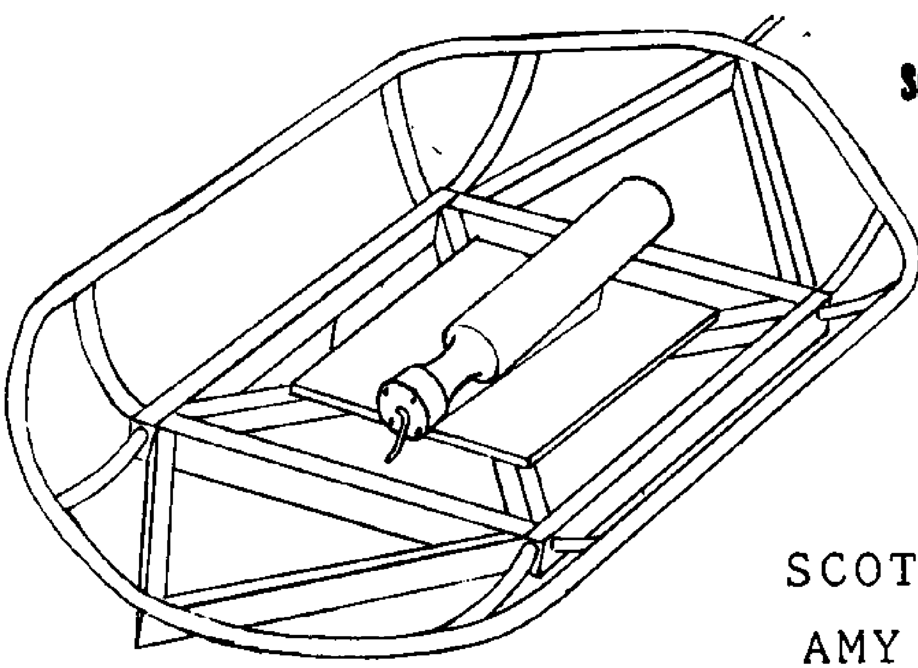
STINGRAY

AN OCEAN BOTTOM DEPLOYED SHEAR WAVE SOURCE



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1. INTRODUCTION

The team goal is to successfully design, build and test a prototype bottom deployed shear wave source for conducting seismic surveys of the ocean subbottom. This source will provide a more sensitive investigative tool for the geophysicist, marine geologist and offshore geotechnical engineer interested in subbottom engineering and physical properties.

For this particular project a source will be created which will cause what are referred to as SH-waves. This means that a horizontal impulse force will be made so as to produce a shear wave which travels at 90 degrees to the impulse into the subbottom.

The problem which has been presented evolved as a result of other seismic research. Extensive studies have been made on foundation parameters with compressional waves, or P-waves, because of the ease with which these waves can be propagated and collected, as well as the simplicity of the calculations involved in understanding the sub-structure of the soils that were being studied.

Recently, work has been reported with shear, or S-wave, sources. Shear waves are caused as a result of a shearing motion which occurs perpendicular to the direction in which P-waves are propagated. Unlike P-waves, S-waves do not travel through liquids or gases, but instead are carried in the actual structure of a solid. S-waves provide a more representative picture of what is occuring in sediment structure which may be holding water or other liquid or gaseous substances. Shear wave velocity is much slower than compressional wave velocity. Therefore, determining whether or not shear waves are in the data is possible.

Other people who have begun research in this area of study are a team of scientists at the University of Kiel in West Germany. The extensive research done by this group has still not been perfected and thus the need for more research. Geo-Physi-Con Co. Ltd. of Calgary, Alberta has also attempted a project in this area of interest, obtaining some results, but without ever deploying it on the ocean bottom. The only other similar project is one at Wood's Hole Oceanographic Institute (WHOI). Their project was very rushed and underbudgeted, and they have expressed an interest in helping any way they can.

There are many uses for this type of source. The study of the sub-structure of the ocean floor could lead to the unexpected discovery of pockets of crude oil or natural gas locked in the substrate. Earthquake fault lines could be studied further and new faults may be discovered in the future, this being due to the S-waves inability to travel through gaseous or liquid mediums. Taking everything into consideration, the successful design and testing of an ocean bottom deployed shear wave source seems to be an important step in the right direction for the future of Geophysics.

II. SLED DESIGN

Introduction

The sled is the section of the system which incorporated all the other sections. The sled is the basic framework to which all other subsystems are attached. The sled must be designed with the coupling, source and towing components in mind.

The sled design had to satisfy all the different wave generation technique requirements. This constraint required the sled to have the structural integrity to withstand the maximum input force. When this force is transmitted to the sled, it must ensure upright sled stability. The sled design, working with the source input section, must also consider a proper mounting technique.

The sled design had to incorperate a proper mounting technique for the different coupling apparatus . This was a critical component because this was to be directly related to the stability of the sled when fired in the transverse direction. The final consideration in the sled design was how the sled was going to be towed by the Jere Chase.

Design

From this design basis, versatility is the key ingredient to a successful sled design. This design has to satisfy several firing techniques as well as different coupling techniques. If these objectives were satisfied, the sled design would be considered successful. To satisfy these objectives, the design section was broken up into four stringent requirements.

1. Sled must be lightweight and corrosion resistant.
2. Sled must be structurally sound.
3. Sled must be structurally stable.
4. Sled must create a partition between the source and the runners.

Firstly, the sled had to be lightweight. Based on the WHOI experience, this project could be achieved successfully with a base sled weight of 125 lbs. (See appendix A for sled weight approximation). The WHOI project tried to achieve proper coupling by means of a large sled weight, thus creating a large normal reaction force from the ocean bottom. Project Stingray investigated other coupling techniques (to be discussed in detail in the other sections) besides large weight to ensure proper coupling. The reason for the lightweight sled was so that the sled could be handled easily in and out of the water. This requirement suggested that a high strength to weight ratio material be used. Aluminum (6061) met this requirement as well as offered additional beneficial features. Aluminum (6061) is a material known for its anticorrosive characteristics. This is a vital characteristic when dealing with the harsh ocean environment. Future uses of Stingray should consider anodizing but time restrictions only allowed a coat of paint to additionally aid in the prevention of corrosion. Electrolysis is always a serious problem when dissimilar metals are in contact in a liquid due to their unequal potentials. To resolve this problem, zincs were mounted onto the sled frame near the dissimilar metal locations. (fig. 1)

SLED DESIGN(FRAMEWORK)

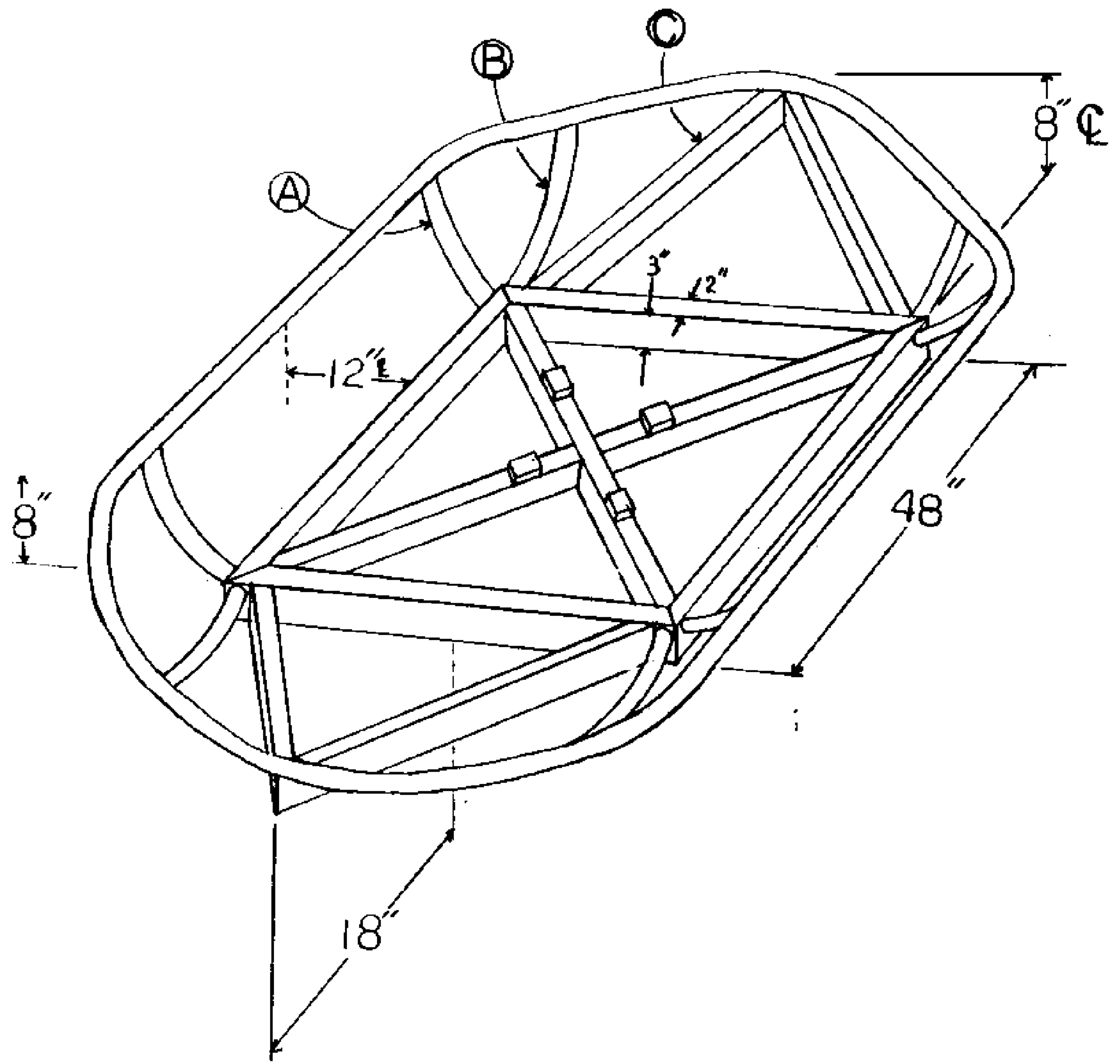


FIG. 1

A second requirement of the sled design was that the sled had to be able to structurally withstand the input force. An input force of 5232 lbs (the gun force at 2000 psi) was the basis for the member analysis calculations shown in appendix A. This value ensured a factor of safety in the design because the gun will never be fired at 2000 psi. Different factors were taken into consideration when choosing the frame's member cross-sectional type. Firstly, a strong geometry as well as a highly weldable shape was a requirement. This narrowed the decision to two highly attainable cross-sections: I-beam and hollow rectangular tubing. Secondly, the cross-section had to have a 'mountability' quality. Many fixtures and pieces of hardware had to be mounted onto these members. The rectangular tubing exemplified this quality more than the other so it was chosen as the cross-section to be used. Deflection calculations show that a 3"x2"x1/8" cross-section will not deflect significantly at the centerpoint (Shown in Appendix A). These dimensions present a shape with mounting and handling convenience as well as structural integrity. A compromise between practicality and structural soundness was made in the cross-section size dimension selection. As shown in the member analysis calculations in Appendix A, the results suggest that a smaller cross-section could be used but practicality suggests dimensional shape similar to the one that was used. Also as seen in the weight approximation calculations in appendix A, a smaller cross-section would have resulted in a lighter sled. This was not a desirable result because the current base sled weight of 115 lbs is a minimum weight and it shouldn't be exceeded due to coupling reasons. This resulted in a high safety of factor in the member analysis calculations which signifies an over designed truss system. The

3"x2"x1/8"(see fig. 1) was the result of the compromise. All members of this truss system were welded at all junction points. Welding results in a structurally strong and rigid structure. This structure would allow the gun to be mounted in both axial and transverse firing directions. Tapped blocks would be welded on the top of the frame so that the gun plate could be mounted securely. Similarly, tapped blocks would be mounted to the bottom of the frame so that the coupling apparatus' could be bolted securely. Small holes drilled in the frame would allow the rectangular tubing to fill up with water thus eliminating all major bouyancy effects of trapped air.

A third requirement of this sled design was that its design dimensions should be large enough to prevent tipping due to the source input. The tipping analysis results in appendix A indicate that a sled width of 49.0" would be needed to prevent transverse tipping when the source is fired at an angle of 15 at a pressure of 1000 psi (2616 lbs.). The pressure as shown would have to be decreased to maintain stability. There are several factors of safety incorperated into these calculations. Firstly, it was assumed that the runners would not penetrate the soil. Secondly, the water inside the sled frame was not taken into account. Thirdly, the water surrounding the sled would act as resistive force counteracting any tipping motion of the sled. These pressure values, therefore, are conservative. All these calculations are for the transverse tipping but can be applied to the axial case if the axial skiis are at least 49" long.

The fourth requirement of the sled design was taken from the WHOI sled design. In low density substrates, the sled runners will elevate large quantities of substrate to the level of the source. Air guns do not perform well in these types of environments due to the blockage of the pneumatic passages in the air gun. To minimize these problems, a partition between the source and the runners must be fabricated. This is called the 'shroud'. The shroud's primary purpose is to provide the source with a clean environment. The shroud material and it's structure should be lightweight, strong and flexible. The shroud should have minimal contribution to the sled's total weight(appox.=15lbs). It must be a strong material because it's proximity will be near the gun housing's exit thrust. There will be a significant pulse shock to this when the gun is fired at its lowest angle. But the shroud must be designed so that it's not in the direct line of fire of this exit. This suggests a low and wide shroud profile. The material used was Cal-lite fiberglass which satisfied all the material requirements. The supporting structure was circular aluminum tubing(1"x 1/8"). This structure was designed so that it would be below the line of fire when fired in both the axial as well as the transverse direction(see fig 1). This shroud would be symmetrical so that the sled could be towed in both directions and fired in all four directions. Keeping the sled symmetrical also keeps the center of mass directly under the source so that no rotation about the vertical axis will occur. To aid in towing support,two additional (3"x2"x1/8") rectangular aluminum tubing members would attach directly to frame from the tow cable hook-up location. This will be fabricated on the front as well as the back of the sled and will be covered by shroud material.

Meeting these requirements would ensure a successful design. This design would provide a lightweight low corrosive sled which could be adapted to the various source and coupling configurations planned. The sled would then be a highly versitile test platform for future coupling source prototype testing.

III. SOURCE SELECTION

INTRODUCTION

The following criteria were considered in evaluating each source:

AVAILABILITY:

fabrication - can the source be made in the machine shop?
cost - is the source affordable?
lendable - can the source be borrowed?

GOOD SIGNAL INPUT:

low noise - does the source have a high signal-to-noise ratio?
sufficient power - will the input be received from more than 50 feet?
repeatability - is the source's signature constant?

EASE OF OPERATION:

start-up - does the source require secondary equipment?
operation - is the source easy to operate?
maintenance - does the source need frequent repairs?
- does the source need to be cleaned after each use?

DESIGN CONSIDERATIONS:

size - is the source's size advantageous?
weight - does the weight follow design specifications?

EVALUATION OF THE POSSIBLE SOURCES

PENDULUM SYSTEM

The pendulum system consists of a motor-driven heavy mass pendulum whose oscillations cause reaction forces in it's housing (fig 2.1). The system is operated by cocking the pendulum arm and then triggering it's release. At the bottom of it's arc the mass will collide with a stationary fixture, thus delivering the input force. As such a system is not commercially available, nor is it possible to borrow one, it would need to be fabricated.

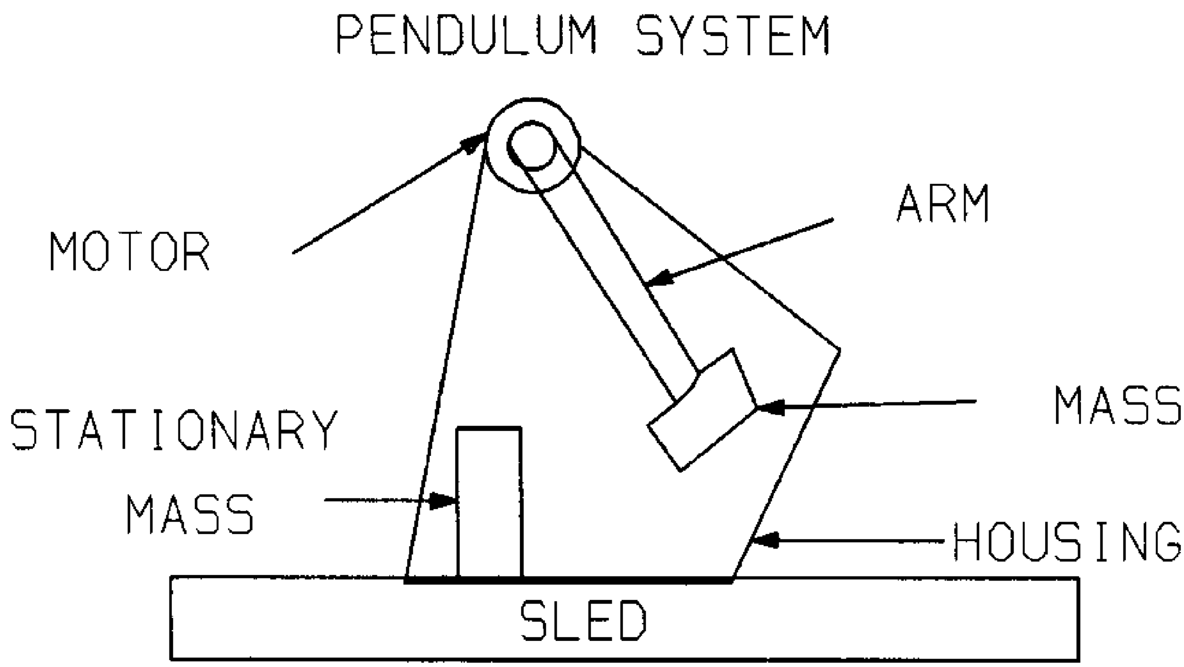

PENDULUM SYSTEM
MOTOR
ARM
MASS
STATIONARY MASS
HOUSING
SLED

FIG 2.1

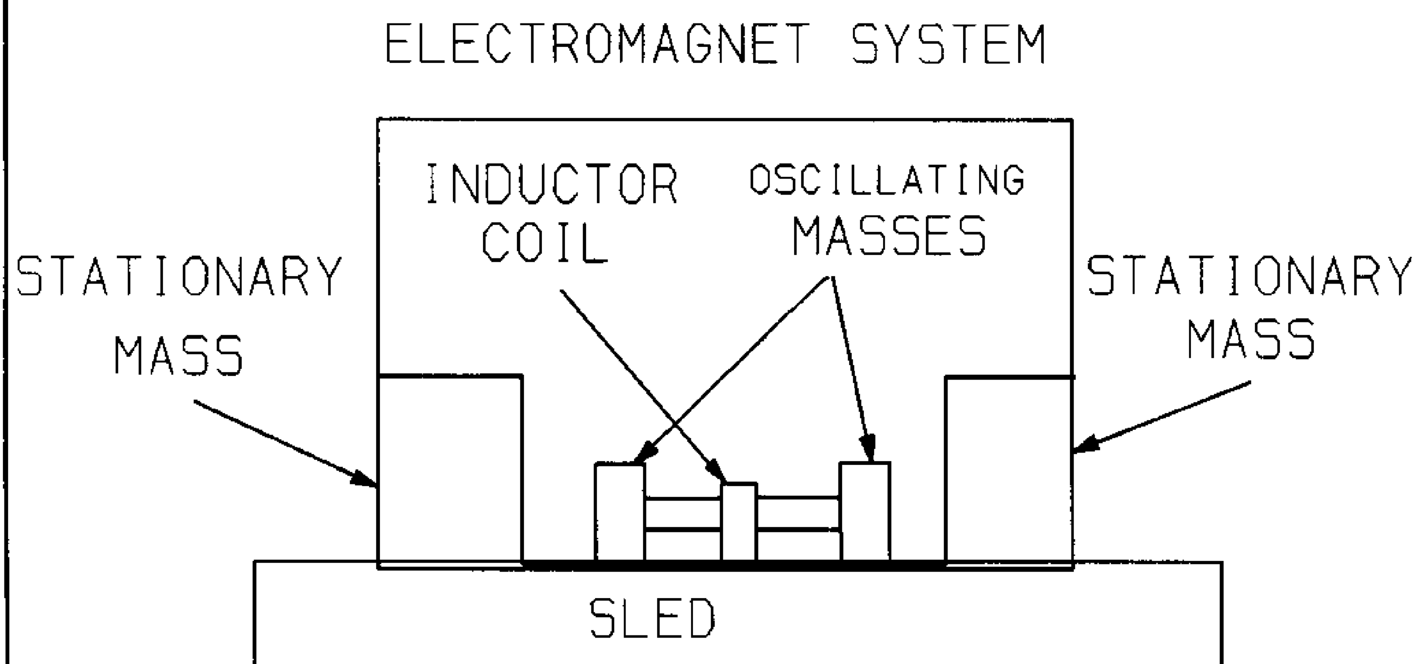

ELECTROMAGNET SYSTEM
INDUCTOR COIL
OSCILLATING MASSES
STATIONARY MASS
STATIONARY MASS
SLED

FIG 2.2

As for the signal input, this source would probably have a low signal- to-noise ratio. This is due to the fact that the pendulum output will be relatively weak (200 lb.). Therefore, the amplification will need to be increased and excess noise will be introduced into the system. It requires an input force of approx. 1500 lbs. to have sufficient wave generation. It is not known how to deliver such a large force with the pendulum while keeping it's weight within design parameters. In an attempt to rectify this problem the length of the arm could be lengthened, but the stability of the sled might be jeopardized.

The operation of the pendulum system would be relatively easy once the system if fully functional. Running the motor and triggering the arm are the only necessary functions to operate the system. The repeatability would be high as the source's signature would remain fairly constant. This equipment would be low maintenance, with the upkeep of the motor being the only necessity.

ELECTROMAGNET SYSTEM

The electromagnet system consists of a large rod shaped mass which is accelerated into a fixed mass by use of an inductive coil. This collision causes a reaction force which is the input to the sled. The mass could then be accelerated in the opposite direction by switching the polarity of the electromagnetic coil, hurling it into another fixed mass, resulting in an opposite input force. (FIG 2.2)

It is not possible to purchase an entire electromagnet system, however, the electromagnetic coil and large masses are readily available. The system would need to be assembled in the machine shop.

For the same reasons as the pendulum, the electromagnet would have a low signal-to-noise ratio and high repeatability. However, no way is seen to generate the necessary input force using this system. If the mass is increased the overall sled weight restriction may be violated. The size is agreeable with the sled design, however. If some way around this weight/force problem could be devised this system has potential.

Operation would require a generator and switching network capable of accelerating the mass back and forth within it's housing. Once operational the system is easy to run and relatively maintenance free.

AIR GUN SYSTEM

An air gun is a pneumatically energized source which explosively releases high pressure air into the surrounding medium. By housing this air gun in an open-ended canister an impulsive thrust can be obtained.

The cost of a small air gun (<2000 psi) is approximately twice the entire project's budget. Also, it is highly unlikely that one could be machined specifically for this project. However, WHOI has agreed to lend the following:

1 Bolt Par 600B Air Gun (with 40 cubic inch air chamber)

1 Air Gun Solenoid (with firing box)

Air and Solenoid Lines

1 3200 psi Air Compressor

The air gun has very low noise and excellent repeatability, coupled with a high power output. When fired at 2000 psi the corresponding input thrust to the sled is 5200 lbs. (see Appendix B).

The use of an air gun requires a powerful compressor to charge the gun and a solenoid with firing box to trigger the gun when the desirable pressure is reached. The firing procedure is very simple and can be repeated every minute if necessary. The air gun needs to be taken apart and cleaned after each test session. This cleaning, along with inspecting the gun's O-rings and shuttle, and monitoring the general upkeep of the compressor, are all the maintenance that this system requires. The weight (40 lbs.) and size (fig 3) of the air gun are both very appropriate for the sled design.

SOURCE CHOICE

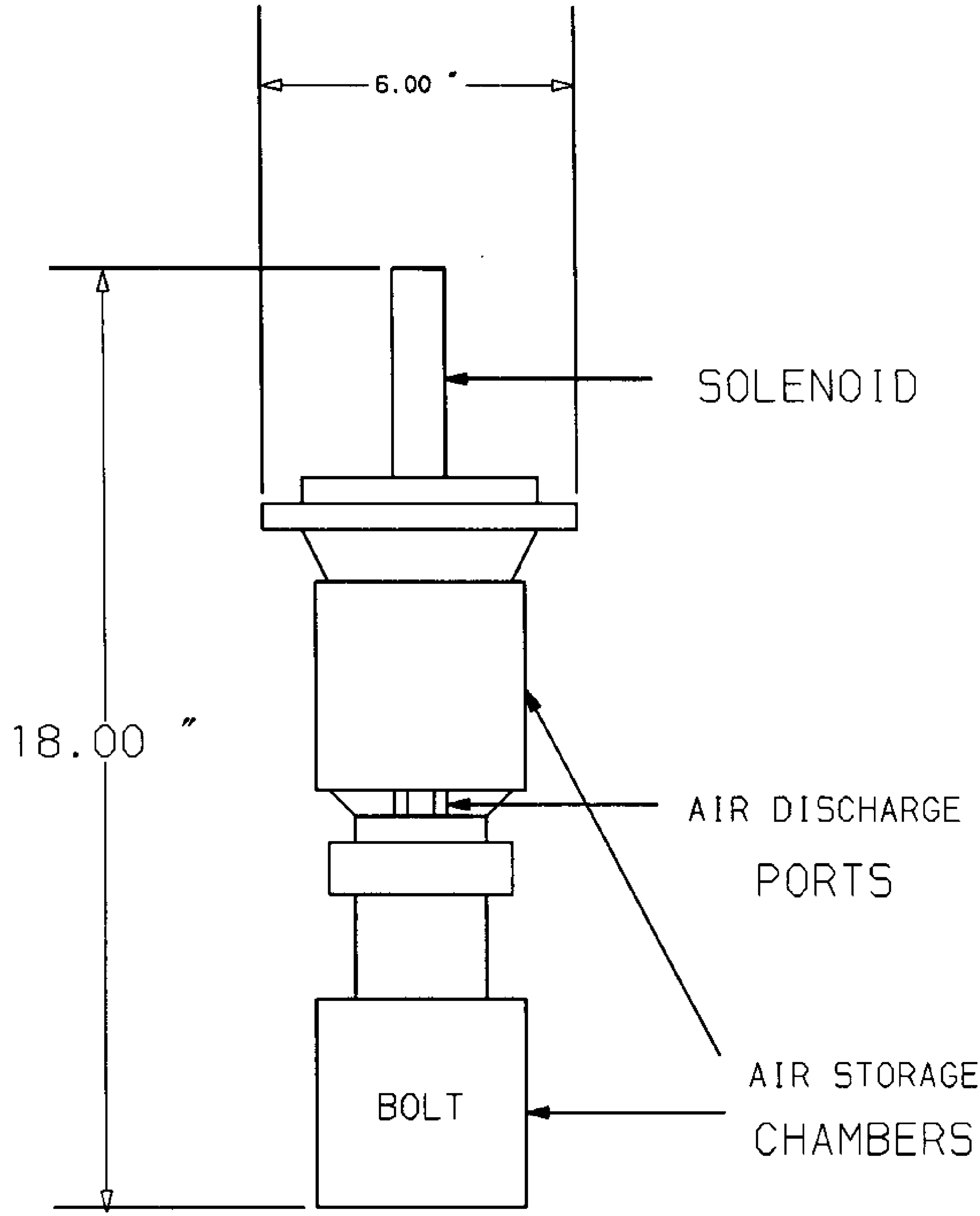
After careful consideration of the three possible sources, the air gun was chosen for this project. This choice was based on the following:

- the air gun's high marks on all the major design criteria
- the knowledge that air guns have been used successfully in similar applications
- the pendulum system was questionable on sufficient power, repeatability, and size and weight considerations
- the electromagnet system was questionable on sufficient power and weight considerations

AIR GUN HOUSING AND MOUNTING DESIGN

INTRODUCTION

After the source selection process was completed, the design of the air gun housing and mounts was begun. What follows is a step-by-step description of the design process.



AIR GUN

FIG. 3

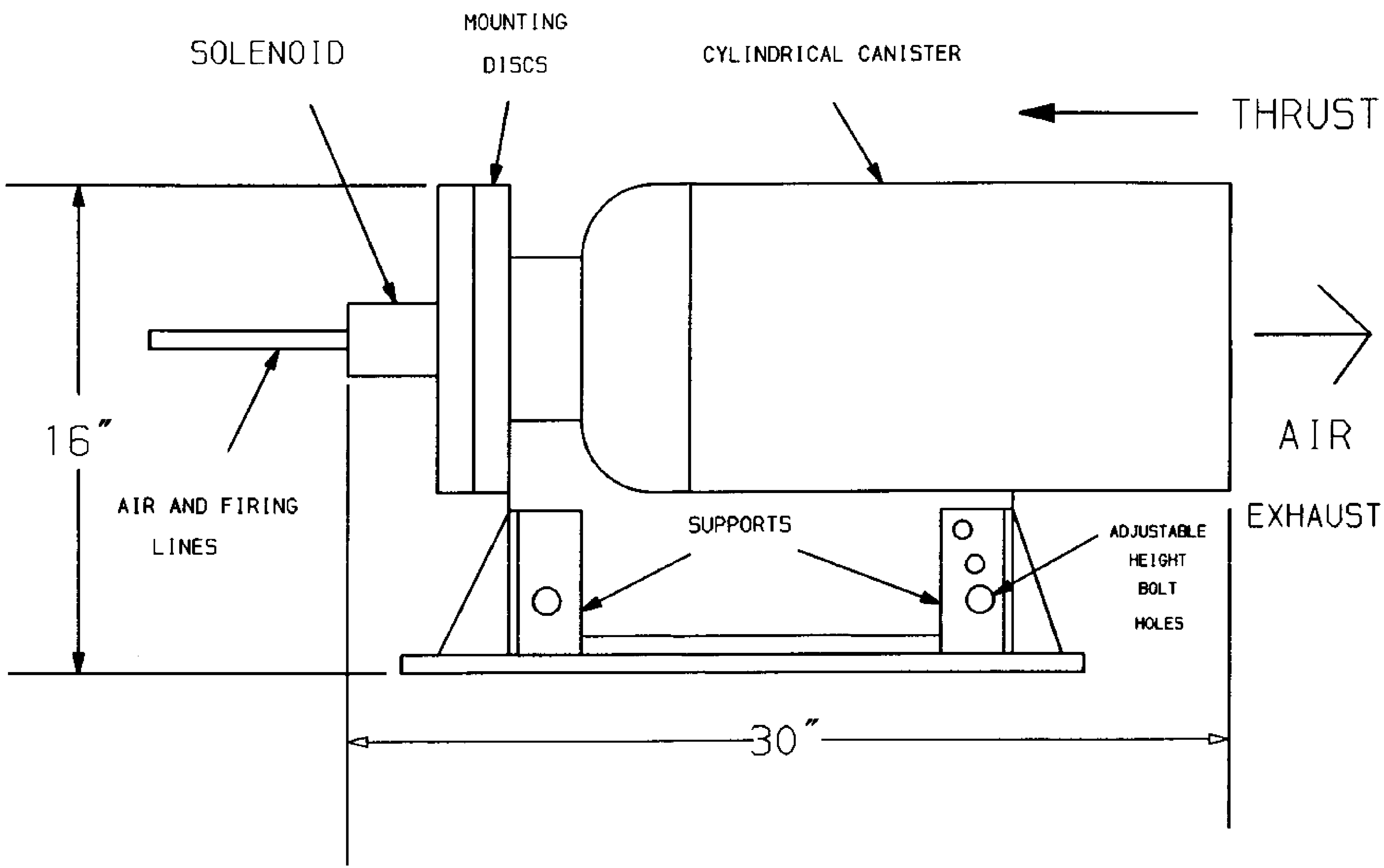
1:2

AIR GUN HOUSING

The goal of the airgun housing is to redirect the multi-vented high pressure air blast into one axially directed impulsive thrust. This is done by securing the air gun inside of an open-ended canister where the air exiting the discharge ports is redirected down the canister and out the open end (fig. 4). The canister is made from welding a 20 inch long cylinder to an end cap with a 4-5/16 inch diameter hole through it's center for the air gun insertion. Both pieces are 1/4 inch thick, 8 inch I.D., 6061 aluminum. The gun is clamped into the canister using eight 1/2 inch-13 bolts 3 inches long. The analysis of the cylinder and bolts strengths is in Appendix B.

AIR GUN MOUNTING

The goal of the air gun mounting is to securely fasten the air gun housing to the sled while allowing the thrust's angle of inclination to vary between zero and fifteen degrees above the horizontal. The mounting should also allow the gun to be rotated and fastened in 90 degree increments on the sled. The mounting system is fabricated by welding a variable inclination vertical plate to the underside of the air gun housing. This 1/2 inch aluminum plate is supported by four sections of angle aluminum, each of which is welded to a horizontal mounting plate (fig. 4). The housing is rotated by rotating this horizontal plate. The vertical plate is secured to the supports using two 5/8 inch-13 bolts 3 inches long, the horizontal plate using nine 1/2 inch-13 bolts 1 inch long. All the bolts are hardened stainless steel. The angle of canister inclination is varied by setting the forward support bolt to a different insertion point. The force calculations, weld and bolt strengths appear in Appendix B.



AIR GUN HOUSING

FIG. 4

IV. COUPLING

The major design criteria of the sled runners was to be sure they would couple to the ocean bottom to transfer airgun impulses. Coupling has been addressed as the major design concern by both WHOI and the University of Kiel (Ref. Neidell). Accurate results and repeatability of tests requires good coupling since movement of the sled during firing would fail soils in the area and distort the data received. Recognizing the significance of coupling, the sled was used as a test bed. Two pairs of runners have been designed.

Both WHOI and the University of Kiel fired transversely. The present sled system, as mentioned, has the capability of firing transversely and axially. One pair of the two runners was axially designed and one was transversely designed.

The width of all the runners was determined by the bearing capacity equation, to be 0.81 inches for sand and 4.4 inches for siltier sediments (Appendix c). Siltier sediments would be the worst case so both pairs of runners were made to be 4.4 inches wide.

Axial Design

To enhance coupling for the skiis three teeth were welded to the to the bottom of each runner. When firing axially the runners are positioned along the x-axis, with the flat sides of the blades facing the negative x direction. The open end of the air gun chamber faces the positive x-axis. The main criteria of the teeth was that failure zones created by each tooth should not overlap. Overlapping of the failure zones would mean only the first teeth on the skiis would be effective upon firing an impulse. The other teeth would be reacting against a soil with very little bearing capacity. The teeth were placed five times the length of themselves (tooth is 3 inches) away from the others (Lambe/Whitman, pg. 105) The runners, being 54 inches long, allowed three teeth per runner.

The angle behind the straight edge of the teeth, γ, was to be at least 45 degrees since any angle smaller would only produce the same failure pattern by laws of soil mechanics. Typically γ is $45 + \phi/2$ where ϕ is the friction angle. Choosing a table value of 26 degrees for ϕ, since testing was for uniform fine to medium sand, γ equalled 58 degrees (Lambe/Whitman, pg. 149)

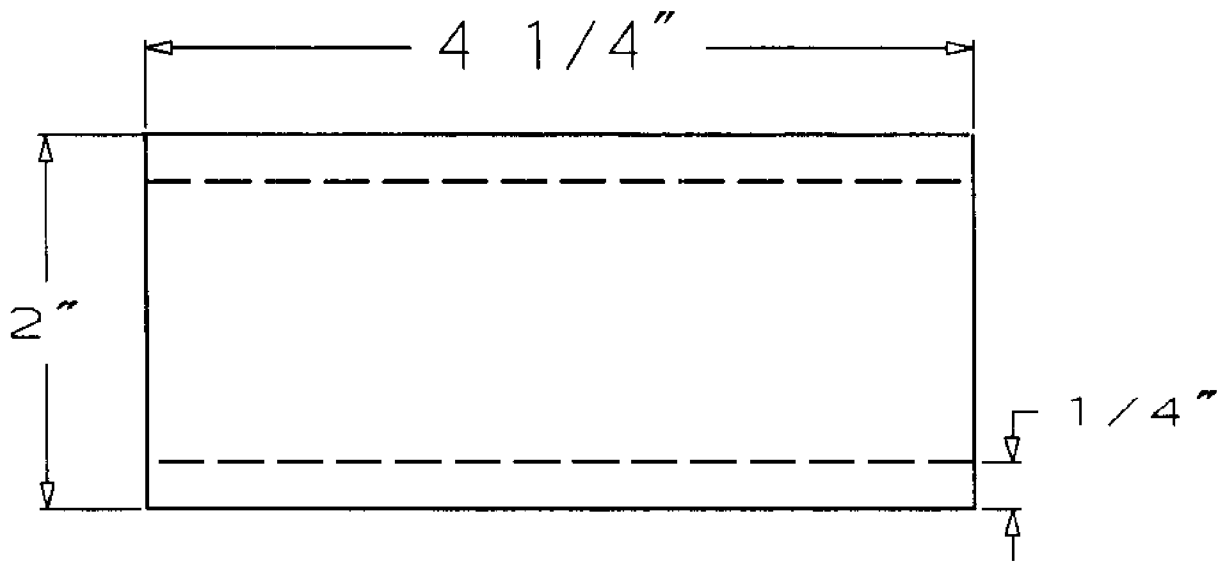
Knowing the length of each tooth to be 3 inches and to be 58 degrees, the depth of each tooth was determined to be 1.87 inches. To simplify fabrication depth was rounded to 2 inches (fig. 5)

Axial Fabrication

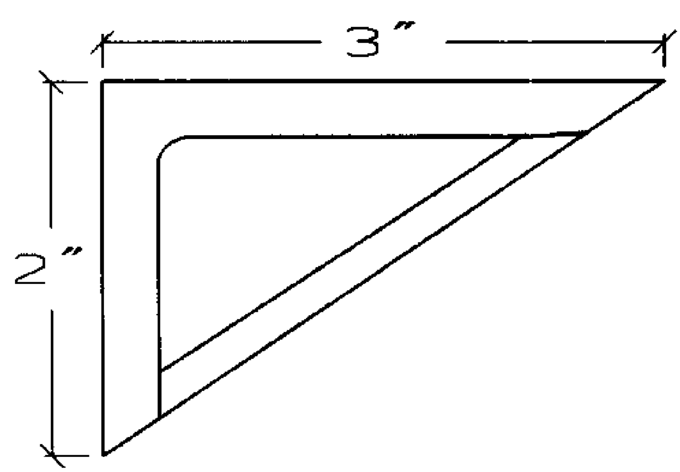
All the material of the skiis is aluminum 6061 except for the 1 inch, 1/8inch diameter stainless steel screws with which the skiis are attatched to the sled bottom. Zincs have been attatched to the sled body to prevent anodic reactions.

All six teeth, three for each ski, were cut from 3 inch by 4 inch web aluminum angle. A support plate was welded to the back side of each tooth and the teeth were welded to the runners (fig. 6).

AXIAL TEETH



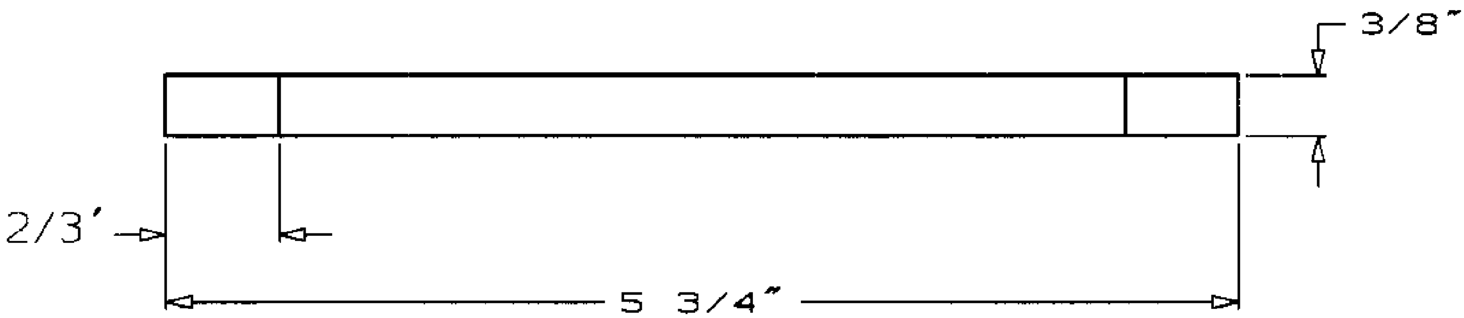
FRONT VIEW



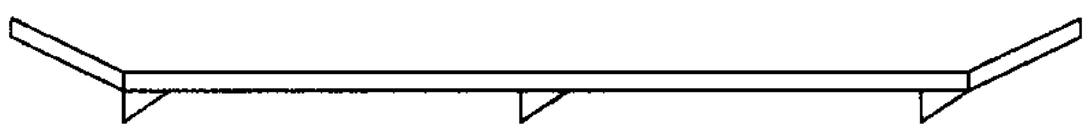
SIDE VIEW

FIG. 5

AXIAL SKI



TOP VIEW



SIDE VIEW

FIG. 6

The runners are easy to remove and attach leaving versatility to try other designs.

Runner Fabriction

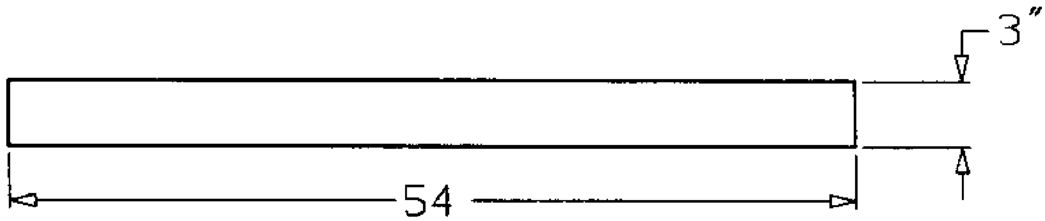
The runners are also aluminum. They are 54 inches long with 8 inch upturned ends for easy towing.

Transverse Fabrication

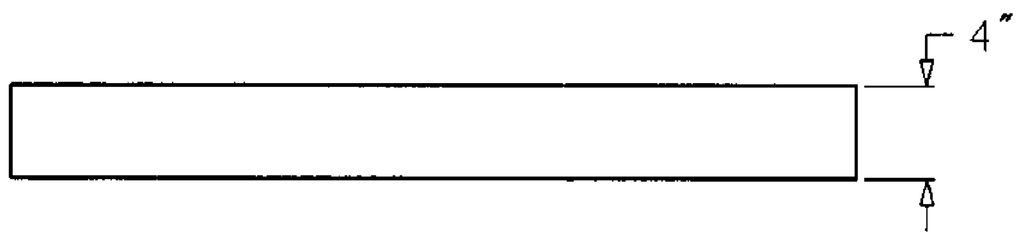
There are numerous possibilities for runners in the transverse position since failure zones are adequately seperated. When firing transversely the runners, which have no teeth, are positioned along the x-axis but the opening of the air gun chamber will face the positive or negative y direction. Our design for transverse runners consisted of a 3 inch width, a 4 inch depth and a 54 inch length(Fig.7). For more versatility these runners were adapted so that they could be removed, flipped over and reattached, so the adapted transverse runners would have a depth of 3 inches, and a width of 4 inches.

Transverse fabrication: A 54 inch piece of 3 inch by 4 inch web aluminum was cut from stock and a supportive plate was welded onto the back. The supportive plate has 3 ovals cut from it at the location of the screws (2 screws at each location) for easy removal and attachment of the runners with a screwdriver. The runners are mounted on the sled with the flat sides facing each other. This mounting design allows the sled to be towed straight and more importantly entraps the soils between the straight edges for further system stability when the airgun is fired.

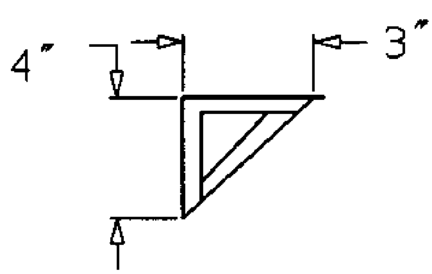
TRANSVERSE RUNNER



TOP VIEW



FRONT VIEW



SIDE VIEW

FIG. 7

V. Experimental Considerations

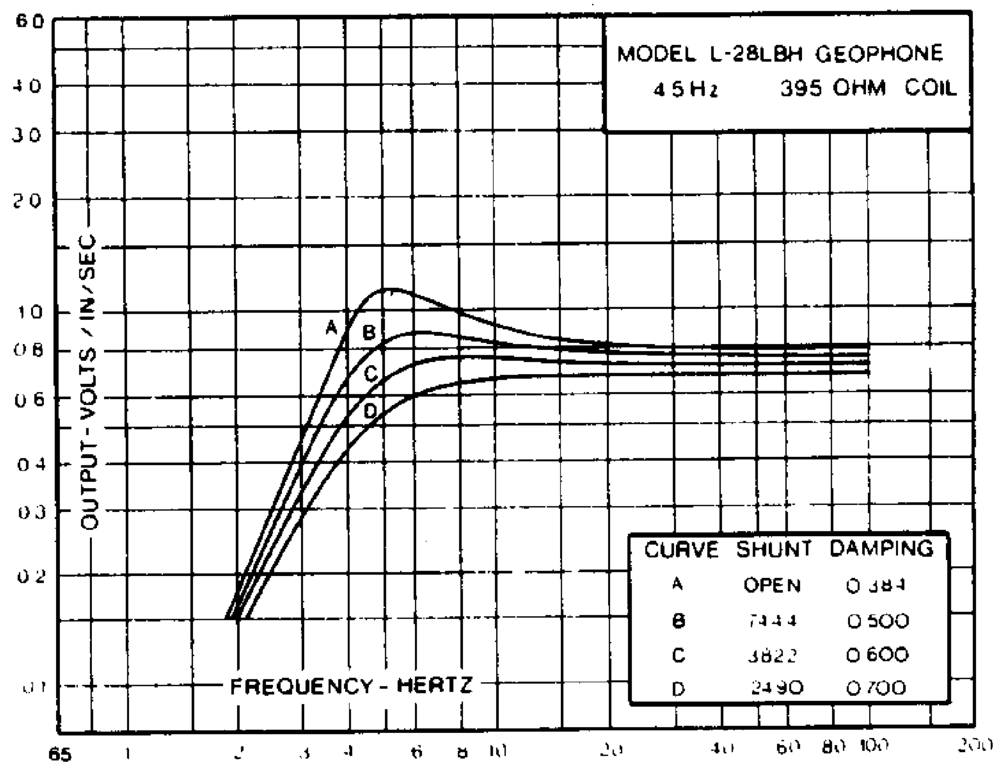
Introduction

Once waveforms are propagated, a system is necessary for receiving, transferring, and storing them, so that future analysis of the data can be achieved. The following section describes the type of equipment used to achieve this, an actual set-up of the equipment used in the field, and the experimental procedure used to obtain results.

Geophone Selection

Signal reception is achieved by using a pair of 3-axis geophones. The 3-axis geophone system consists of one vertical coil and two horizontal coils, one which is axially oriented and one which is transversely oriented. The particular units chosen were Mark Products' L-28LBH and L-28LB geophones. (Appendix D) These devices have a resonant frequency of 4.5 Hz and a coil resistance of 395 ohms. An additonal resistance was added to produce a 7.0 percent damping in each of the coils (fig. 8). The L-28 geophone is particularly good for shear wave studies due to its frequency range and very low distortion.

The L-28 geophones are incorporated in Mark Products' TDC-II land case (Appendix D). These cases are sealed water-tight to 50 psi by using "o" ring seals. The land case includes a replaceable level bubble and a trangular spiked pattern. These help to provide accurate orientation and good coupling to the ground.



MODEL L-28LBH GEOPHONE
4.5 Hz 395 OHM COIL
OUTPUT - VOLTS / IN/SEC
FREQUENCY - HERTZ
CURVE SHUNT DAMPING
A OPEN 0.384
B 7444 0.500
C 3822 0.600
D 2490 0.700

Fig. 8

Reception System

Once a signal is received by the geophone, the information is transmitted to an amplifer/filtering system which adds up to 90 dB of gain and effectively suppresses the noise over the desired frequency range of 2 to 200 Hz. This signal is then sent to a Nicolet 3091 oscilloscope which monitors the signal and stores each shot. The scope's stored information is down-loaded to and Apple IIe computer via the RS-232 bus incorporated on the Nicolet scope. The computer processes the information using the software package Apple 31, designed specifically for use with the Nicolet oscilloscope and Apple IIe. Once transferred, the waveforms can be viewed on the monitor and stored on a floppy disk for future reference. Although the scope down-loads 4000 points per trace and the computer stores all of these in memory, only a rough trace can be viewed on the monitor because of it's resolution.

Field Logistics

In actual field testing procedures, the two 3-axis geophones are used in the following manner. Use figure 9 as a simple block diagram reference. The two geophones are oriented perpendicular to the source; one is a known distance away from the other, which is between itself and the source (fig.10). The transverse axis of the geophone is the one of primary interest for shear wave study. The other axis maybe monitored periodically for other wave information if desired. A hydrophone used as an external trigger for the oscilloscope. The hydrophone receives P-wave transmission, which occurs much faster than S-wave information, therefore making it a good triggering source. The

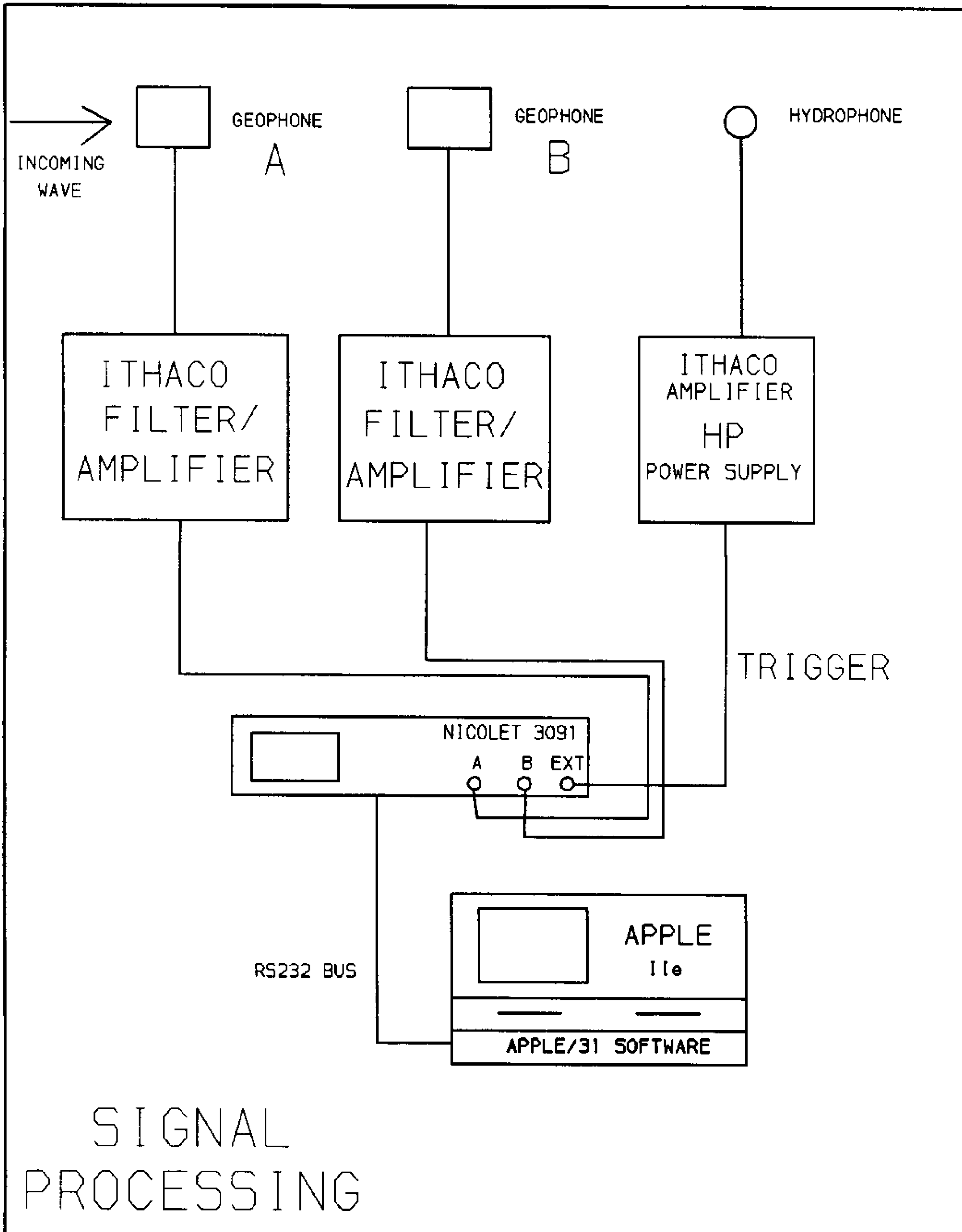

INCOMING WAVE
GEOPHONE A
GEOPHONE B
HYDROPHONE
ITHACO FILTER/ AMPLIFIER
ITHACO FILTER/ AMPLIFIER
ITHACO AMPLIFIER
HP POWER SUPPLY
TRIGGER
NICOLET 3091
A
B
EXT
RS232 BUS
APPLE IIe
APPLE/31 SOFTWARE
SIGNAL PROCESSING

FIG. 9

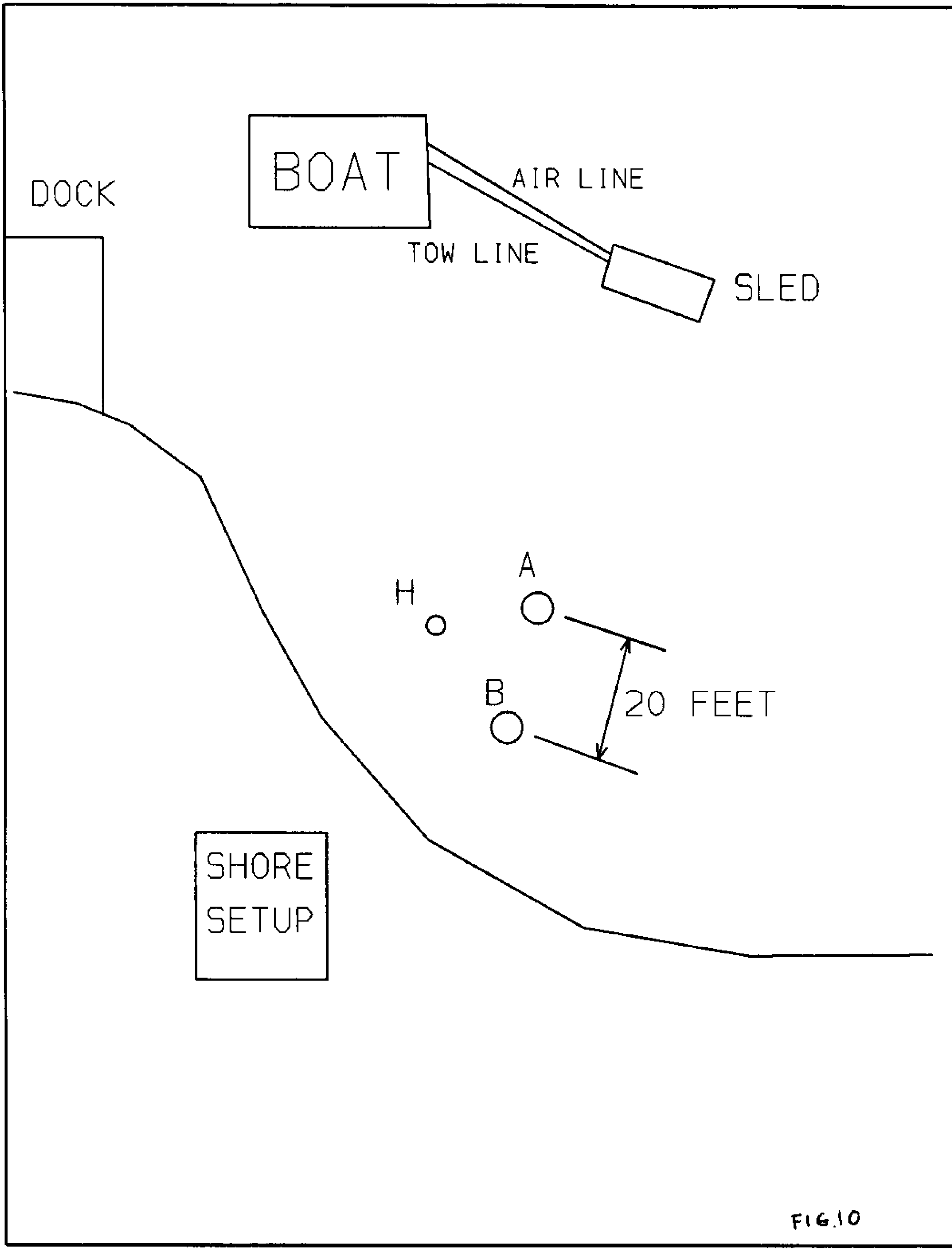


FIG.10

phones are connected to channels A and B of the scope after being amplified and filtered as previously described. The known distance sets up a time differential between the reception at the first coil and the reception at the second coil. These two known values help to obtain a velocity measurement for the incoming waves. By using the simple equation: velocity = distance travelled/time differential, a result for velocity is obtained. From this equation, the velocities of corresponding pulses received at the two phones can be measured and this information can determine whether or not shear wave information has been received.

Experimental Procedure

A three phase testing procedure, which consists of a test on dry land, a test at the Jackson Estuarine Laboratory, and a test at Wallis Sands State Beach was originally planned. The dry land test was never fully achieved using the entire system. This is because an air gun is a potentially dangerous tool which must never be "dry" fired. It should always be submerged in water before testing and therefore was not fired until the 2nd stage of the testing program.

The stage 1 dry land test was reduced to planting the geophone systems in the ground and using one to trigger the other on the scope. It was at this point that the necessity of more amplification and filtering than the Nicolet scope provides became apparent. A wooden beam was pounded into the ground near the trigger phone and hit repeatedly with a metal pipe. This produced compressional waves which were easily picked up by the geophones. The trace on the scope was then easily downloaded to the computer with the aid of the software package.

The geophones, scopes, amplifiers, filters, computer, and software were all tested in the dry land test and were all found to be in satisfactory working order. The compressor system that was borrowed from Wood's Hole Oceanographic Institute was found to have a 230 volt, single phase motor which forced the installation of a waterproof housing and outlet, as well as a dual 20 amp circuit breaker on board the surface vessel, the Jere A. Chase before stage 2 testing could be attempted. The compressor also checked out alright before it was actually used for the experiment. The only unknowns left were the air gun's performance and the ability of the sled to produce the desired shear wave.

The stage 2 test, an overall system test at Jackson Lab, proved to be a very complicated and slow moving procedure. The compressor system, which weighs approximately 200 lbs. and the sled, which weighs approximately 175 lbs. had to be loaded aboard the Jere A. Chase. All the electrical and pneumatic connectors were included on a checklist, which was reviewed several times before leaving for the experiment site. The checklist included other important items, such as the air gun's solenoid firing box, various connectors, tag line for the sled, tools necessary for field adjustments and repairs, and all of the equipment mentioned in the previous test. Loading equipment on to the boat with the help of it's winch became second nature after the first outing.

The first outing proved uneventful due to a solenoid malfunction. Experience was gained in deploying and retrieving the source sled. The geophone system was set up on the banks of a small inlet near the lab. The tide rose above the phones and no malfunctions occured when the phones were submerged. The area proved to be noisy because of a nearby Air Force base which flies frequent, ground-shaking missions. The jets flying overhead allowed a quick test of the receiving system, which again displayed no problems. The reception system is sensitive enough, with the available amplification, to pick up a person's footsteps several feet away.

The second trip proved to be much more eventful because of a functioning solenoid and air gun. Some data was obtained, but it is thought that the sled source spent most of the time on it's back, thus rendering the data useless. In future experiments a diver will be employed to alleviate this problem. Further improvements must be made in reference to towing the source into a proper orientation with respect to the geophone system. The sled must remain upright to insure that the coupling mechanism is being employed. The source must also fire perpendicular to the geophone array for best shear wave information transfer to the receivers. Future experiments have been planned for stage 2 with high expectations of total project success. Records are being kept including source firing pressure, number of shots and stored waveforms on floppy disks.

Stage 3 of the testing procedure has been cancelled for now. Time, as a major consideration, forces the continuation of the stage 2 procedure until every detail can be worked out and adequate data can be aquired. It is also thought that Wallis Sands State Beach would prove to be a much more difficult place to conduct a controlled experiment due to the ambient noise. The pounding of the surf would almost certainly cause unnecessary noise in the received signals. There is a nearby road that is highly travelled and traffic movement may also cause a significant problem in reception due to the fact that traffic noise is in the lower part of the bandwidth of frequencies being observed and recorded. An early morning experiment may correct this problem, but poor lighting may add a new problem which is unnecessary.

Deploying the source in the ocean is an important step once stage 2 testing is complete. The availability of underwater video will aid in discovering if the coupling mechanisms work as well in actuality as they do on paper. Videos will be very important in observing if the source has a tendancy to try to flip over when the air gun is fired. The source should be able to couple itself to the ocean floor so that repeated shots may be observed, recorded, and studied. An upgraded receiving package will probably have to be assembled to achieve accurate readings from repeated shots on the ocean floor. The overall planned testing procedure has proven itself to be adequate to this date.

VI.Results and Conclusion

The primary objectives of this project have been met. The sled design met all structural and handling requirements. The source selection met all requirements that were proposed in the first semester. The sleds towing capabilities were also adequate for the testing purposes.

Due to time restrictions, only the axial coupling technique was tested. Limited data was collected due to memory down loading problems encountered during testing.

The data indicates that horizontally polarized shear waves were produced by the sled at low pressures. The waves appeared to have the typical shear velocity of a soft sediment. The velocity of the shear waves collected from SITT are about 50 m/s. Reports from the Journal of Geophysical Research, article "Elastic Properties of Marine Sediments" written by Edwin L. Hamilton in the January 10,1971 issue, measured shear waves of 50 m/s for deep-sea sediment and 90 m/s for bay mud. During testing, coupling appeared to have been most successful at low pressures. Failure of the soil occurred at higher pressures. This is an acceptable behavior due to the fact that an extremly soft soil was tested. This data was accumulated while using the axial skiis. This coupling technique is new and the data indicates that shear waves can be produced using this technique.

This project needs some fine tuning and modifications need to take place to further improve the useability and versatility of the sled. The following steps should be considered to accomplish this:

1) Annodize sled to prevent long range corrosion

2) Install "troica" (roll cage) on sled to ensure upright sled position
3) Gather data with existing transverse runners
4) Pursue further axial coupling techniques
5) Use thicker gun mounting plate (suggest 1/2")
6) Use a fastening technique stronger than tie-wraps.

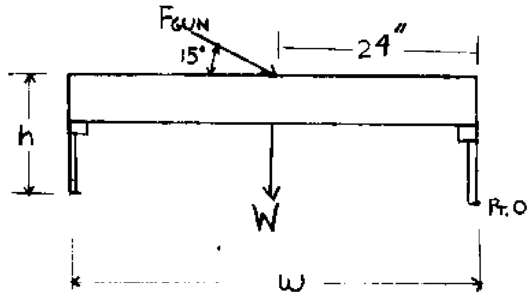
APPENDIX A

Calculations for Sled Design section

SLED STABILITY CALCULATIONS

Calculate width (w) of sled to ensure no tipping by summing the moments about the point of rotation.

Transverse case: rotation point (point o) is at the edge of the runners.



Approximate Sled Weight W=250 lbs

At 1000 psi, Fgun = 2616 lbs

Height h = runner height + frame height + the height of two mounting blocks
= 4 inches + 3 inches + 2(1 inch)
= 9 inches

For equilibrium: $\Sigma M = 0$

$$\Sigma M_o = 0 = 2616[\cos(15^\circ)](9) - 250(w/2) - 2616[\sin(15^\circ)](w/2)$$

therefore, w/2 = 24.5 inches

so sled width w = 49.0"

Assumption: No soil penetration
therefore width can equal 49".

Calculate the maximum pressure at smaller angles (7.5° and 0°).

at 7.5 degrees,

$$\Sigma M = 0 = F_{gun}[\cos(7.5^\circ)](9") - 250(48"/2) - F_{gun}[\sin(7.5^\circ)](48"/2)$$

Fgun = 1036 lbs

at 1036 lbs the gun pressure = 396 psi

Similarly at 0 degrees,

Fgun = 666.7 lbs

at 666.7 lbs, gun pressure = 255 psi

As described in report, there are several factors of safety in this calculation approach.

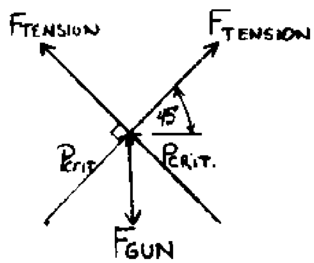
STATIC CROSS-MEMBER ANALYSIS

Failure Criteria (see Reference by Crandall)

$$P_{critical} = CEI/L^2$$

where

P = critical axial member force at onset of failure
E = Young's Modulus
I = Moment of Inertia
L = Length of member
C = Constant dependent on end fastening technique



Method of joints at sled center point

$$\Sigma Fy = 0$$

$$Fgun(horiz) - 4Pcrit(\sin(45^\circ)) = 0$$

with a factor of safety Fgun(horiz) = 5232 lbs (force at pressure = 2000 psi)

therefore Pcrit = 1849.8 lbs

Calculate moment of inertia (I) $Irect = bh^3/12$

$$I = [(2)(3)^3 - (1.75)(2.75)^3]/12 = 1.467 \text{ in}^4$$

Calculate length of member most likely to fail (ie. compression member)

$$L = (24 + 24)^{1/2} = 33.9 \text{ inches}$$

Youngs modulus for aluminum (6061) = 10×10 lb/in^2

C for clamped-clamped members = 20.2

$$1849.8 = 20.2(10\times10^6)(1.467)/(33.9)^2$$
$$= 257,234.4$$

F.S. = 139.1

therefore, members are structurally sound.

DEFLECTION OF CENTER CROSS-MEMBER DUE TO VERTICAL FORCE COMPONENT

Deflection formula for horizontal beam (see Reference #2)

$$Ymax = PB(L^2 - B^2)^{3/2} / [(9)(3)^{1/2}(L)(E)(Iy)$$

where

P = Fgun(vert) = 2616(sin(15)) = 677.1 lbs
L = length of beam = (48 + 48) = 67.88 in.
B = dist. to force from end of beam = L/2 = 33.94 in.
E = Youngs modulus for aluminum(6061) = 10 x 10 psi
I = moment of inertia

Calculate moment of inertia

$$Iy = hb^3/12$$

$$Iy = [(3)(2)^3 - (2.75)(1.75)^3]/12$$
$$= .7718 \text{ in}^4$$

Plugging all variable values into Ymax deflection formula

Ymax = .5716 inches

Conclusion: This is an acceptable value due to the fact that this calculation is for one separate cross-member. In the sled design, there are two cross-members welded at the point of maximum deflection. Also the calculation above is for a beam with free ends, the sled's center members are fixed on both ends. So the actual deflection would be considerably less than .5716 inches.

WEIGHT APPROXIMATION OF SLED STRUCTURE ONLY

WEIGHT = (DENSITY) (VOLUME)

VOLUME = (Area of Cross section) (Length)

Calculate Rectangular cross sectional area

Arect = (2) (3) - (1.75) (2.75) = 1.1875 in^2
Acirc = ( ) [(1) - (.75)] = 1.374 in^2

Density of aluminum = .0975 lbs/in^3

CALCULATE ALL COMPONENT VOLUMES

Rectangular tubing components

Two 68 inch long cross-members
vol 1 = (2) (68) (Arect) = 161.5 in^3

Four 48 inch long base frame perimeter members
vol 2 = (4) (48) (Arect) = 228 in^3

Four 30.7 inch long tow supports
vol 3 = (4) (30.7) (Arect) = 145.8 in^3

Circular tubing components

Two 48 inch long side railsA
vol 4 = (2) (48) (Acirc) = 131.9 in^3

Two arcs (bow and stern) triangular approximation (length=40.25")
vol 5 = (2) (2) (40.25) (Acirc) = 221.2 in^3

Four 11.1 inch long side supports
vol 6 = (4) (11.1) (Acirc) = 61.0 in^3

Four 15 inch long front supports
vol 7 = (4) (15) (Acirc) = 82.44 in^3

Total Volume = vol 1 + vol 2 + vol 3 + ...
= 1031.84 in^3

Weight = (total volume) (density of aluminum)
= (1031.84) (0.0975) = 100.6 lbs

Total Weight = Weight + Shroud weight

Shroud weight approximately = 15 lbs

TOTAL WEIGHT = 100.6 + 15 = 115.6 lbs

Note: This weight does not include any additional weight due to the coupling devices or the source design.

APPENDIX B

Calculations for Source selection section

$V_d = \pi r_d^2 h_d$ where $r_d = 4$ in $h_d = 20$ in

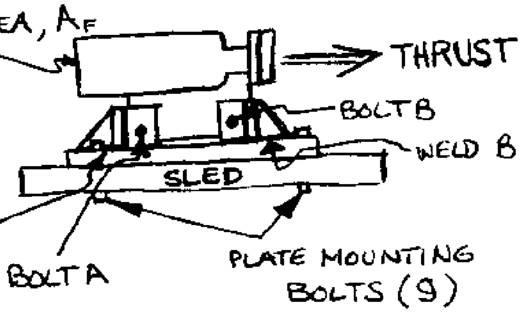
$V_d = 1005.3\,in^3$ $r_a = 2.5$ in $h_A = 12$ in

$V_A = \pi r_A^2 h_A = 235.6\,in^3$

$V_c = V_d - V_A = 770\,in^3$

$A_F = \pi r_F^2 = 50.3\,in^3$

where, $r_F = 4$ in



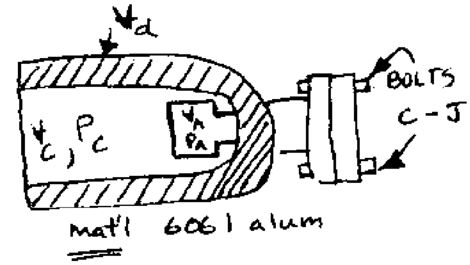
ideal gas law $P_{AIRCHAMBER} V_{AC} = V_c P_c$

worst case $P_c = P_{AC} \dfrac{V_{AC}}{V_c} = 103.90$ psi where $P_{AC} = 2000\,in^3$

$V_{AC} = 40\,in^3$

$V_c = 770\,in^3$

Thrust$_{max} = P_c A_F = 5226$ lbs



cylinder wall analysis

$r_i/t = 16$ (use thick-walled analysis)

$r_i = 4$ in $P_i = P_c = 103.9$ psi

$r_o = 4.25$ in $P_o = 28$ psi (2 atm)

$t = r_o - r_i = .25$ in

because $\sigma_t > \sigma_r$, σ_t calculation needed only

$$\sigma_t = \frac{P_i r_i^2 - P_o r_o^2 - r_i^2 r_o^2 \left(\frac{P_o - P_i}{r_i} \right)}{r_o^2 - r_i^2} = 4.975 \text{ kpsi} \quad (\ll S_y)$$

bolts A & B analysis (hardened stainless steel bolts)

$F_A = F_B = \text{Thrust}_{max}/2 = 2613$ lb/bolt

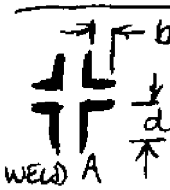
$A_{t(5/8'' bolt)} = .226\,in^2$ (shear) $V = F_A/A_t = 11.561$ kpsi $(\ll S_{sy})$

mounting plate bolts (9 bolts) (hardened stainless steel)

$F_{bolt} = \text{Thrust}_{max}/9 = 580.7$ lb/bolt

$A_t = .1419\,in^2$ $V = F_b/A_t = 4.092$ kpsi $(\ll S_{sy})$

WELD ANALYSIS (WELDS A & B)



h = .25" weld

$A_{WELD\,A\&B} = 2\left[1.414(h)(b+d)\right]$

$A_{WELD\,A\&B} = 3.1815\,in^2$

$V/A = 5226/3.1815 = 1.643$ kpsi $(\ll S_y)$

APPENDIX C

Calculations for Coupling section

Appendix C

Bearing Capacity (Δqs),

$$\Delta qs = NcSu + \gamma td$$

where Nc = the bearing capacity
Su = undrained shear strength
γt = total unit weight of soil
d = depth of footing base, assumed zero for approximations

Calculate Nc:

$$Nc = 5(1 + 0.2B/L)$$

where B = width, unknown
L = length, 54 in.

Application to sled

$$\Delta qs = W/A = W/BL$$

where W = weight of sled, approx. 250 lbs

Values for Su were chosen:

Su = .008 kg/cm.= 16.385 lb/ft for lowest shear and
Su = .045 kg/cm = 92 lb/ft for highest shear

Equating the two equations for bearing capacity and solving the quadratic equation yeilds results of:

B = 4.4 inches for Su = 16.385 lb/ft

and B = 0.81 inches for Su = 92 lb/ft.

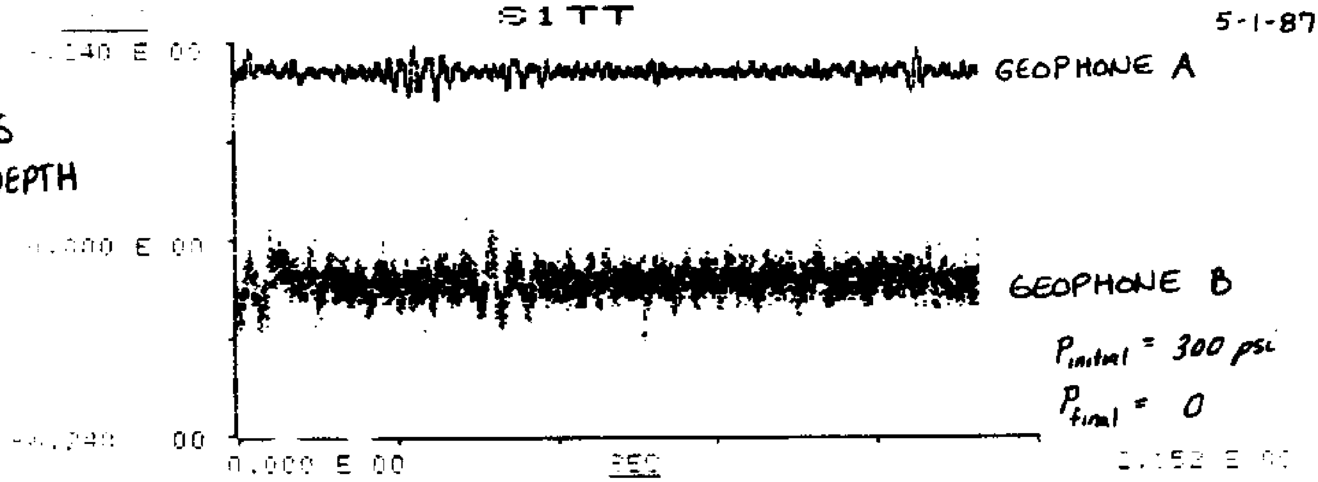
Since Su = 16.385 is the worst case the runner widths are 4.4 in..

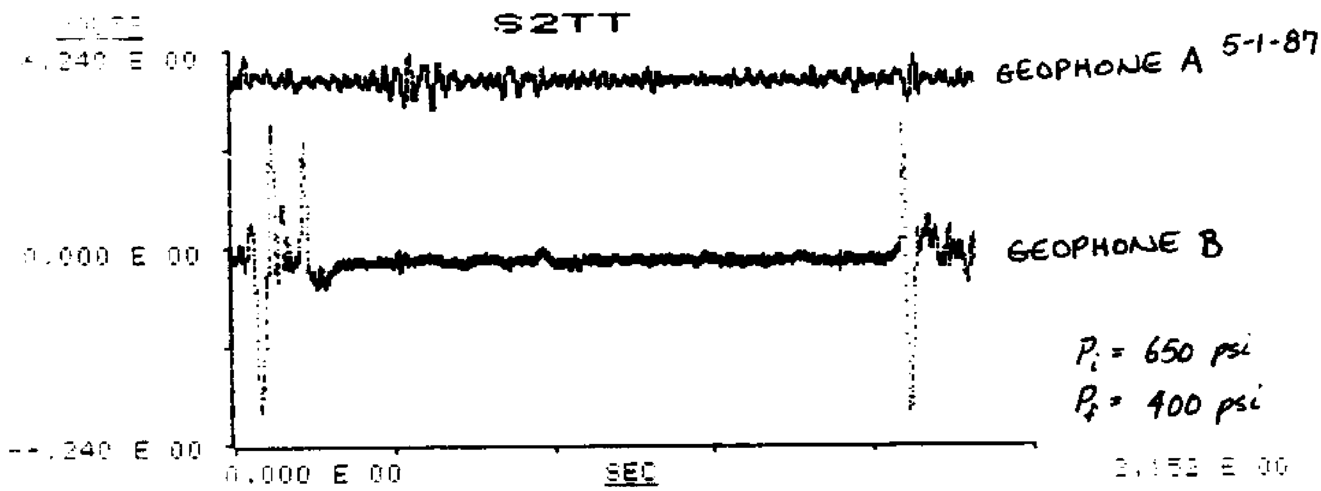
Reference: Soil Mechanics, Lambe/Whitman, p.486

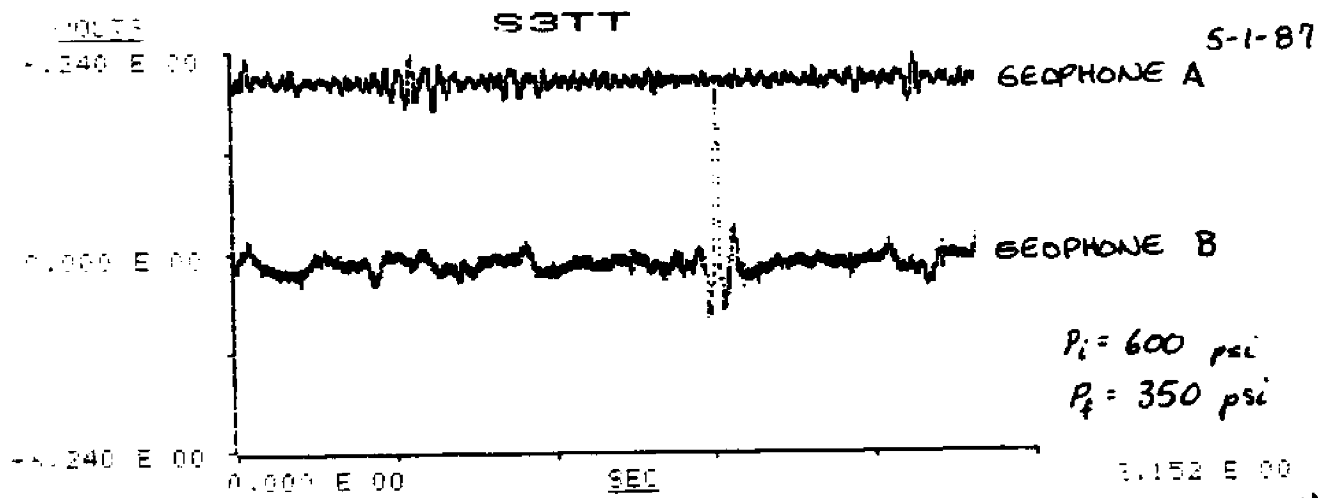
APPENDIX D

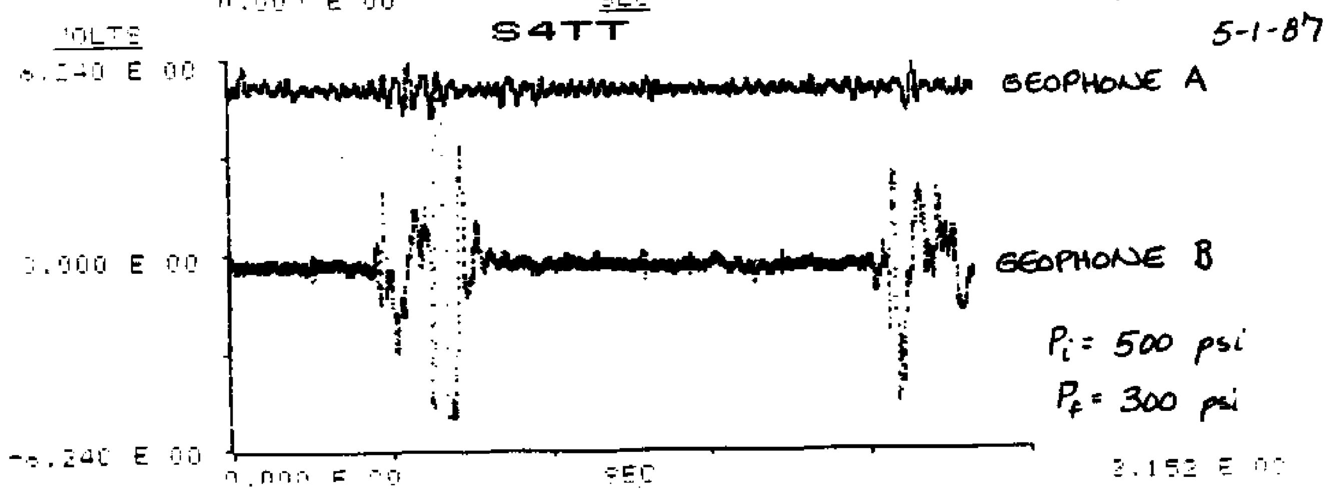
Experimental Information

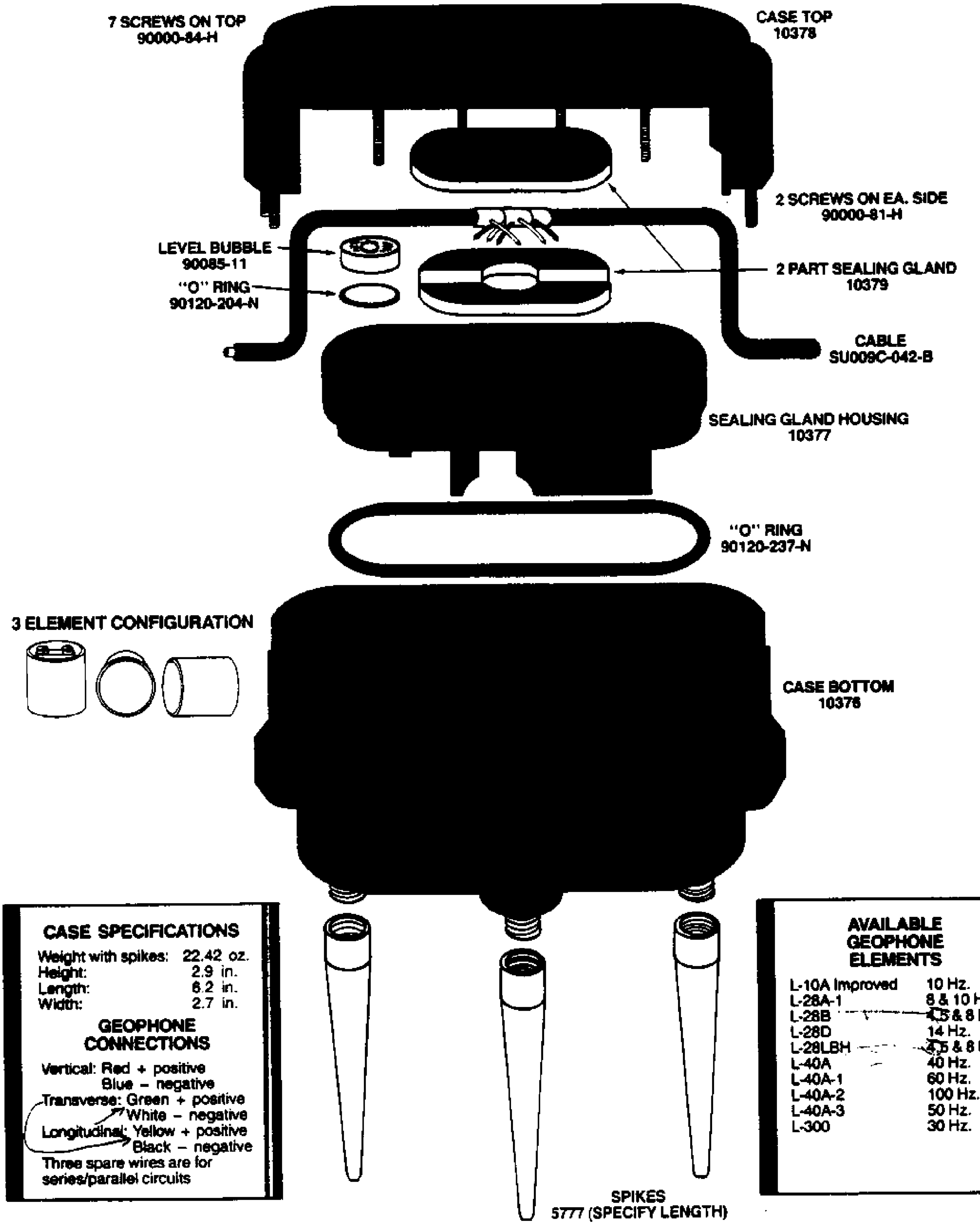
LL SHOTS
16 FT. DEPTH











CASE SPECIFICATIONS

Weight with spikes:	22.42 oz.
Height:	2.9 in.
Length:	6.2 in.
Width:	2.7 in.

GEOPHONE CONNECTIONS

Vertical: Red + positive
Blue − negative
Transverse: Green + positive
White − negative
Longitudinal: Yellow + positive
Black − negative
Three spare wires are for series/parallel circuits

AVAILABLE GEOPHONE ELEMENTS

L-10A Improved	10 Hz.
L-28A-1	8 & 10 Hz.
L-28B	4.5 & 8 Hz.
L-28D	14 Hz.
L-28LBH	4.5 & 8 Hz.
L-40A	40 Hz.
L-40A-1	60 Hz.
L-40A-2	100 Hz.
L-40A-3	50 Hz.
L-300	30 Hz.

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