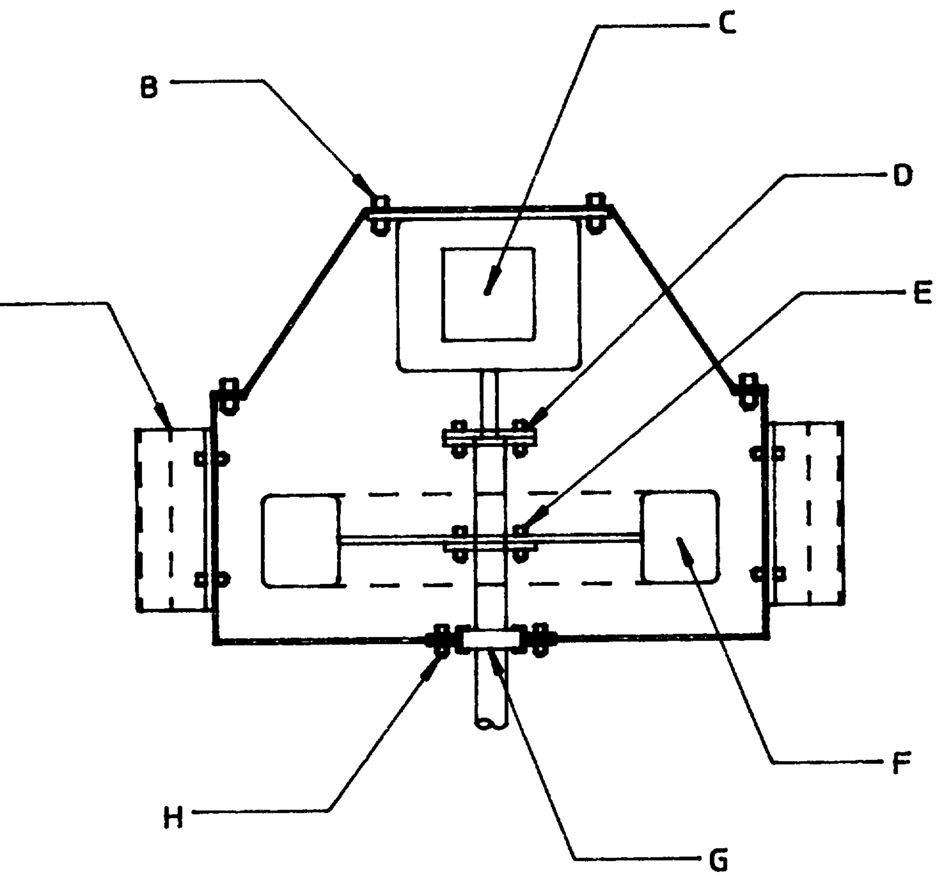
6
5

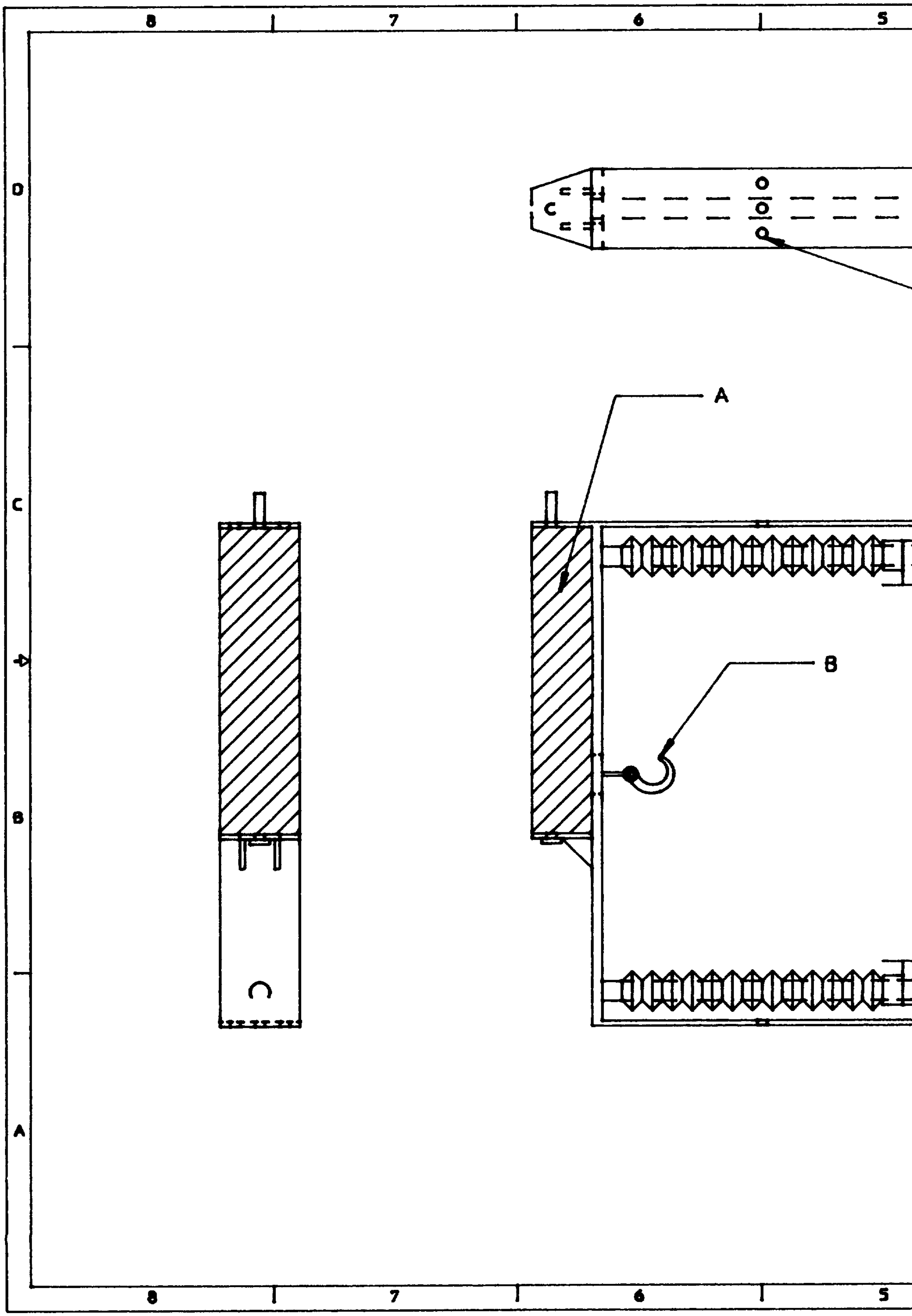
FOLDOUT FRAME 2.



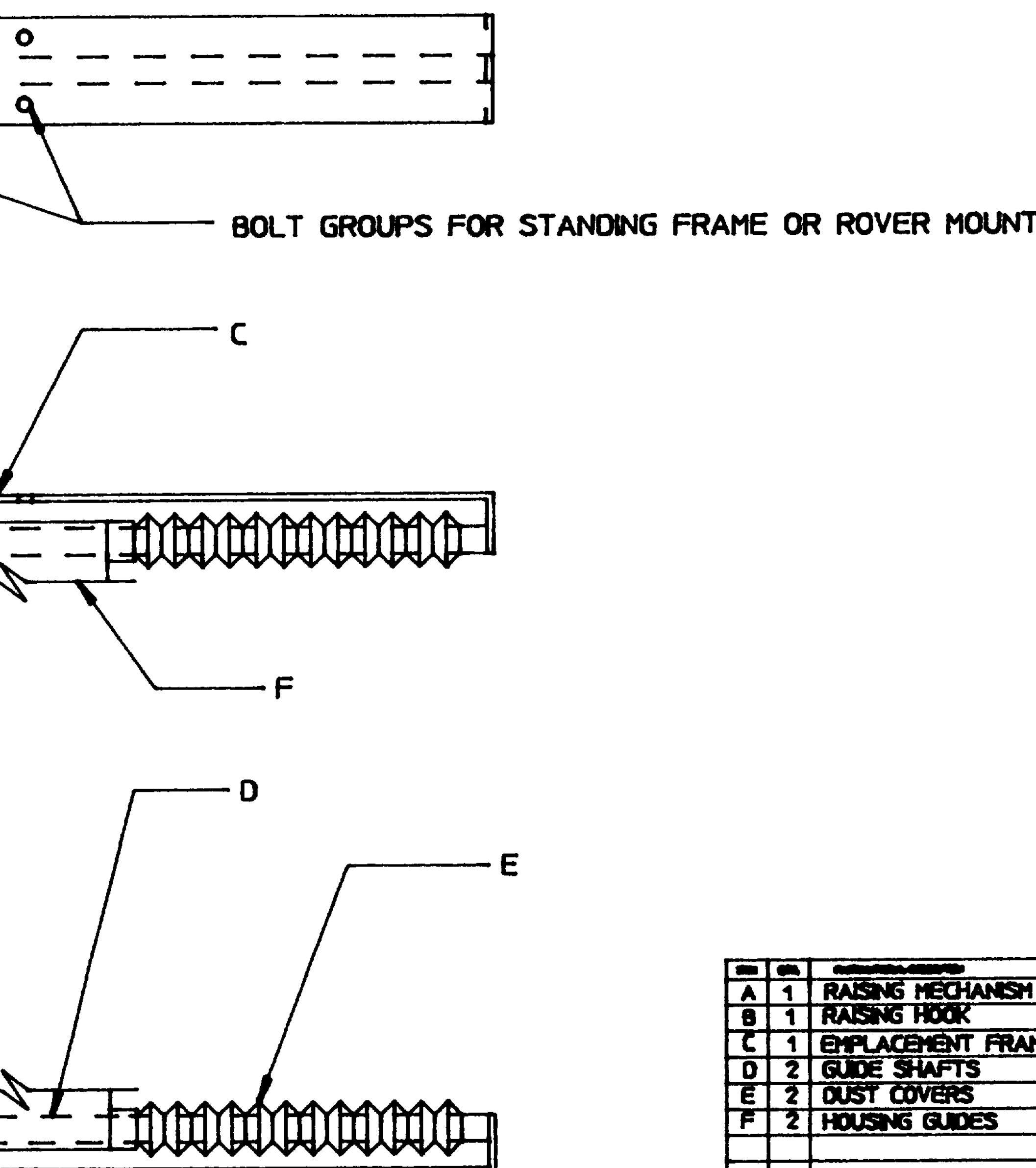
A	2	HOUSING GUIDES
B	30	FASTENERS
C	1	ELECTRIC MOTOR
D	1	ELECTRIC MOTOR COUPLE
E	1	FLYWHEEL COUPLE
F	1	FLYWHEEL
G	1	LUNAR BEARING
H	1	LUNAR BEARING COUPLE

A.B. HOLT	5/20/94	HOUSING	Conceptual Design
			-00000-00000-1

FOLDOUT FRAME 1



FOLDOUT FRAME 2



A	1	RAISING MECHANISM
B	1	RAISING HOOK
C	1	EMPLACEMENT FRAME
D	2	GUIDE SHAFTS
E	2	DUST COVERS
F	2	HOUSING GUIDES

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EMPLACEMENT FRAME

Conceptual Design

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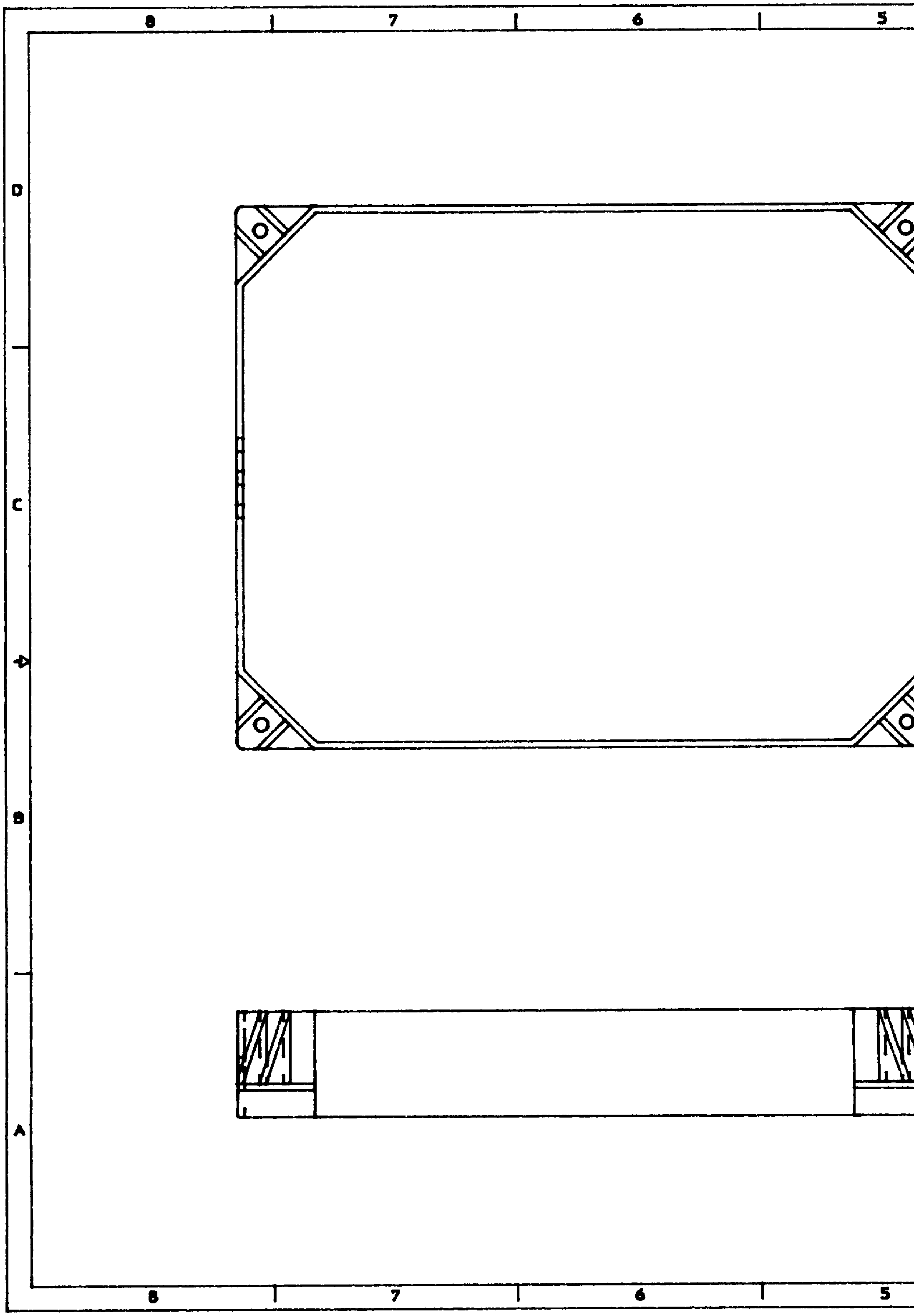
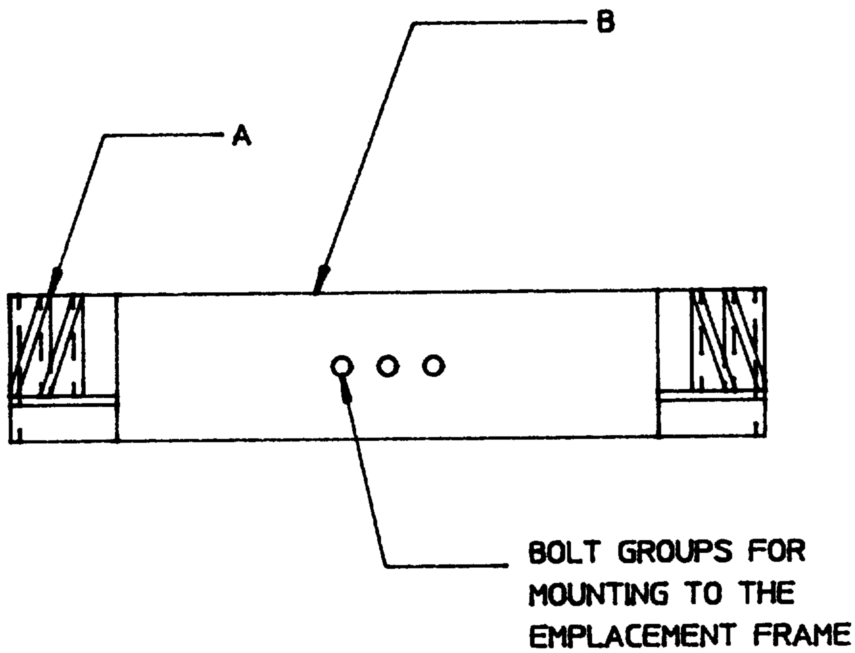
FOLDOUT FRAME /





A	4	TELESCOPIC LEG MOUNTS
B	1	STANDING FRAME

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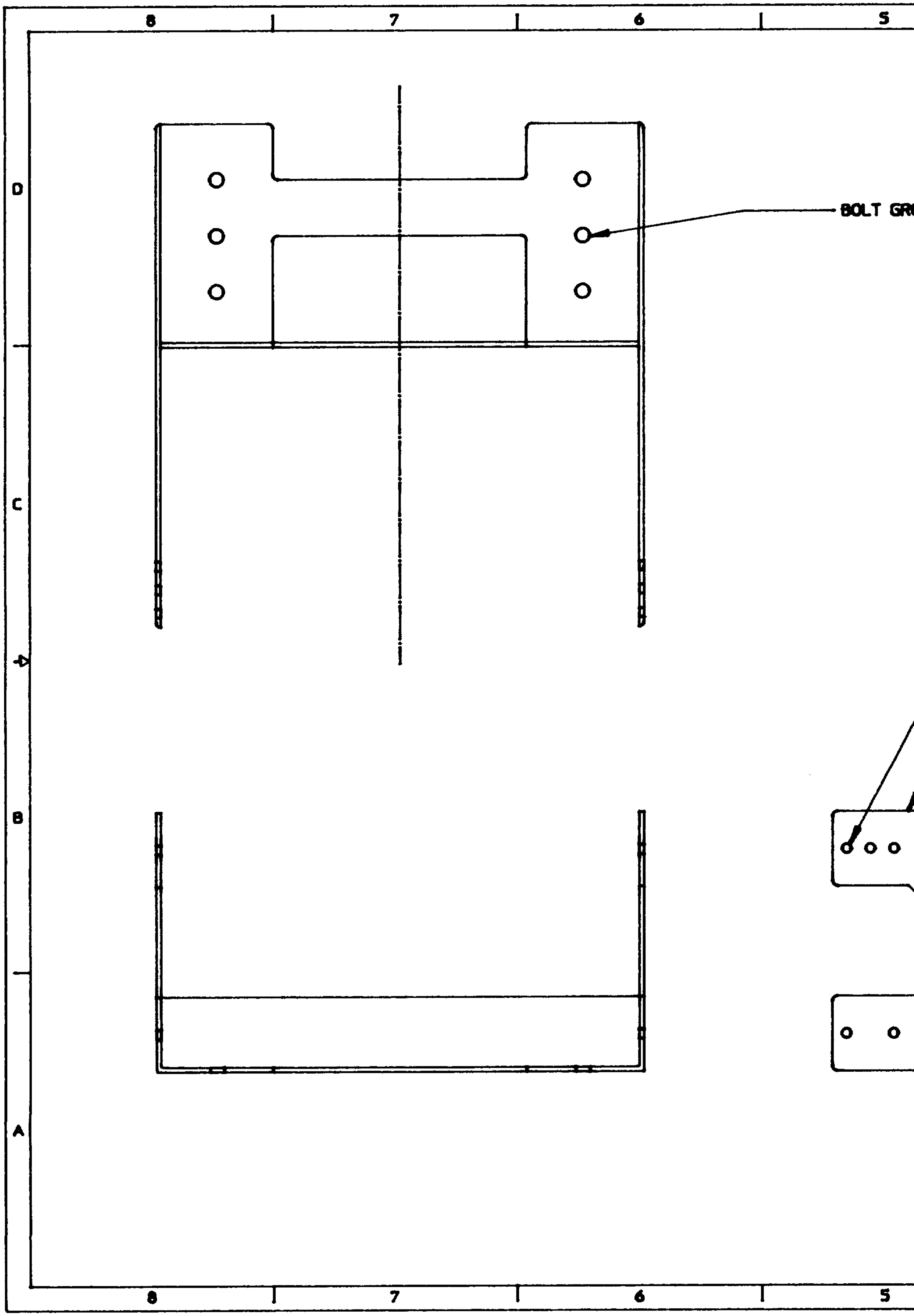
STANDING FRAME

Conceptual Design

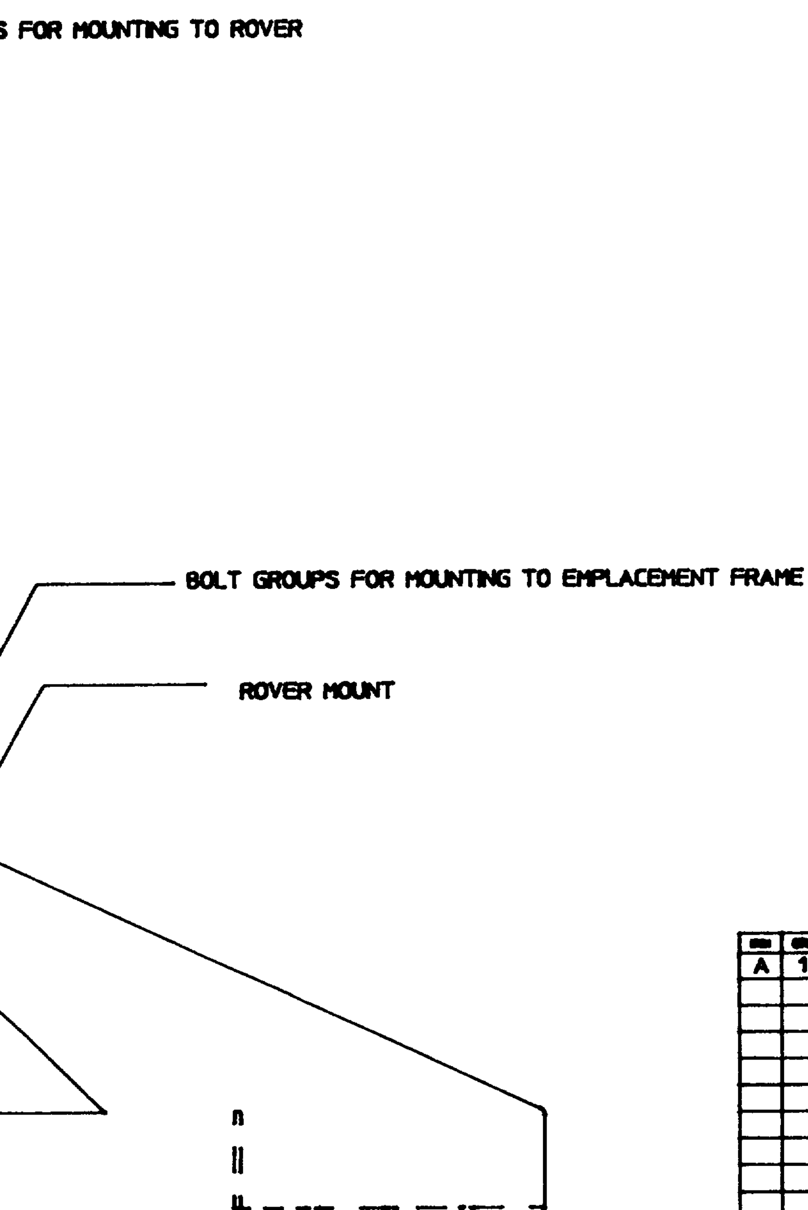
-00000-00000-1

FOLDOUT FRAME



2

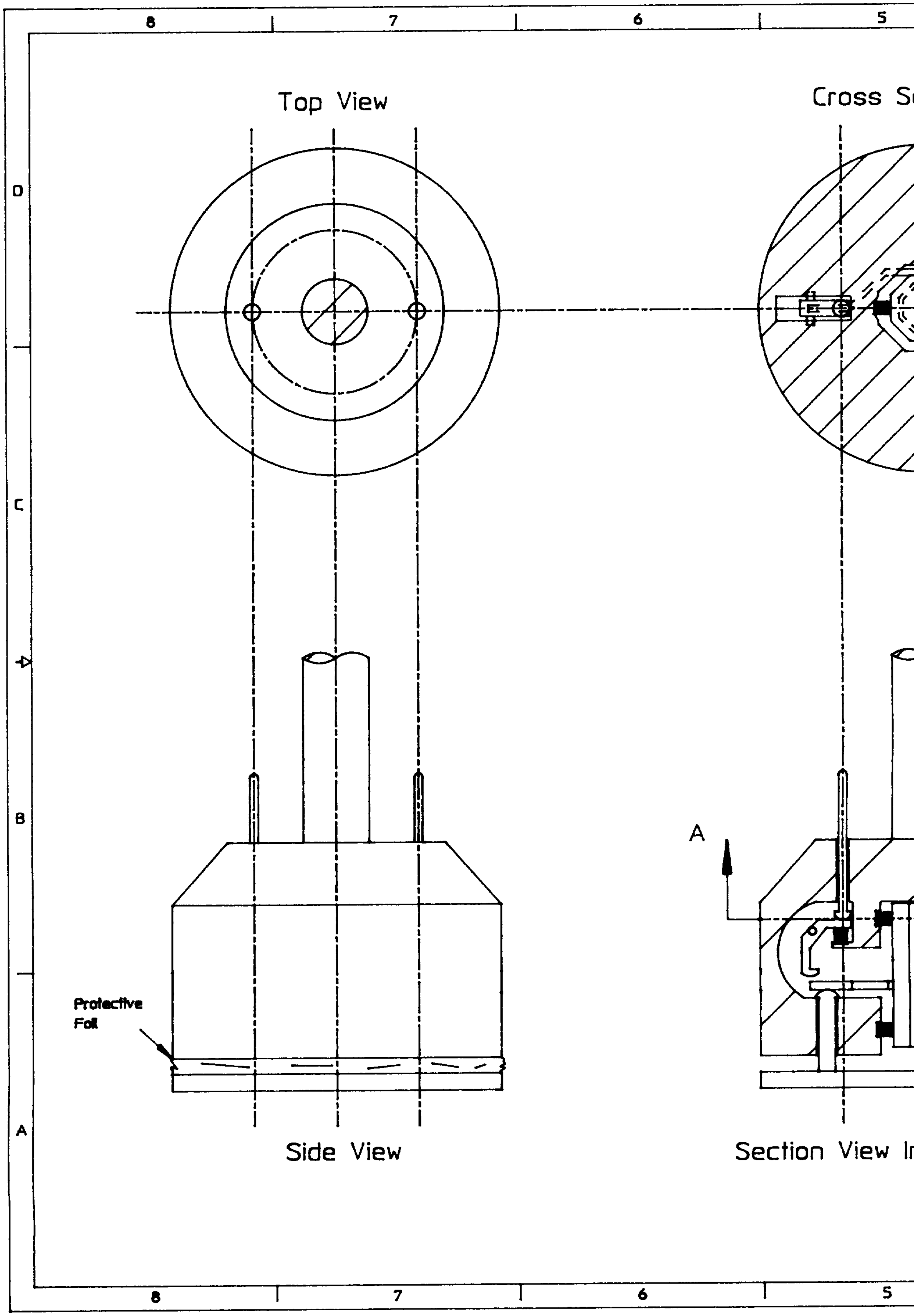
FOLDOUT FRAME

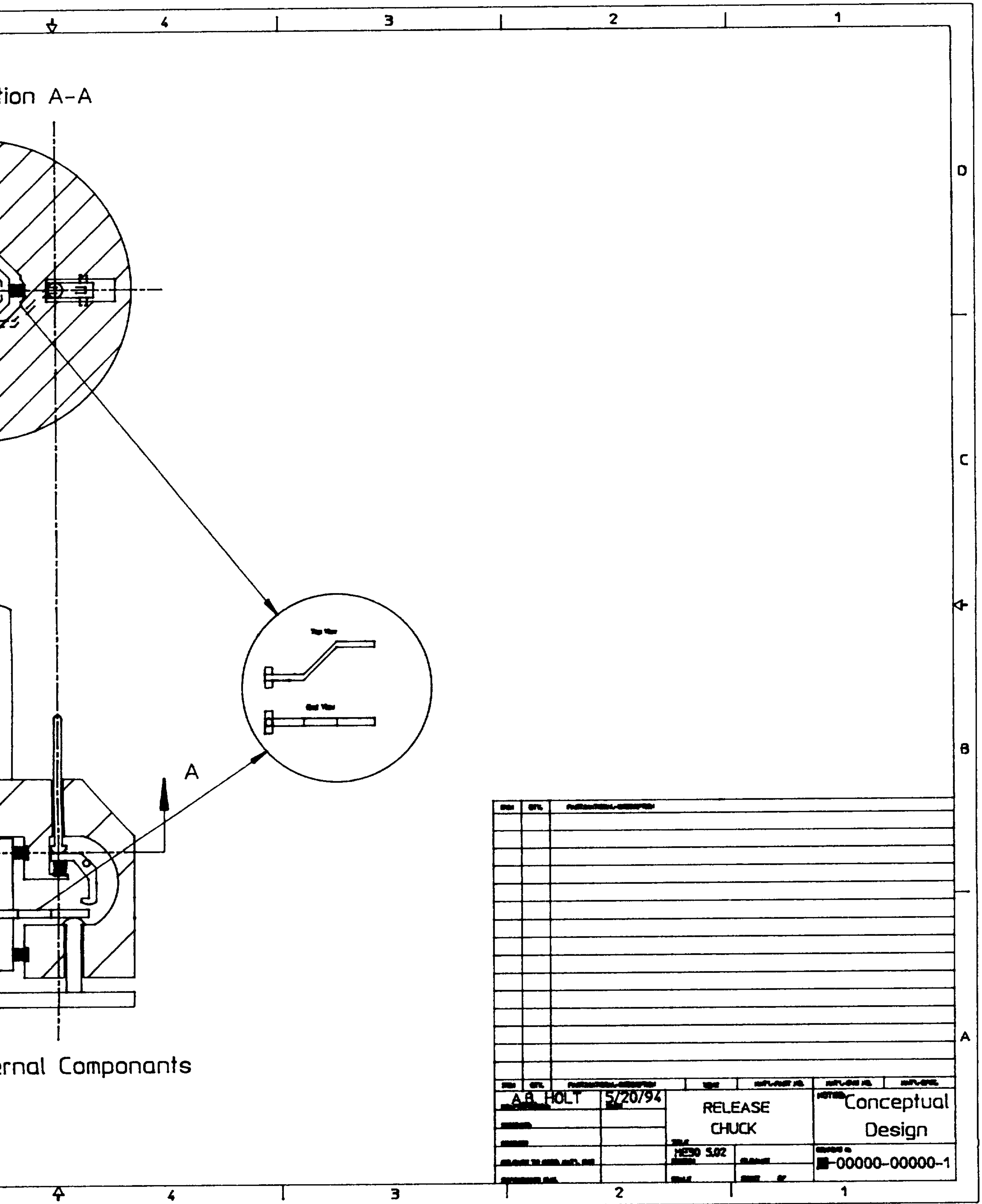


A	1	ROVER MOUNT

A.B. HOLT	5/20/94	ROVER MOUNT	Conceptual Design
			-00000-00000-1

FOLDOUT FRAME 1.




tion A-A
A
ernal Componants
A.B. HOLT
5/20/94
RELEASE
CHUCK
Conceptual
Design
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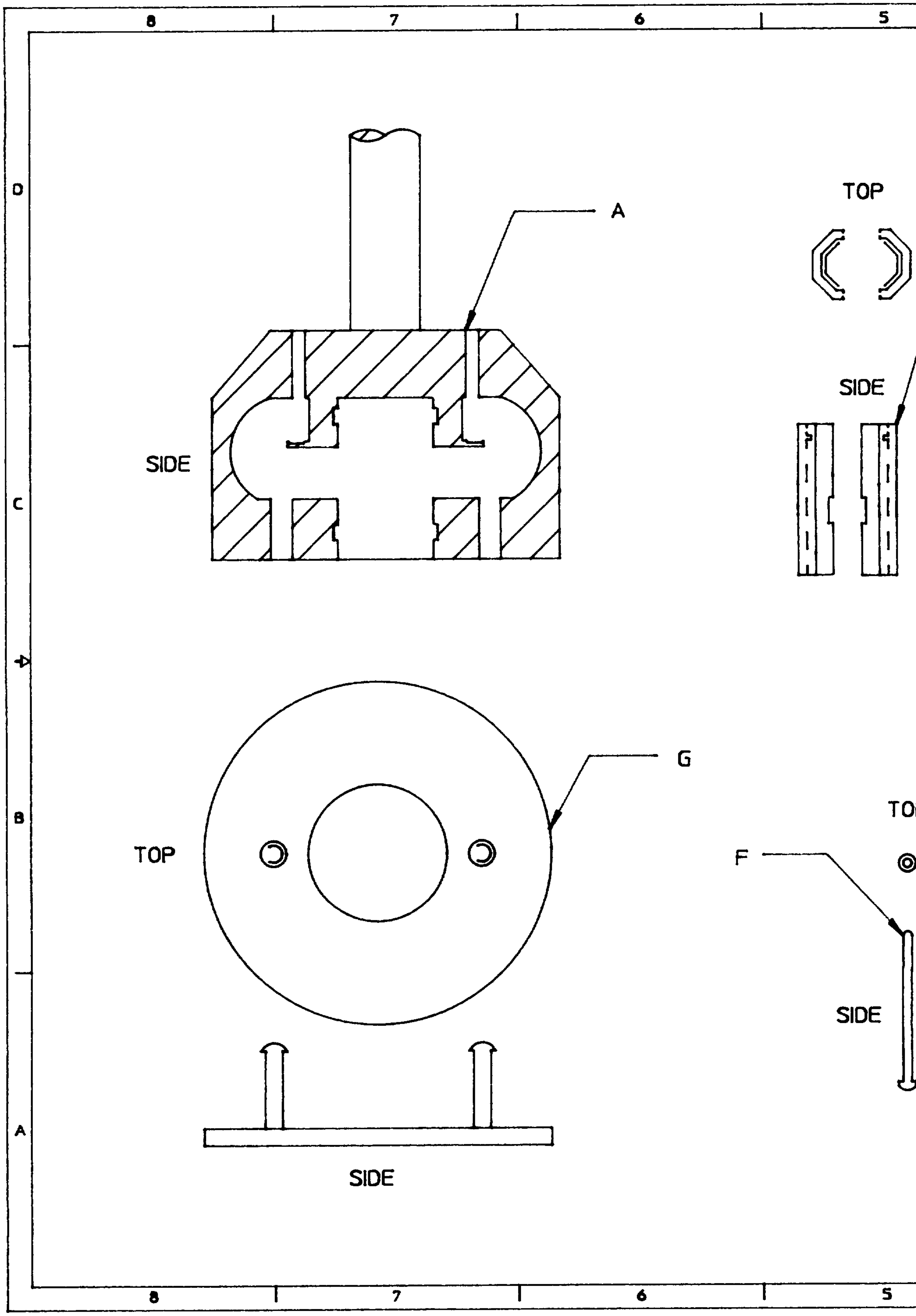
FOLDOUT FRAME /.



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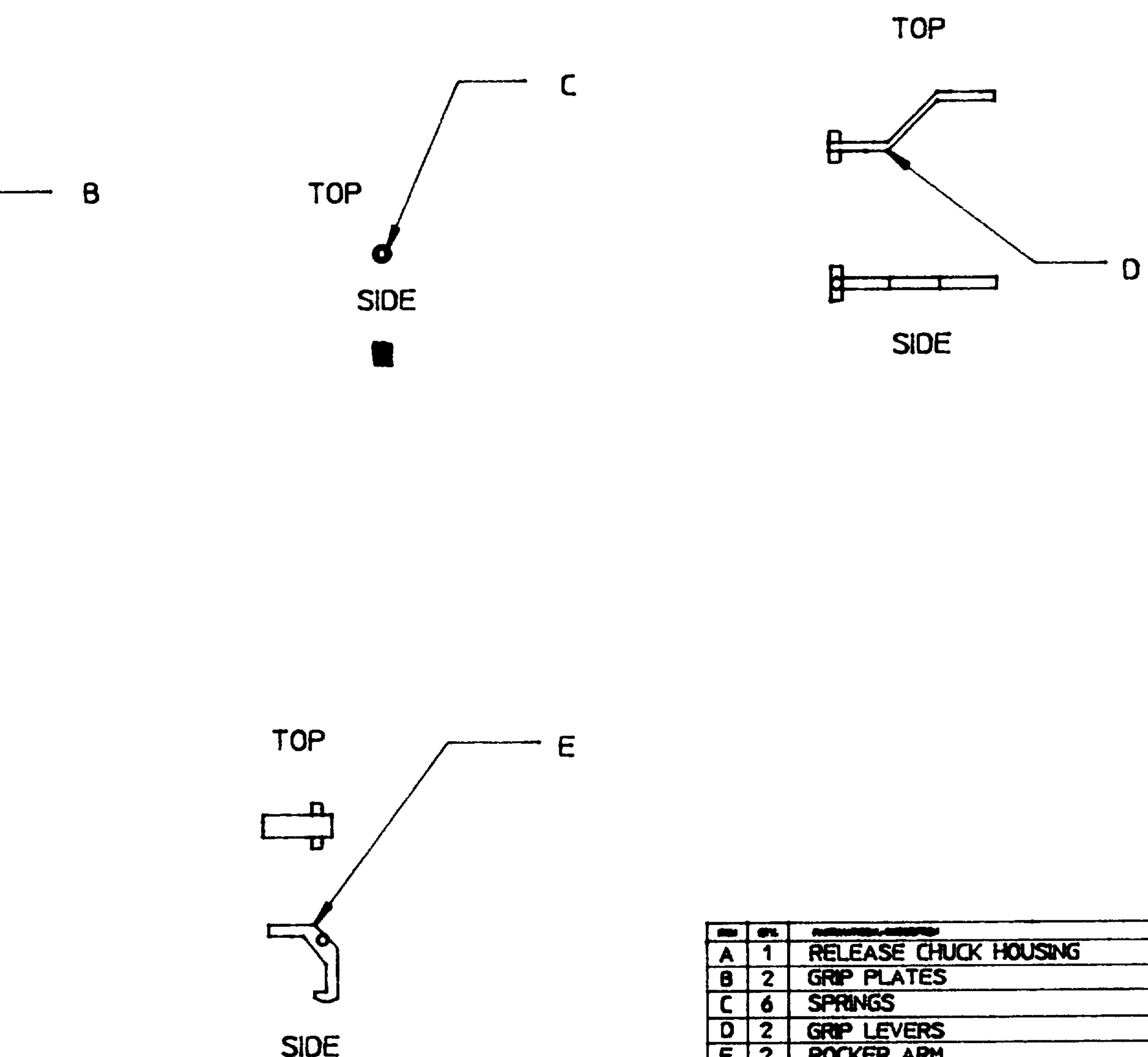

A	1	RELEASE CHUCK HOUSING
B	2	GRIP PLATES
C	6	SPRINGS
D	2	GRIP LEVERS
E	2	ROCKER ARM
F	2	ENGAGING RODS
G	1	RELEASE PLATE

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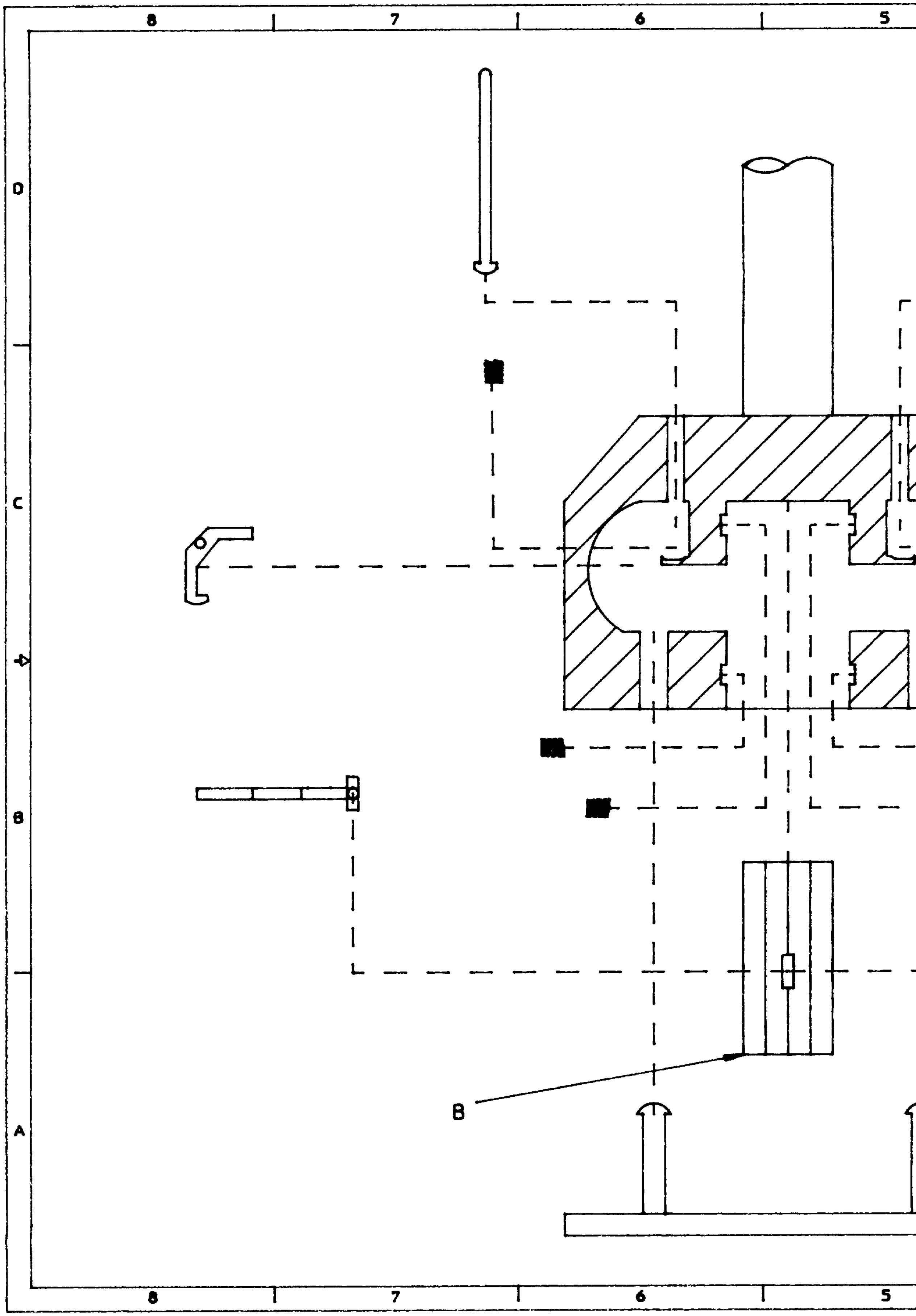
RELEASE PARTS

Conceptual Design

-00000-00000-1

FOLDOUT FRAME /



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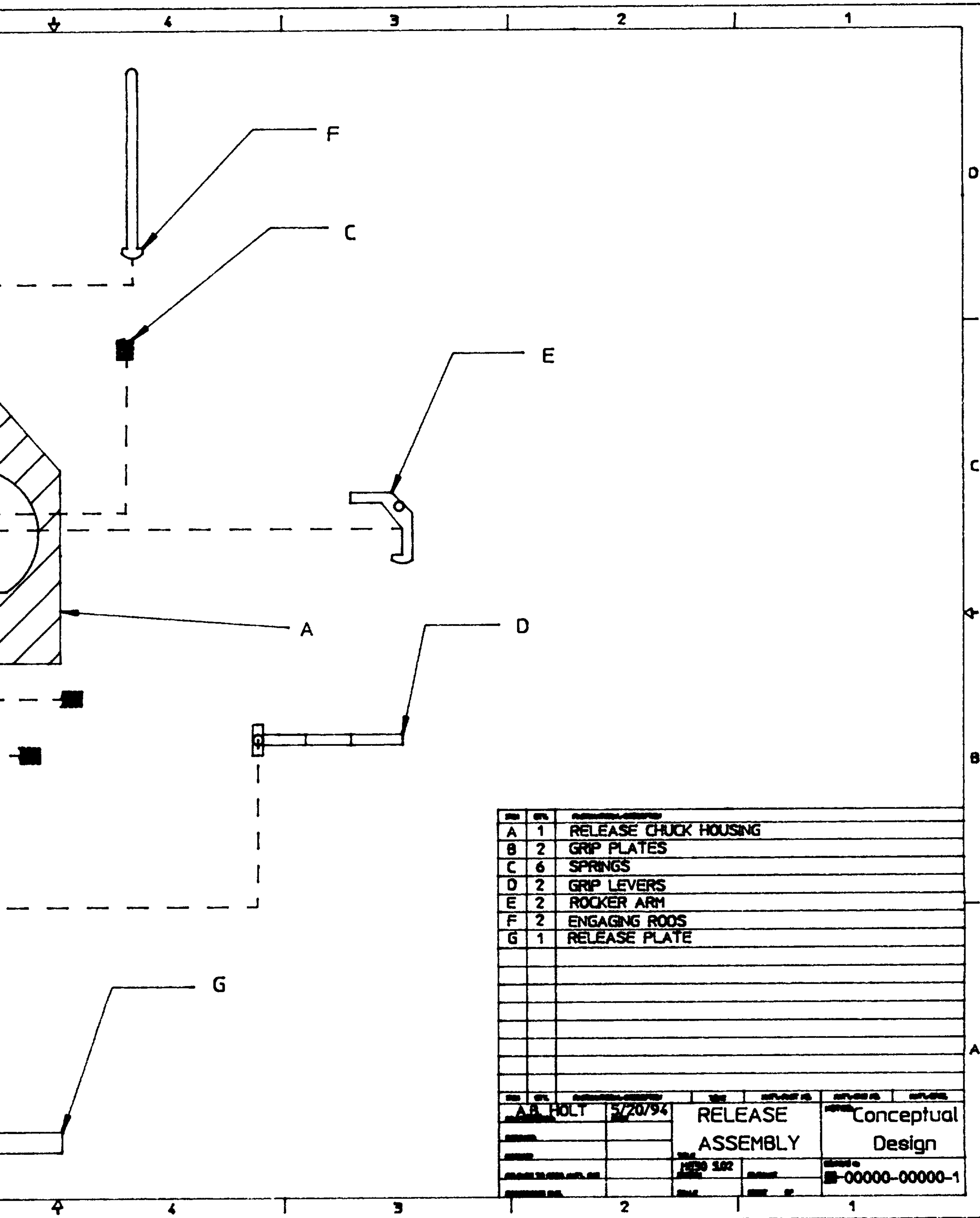

ITEM	QTY	DESCRIPTION
A	1	RELEASE CHUCK HOUSING
B	2	GRIP PLATES
C	6	SPRINGS
D	2	GRIP LEVERS
E	2	ROCKER ARM
F	2	ENGAGING RODS
G	1	RELEASE PLATE

A.B. HOLT	5/20/94	RELEASE ASSEMBLY	Conceptual Design
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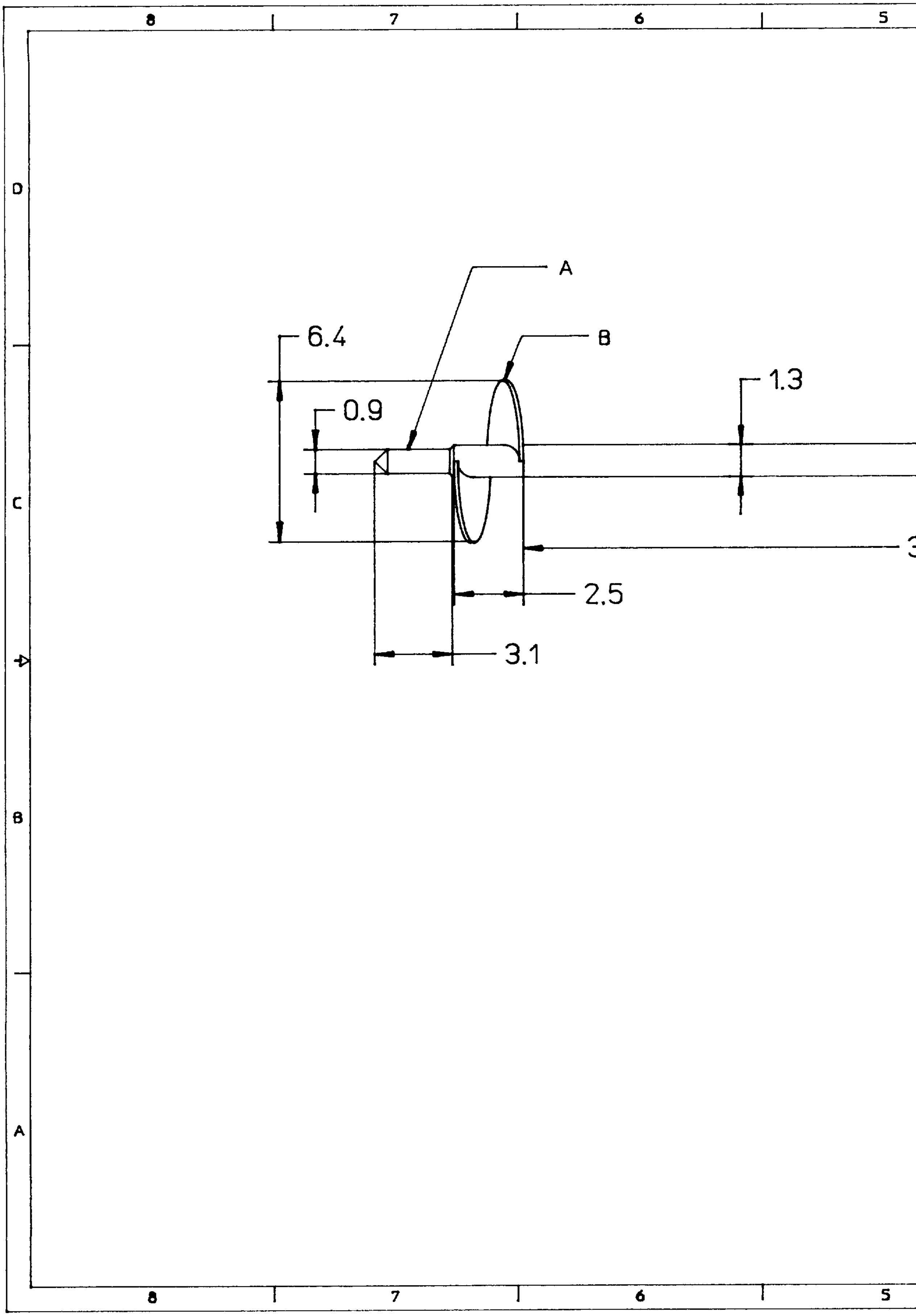
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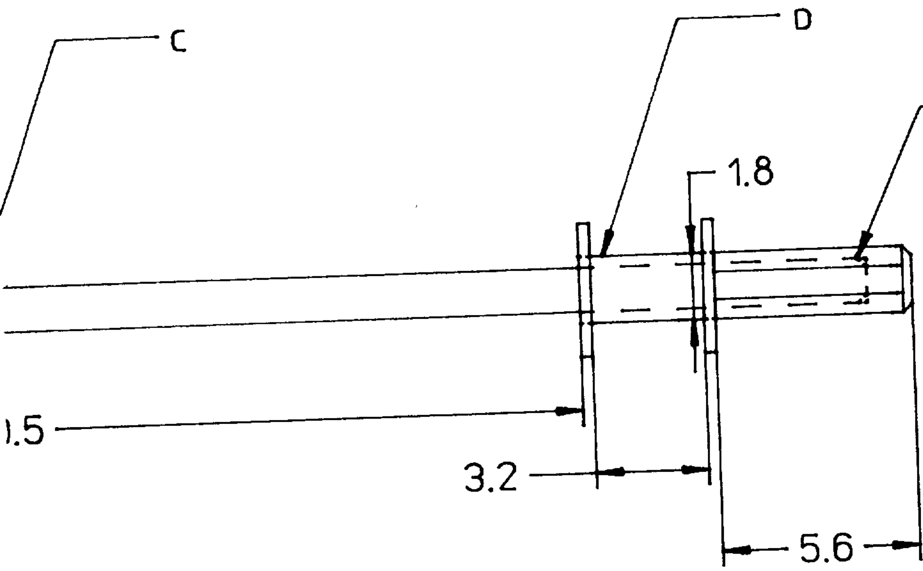
2



A	1	PILOT
B	1	AUGER BLADE
C	1	SHAFT OR STEM
D	1	SPOOL
E	1	HEAD

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ANCHOR ASSEMBLY

Conceptual Design

ME30 5.02

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