AD-A099 110 DAMES AND MOORE LONDON (ENGLAND) F/G 14/2
A PROBE FOR IN-SITU MEASUREMENT OF DYNAMIC PORE PRESSURE.(U)
APR 81 R SIDEY F49620-79-C-0079

UNCLASSIFIED AFWL-TR-81-4 NL

1 of 1
AD
A099110

END
DATE
FILMED
6-81
DTIC

AFWL-TR-81-4

LEVEL III

AD-E200711

AFWL-TR-81-4

AD A099110

A PROBE FOR IN-SITU MEASUREMENT OF DYNAMIC PORE PRESSURE

Roger Sidey

Dames & Moore
123 Mortlake High Street
London SW14 8SN, United Kingdom

April 1981

Final Report

DTIC ELECTE MAY 19 1981 S D B

Approved for public release; distribution unlimited.

DTIC FILE COPY

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

81 5 04 136

This final report was prepared by Dames & Moore, London, United Kingdom, under Contract F49620-79-C-0079, Job Order ILIR7907 with the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico. Mr Joe V. Quintana (NTED) was the Laboratory Project Officer-in-Charge.

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Joe V. Quintana

JOE V. QUINTANA
Project Officer

FOR THE COMMANDER

T. D. McCarson Jr.

T. D. MCCARSON, JR
Lt Colonel, USAF
Chief, Simulation Branch

John C. Galloway

JOHN C. GALLOWAY
Lt Colonel, USAF
Chief, Civ Engineering Rsch Division

DO NOT RETURN THIS COPY. RETAIN OR DESTROY.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWL-TR-81-4	2. GOVT ACCESSION NO. AD-A099 110	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A PROBE FOR IN-SITU MEASUREMENT OF DYNAMIC PORE PRESSURE		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Roger Sidey		8. CONTRACT OR GRANT NUMBER(s) F49620-79-C-0079
9. PERFORMING ORGANIZATION NAME AND ADDRESS Dames & Moore 123 Mortlake High Street London SW14 8SN, United Kingdom		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61101F/ILIR7907
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Weapons Laboratory (NTED) Kirtland Air Force Base, New Mexico 87117		12. REPORT DATE April 1981
		13. NUMBER OF PAGES 78
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This research was funded by the Laboratory Director's Fund.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Piezometer
Pore Water Pressure
Blast Measurement
In-Situ

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report details work undertaken in the development of a new design of fast response piezometer. Intended for measurement of transient pore water pressures in soils; the device features a novel two-stage emplacement technique. The system is capable of achieving a responsive coupling with the interstitial fluid in the region of measurement, and can operate over a broad range of pressures encompassing those encountered in blast loading conditions.

DD FORM 1 JAN 73 1473

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

PREFACE

The author wishes to express his thanks to Dr. Richard H. Bassett of the Civil Engineering faculty of Kings College, London.

Within Dames & Moore thanks are due to Mr. Tony Abbs and Dr. David C. Andrews for management of the project, and to Miss Susie Backhouse, Miss Sylvia Nicholson, and Mrs. Sheila Cocking for their effort in the production of this report. Thanks are also due to Mr. David V. Hinds and Mr. David J. Rainford for assistance with the fieldwork and the laboratory testing.

Appreciation is expressed to the U.S. Air Force Weapons Laboratory for sponsoring, and to the Air Force Office of Scientific Research for administering the contract which enabled the research effort reported herein.

CONTENTS

CONTENTS (Cont'd)

I. INTRODUCTION

Despite significant advances in recent years towards understanding the behaviour of soils under dynamic or shock loading conditions, relatively little is known of the way in which transient pore water pressures affect the response of saturate soils. Much effort has been devoted to the development and refinement of instrumentation for measurement of stresses and motions in soils subjected to dynamic loading but, in contrast, there appears to be a marked absence of work in the area of transient pore water pressure measurement.

There are some difficult problems associated with measurement of the transient behaviour of pore water pressure, particularly when the disturbance is blast induced:

a. Blast or shock generated pressure pulses require a significantly faster responding instrument than that required in conventional piezometer applications.

b. Placement of the probe is critical; soil disturbance can significantly affect the measurement.

c. A large dynamic range of response is required since peak pressures at the start of the loading are typically very large compared to the pressures remaining behind the blast wave. Furthermore, peak amplitudes of blast induced pressures are often difficult to predict.

The distribution of dynamic pore pressure in a soil mass resulting from a disturbance or fluctuation is critically dependent upon local permeability. Disturbance or remoulding of the soil due to placement of instrumentation is therefore an important consideration. In a saturated soil the lumped effective bulk modulus (a critical factor affecting propagation velocity and attenuation of dynamic disturbances) is high. If, during placement, a piezometer introduces any voids of air, a massive local reduction of this parameter can be created. The effect of such a disturbance vanishes rapidly with increasing distance from the inclusion and invariably the total soil mass system will not realize the effect. However, the piezometer at the centre of the disturbed zone will register an unrepresentative dynamic pressure history.

From the above arguments it would be reasonable to conclude that the ideal measurement device would be as physically small as possible, equivalent to, or less than, the nominal grain size of the soil mass. Apart from the obvious problems in design and manufacture of such a device, it is difficult to imagine how it could be utilized for a practical in situ measurement. Furthermore, there would be the problem of isolating the sensor from effective stresses in the soil fabric. For a device so small these loads would be imposed highly irregularly from the surrounding soil grains. Clearly some form of compromise must be struck between the need to produce a physically small, fast response device, and the requirements for a rugged sensor capable of surviving emplacement and the subsequent operating conditions.

This report details the design and development of an instrument intended to approach the problem of dynamic pore pressure measurement. Known as the Dynamic Pore Pressure Probe, the device embodies a number of novel design features. Laboratory testing has demonstrated that the instrument is capable of a frequency response extending beyond 1 kHz, and the simplicity and inherent ruggedness of the sensor system allows the equipment to function over a very broad range of pressures.

II. PRINCIPLE OF OPERATION OF THE MEASUREMENT SYSTEM

The Dynamic Pore Pressure Probe utilizes a number of design features specifically incorporated to overcome the measurement problems discussed in the previous section.

a. The pressure sensing system is highly miniaturized by comparison with conventional geotechnical piezometers. The sensing element is physically small and has a high effective bulk modulus. Pressure from the surrounding pore water acts on the element via a special coupling medium which is used to pack the chamber containing the sensor.

b. The instrument is emplaced by pushing it into the ground. This method, used extensively in cone penetrometer site investigations, applies relatively high stresses to the probe and in order to protect the miniature pressure sensor, the system features a novel two-stage emplacement technique. The miniature sensor is contained within a larger more robust probe which is used as a vehicle to protect the sensor and deliver it to the selected measurement region. At the desired depth of placement a secondary probe containing the sensor is ejected into the soil. This secondary system is pushed into the undisturbed soil ahead of the larger probe.

c. During the initial phase of emplacement the miniature sensor is effectively contained within a sealed chamber in the larger probe. The system is not affected by the unsaturated soils while being transported to the measurement region and hence, air is not entrained and the pressure coupling medium is not lost. When the larger probe reaches the saturated soil of the measurement region and the miniature sensor is ejected, intimate coupling with interstitial fluids in the surrounding soil is achieved.

Placement of the instrument is depicted in Figure 1 in which it can be seen that outwardly the probe resembles a cone penetrometer. The probe is driven by means of a system of stout hollow rods. Being susceptible to buckling under the driving loads, the rods are relatively short and are arranged with threaded joints at each end. Connections to the probe are accommodated within the central hole in the rods and are led out at the top of the string by means of a specially slotted driving cap. The smaller

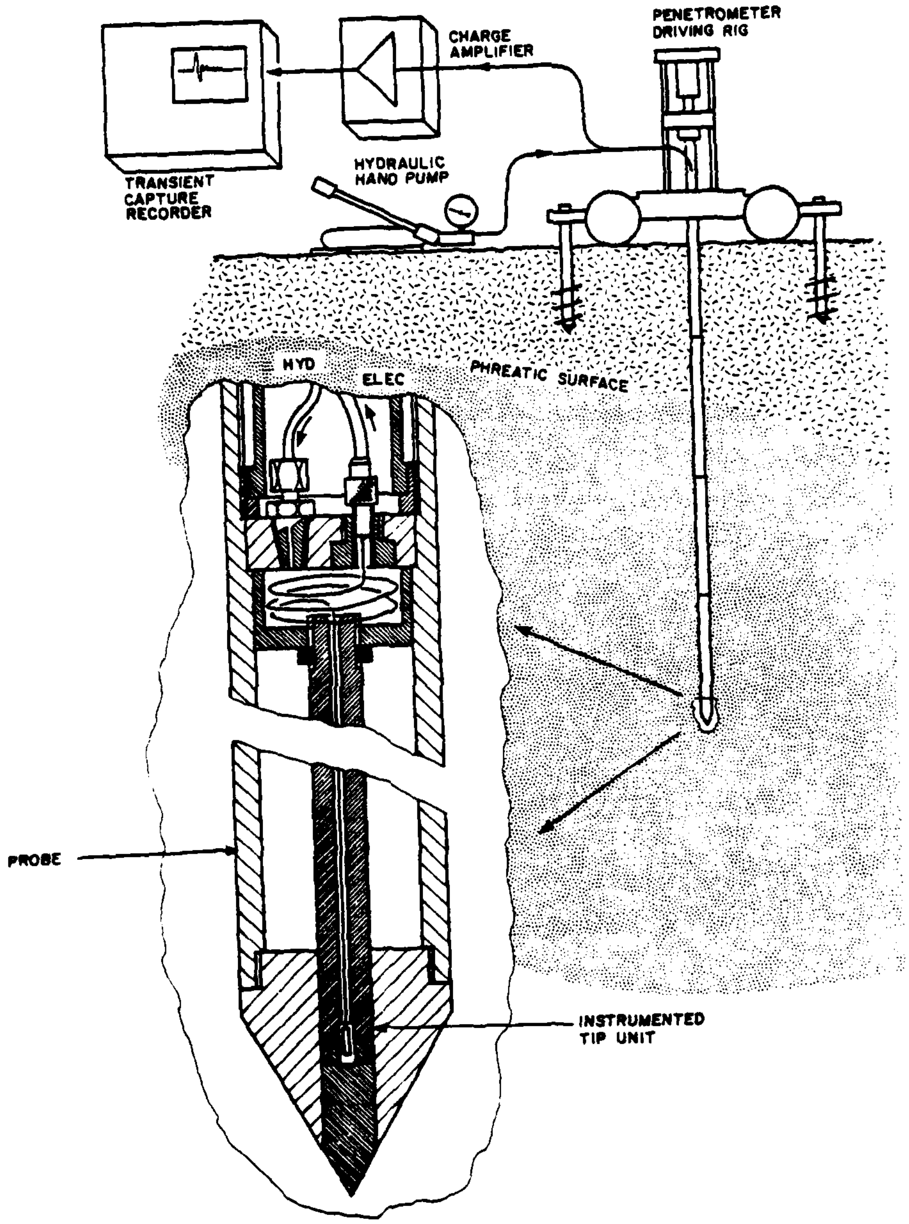


Figure 1. Pore Water Pressure Measurement System.

instrumented tip is hydraulically ejected from the larger probe, this being accomplished uphole by the use of a hand operated pump. By expelling air from the hydraulic system, a positive displacement action results and a controlled ejection of the instrumented unit can be achieved.

III. DESCRIPTION OF THE PROBE

3.1 THE INSTRUMENTED TIP UNIT

The heart of the probe is the miniature instrumented tip unit. This assembly houses the pressure sensing element and isolates it from effective (soil fabric) stresses. Both the method of isolating soil stress from the sensor and the configuration of the sensor element have been the subject of part of the research and development work on the Pore Pressure Probe, and these developments are discussed in the following sections. The final design of the unit is shown in Figure 2.

3.1.1 The Pressure Transducer

The sensing element thought to be best suited to the Pore Pressure Probe application is a piezoelectric ceramic. Acting as a pressure transducer, this material generates an electrical charge in response to applied pressure. Being highly stiff and possessing practically no damping, the transducer characteristics of the basic material are highly linear and the range of pressures over which a usable signal can be achieved is extremely broad. A piezoelectric pressure transducer is self-generating, that is, the power in the output signal is derived from the mechanical input to the sensor. No electrical energization is required and hence, the number of connections to the sensor is correspondingly minimal. The drawback to this type of sensor, however, is the lack of static response. The charge generated by a given pressure charge ultimately will be drained away by electrical shunt resistance across the transducer. This results in a response with a limiting frequency below which the sensitivity of the sensor begins to fall off. Figure 3 illustrates the transducer action of the sensor element and shows an electrical equivalent circuit of the device.

Operating in the manner described here, the piezoelectric sensor is modelled as a voltage generator in series with a capacitor. The output of the voltage generator is proportional to the stress applied to the element and the capacitance is the physical value measured at the connections to the device.

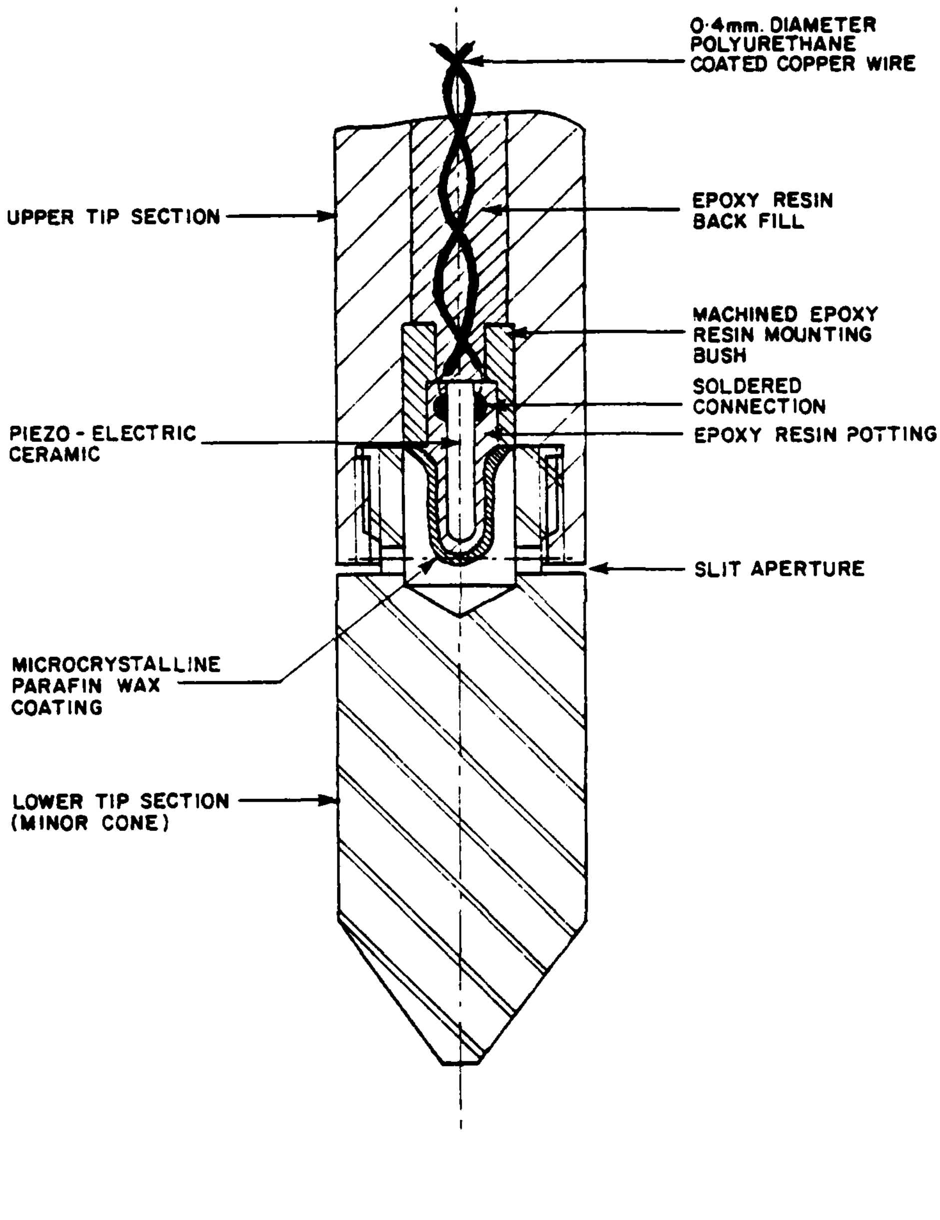


Figure 2. Enlarged Section View of the Instrumented Tip Unit.

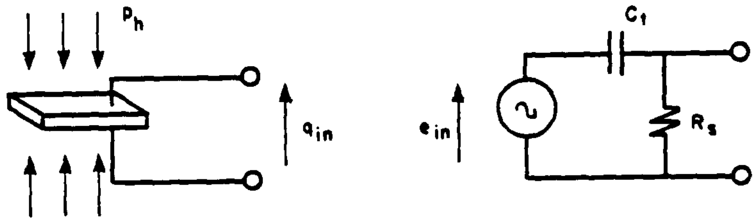


Figure 3, Schematic of the Transducer Action of the Piezoelectric Sensing Element.

There are basically two ways in which the signal from a source such as that shown in Figure 3 can be amplified to a useful level; voltage or charge amplification. With voltage amplification, the output from the sensor is fed via an interconnecting cable to the high impedance input of a buffer amplifier. The low frequency response is determined by the combined transducer and cable capacitance in parallel with the total effective resistance of the system. With this arrangement it is essential to maintain high insulation resistance in the circuit and to use a high input impedance amplifier. The low frequency response is fixed at this point in the system and cannot practically be improved beyond the value determined by these parameters. Another disadvantage of voltage amplification is the effect of cable capacitance. With an essentially capacitive source, the cable acts in combination with the source as a potential divider to attenuate the signal level. In these circumstances it is often found that mounting a head amplifier close to the signal source is a practical solution. This, however, requires that power supplies be led to the amplifier, that space be made available for it, and, perhaps most undesirable, that the sensitivity or full scale output of the system is fixed at this point. For the Pore Pressure Probe, this latter effect would seriously limit the experimental flexibility of the instrument.

The alternative method of charge amplification offers important advantages. With this technique, the source feeds directly into the summing junction of a high gain differential amplifier. With the amplifier connected in the inverting mode the summing junction appears virtually as a short circuit across the source. The effect of the amplifier is to balance the flow of current into the junction from the source, with an opposing current derived via a feedback network from its output. Under these conditions it is the charge (i.e., product of total effective source capacitance and the open circuit output voltage of the source) which is balanced. Additional shunt capacitance due to the cable reduces the output voltage of the source but, in the same proportion, increases the effective capacitance of the source. Thus, the charge entering the summing junction is the same, and the effect of cable capacitance is to a large extent eliminated. The amplifier balances the currents at the summing junction by developing a charge across the feedback capacitor which opposes the input charge. In this way the output voltage of the amplifier reproduces the charge signal from the source.

An additional advantage yielded by charge amplification is the ability to control the low frequency time constant and hence, the low frequency response of the measurement system. By cancelling the source output voltage the effect of shunt or leakage resistance in the circuit is considerably reduced. Providing that the amplifier can provide high gain at the frequency of interest (which is easily achieved for low frequencies), it can introduce a dominant pole in the response of the system which is almost entirely determined by the feedback components of the circuit. Hence, this vital parameter can be controlled and maintained constant at the point of amplification and, perhaps most important, can often appreciably be improved in cases where the intrinsic time constant of the source is relatively short. This is an important advantage since leakage resistance, the principle factor affecting the source time constant, is difficult to control and can vary considerably from item to item and with environmental factors such as temperature.

Naturally there are limits to the amount of shunt capacitance and leakage resistance for which compensation can practically be achieved. These limits are determined both by their relative values compared to those of the feedback components of the amplifier circuitry, and by the open loop gain of the amplifier. Appendix B gives a low frequency model of a measurement system using charge amplification. An analysis is given which incorporates the fundamental parameters determining low frequency response. The amplifier is realistically modelled, and the analysis defines the circumstances under which the time constant introduced by the feedback components of the circuit can be made to dominate the low frequency response of the measurement system.

In order to act as energy conversion devices, piezoelectric ceramics must possess a polarization or intrinsic orientation. This process is carried out at the manufacturing state and results in the element possessing a sensitive direction or axis, along which the stresses that are required to be measured must act. For the Pore Pressure Probe application, the element is required to sense a hydrostatic pressure function and hence, the first choice of configuration for the sensing element would reasonably be a radially symetric one. A radially polarized cylinder or ring would exhibit a uniform response to any given stress at right angles to its axis, and would yield an optimum sensitivity for sensing hydrostatically applied stress. This configuration was indeed the first choice for the Pore Pressure Probe sensor, but difficulties encountered in mounting the element and in implementing reliable electrical connection to it ultimately precluded its use. This has not resulted in a significant reduction in performance of the probe, however, since the alternative plane polarized configuration for the sensor element responds to hydrostatic pressures in exactly the same manner as the radially polarized device; the difference being a reduced transducer sensitivity. The lower sensitivity of the plane polarized, or plate configuration, is due principally to two effects:

a. a reduced area of aligned sensing surface exposed to the applied pressure;

b. the effect of the Poisson's ratio of the material where, under hydrostatic conditions, a portion of the stress acting normal to the sensitive axis effectively subtracts from the aligned stress.

The use of a plane polarized plate for the sensing element, by comparison with a radially polarized cylinder of similar nominal dimensions, results in a factor of approximately forty in the reduction of transducer sensitivity. This factor relates the measured sensitivity of a mounted plate to the calculated maximum sensitivity of a cylinder. In any practical design for the cylindrical configuration this factor would be considerably reduced by the effects of the mounting arrangement for the element. Even, however, assuming worst case values there is still ample sensitivity provided by the plate configuration. In the applications for which the probe is designed, i.e., blast induced pore pressure variations, the design maximum pressure is high. The corresponding signals from the sensing element are of high amplitude compared to the inherent electrical noise in the measurement system and can, therefore, tolerate a considerable amount of attenuation before the performance of the system is degraded.

Figure 2 shows the convenient and relatively simple mounting of the sensor element in the final design for the instrumented tip. A rectangular slither of ceramic is mounted by potting it into the upper tip section of the assembly. Leadwires are attached to the bulkhead end and approximately half of the slither protrudes into an open chamber, this portion being protected by a dip coating of epoxy resin. It is this protruding section which is used to sense pressure in the coupling medium. The relatively thin coat of epoxy resin, coupled with the extremely high stiffness of the ceramic, result in minimal attenuation of the pressure applied to the ceramic from the coupling medium. A relatively thin plate (width 2 mm, thickness 1 mm) was chosen for the ceramic with the direction of polarization being normal to the larger surface. This geometry minimizes the desensitizing effect due to Poisson's ratio, and provides the addition benefit of maximizing the electrical capacitance of the element.

3.1.2 Coupling Pore Water Pressure to the Sensing Element

Mention has been made in the foregoing sections of a pressure coupling medium. This is the phrase used to describe the medium which is required to fill the spaces in the pressure sensor cavity and the soil stress isolation filter. The medium must be fluid, or at least, have negligible shear strength and, in order to achieve a fast response for the system, it must be relatively incompressible. In the early stages of the Pore Pressure Probe development program water was chosen for the coupling medium. It was proposed to saturate the pressure sensor system prior to assembling it into the probe, and thereafter, to maintain it in that state by containing it within a sealed chamber in the larger probe. By this means, the sensor could be conveyed to the measurement location through the unsaturated soils without entraining any air. Once in the saturated soils, the instrumented unit could be ejected, at which point a highly responsive coupling between the surrounding pore water pressures and the pressure applied to the sensor element via the coupling medium would be achieved. Figure 4 shows an early design for the instrumented tip where the chamber containing the saturated sensor is formed by a pair of piston type O ring seals machined in the outside of the upper and lower sections of the unit. For this design it was proposed that the instrumented tip be saturated and de-aired in a partially filled and evacuated water tank, and that the assembly of the major cone of the larger probe and the instrumented tip be conducted underwater. Thereafter, the remaining assembly work for the probe would be done without breaking the seal of the water chamber.

This early design for the instrumented tip was found to suffer from a number of drawbacks. Apart from problems associated with mounting and sealing the sensor element, the proposed procedure for de-airing and saturating the assembly was found to be particularly difficult in practice. This led to a redesign for the assembly which involved changes both to the configuration of the sensing element, and, as discussed in the following section, to the design for the effective stress filter. Despite these changes, the principle of operation of the unit remained the same as that of the original design and, accordingly, there was the need for a coupling medium in the system. It was again first thought that water would be suitable and the unit was, as with the original design, arranged with an O ring sealed chamber to retain the coupling medium during emplacement of the larger probe. The problems with de-airing were overcome in the revised design by splitting the sensor chamber and introducing a circumferential slit type filter at the joint in the assembly. This allowed for the unit to be de-aired in the dismantled state where all recesses and surfaces of the sensor chamber and the effective stress filter were readily accessible. The slit for the effective stress filter is formed when the upper and lower section of the transducer housing are assembled. The dimension of the gap is controlled by the bottoming-out action of a threaded shoulder on the lower section. Stresses due to emplacement of the probe are transmitted through this shoulder, and the coupling medium acts through a number of radial holes in the feature.

During laboratory testing of the revised design of instrumented tip unit, it was noticed that the degree of contamination of the water surrounding the pressure sensor had an effect on the quiescent-state electrical noise in the system. Despite being coated with both epoxy resin and parafin wax to provide an impervious moisture barrier, the pressure sensor, in certain circumstances, was observed to generate a random pulse or popcorn type noise. This noise was found to be associated with contaminated water, and was particularly apparent when impurities from a pump used to pressurize the water in the testing were present. It was concluded that the noise was due to electrochemical activity in the fluid and that the high electrical impedance of the sensor was allowing an otherwise weak source of interference to become apparent. This led to some concern since it was felt that a similar situation could arise if the piezometer probe were used in regions where the groundwater was not sufficiently inert. A convenient solution to this problem was found by using silicone grease as the coupling medium. While not a true fluid in the sense that it can maintain a certain amount of physical form, it possesses only a minimal shear strength. The particular benefits afforded by the grease are due to its excellent water imperviousness and insulation resistance characteristics. Laboratory testing has demonstrated that the use of silicone grease as the coupling medium has not noticeably degraded the high frequency performance of the probe. This was verified in tests where a specially designed apparatus was used for generating fast pressure transients. No discernible effect on the high frequency response was found and, due to the difficulties involved in generating pressure transients sufficiently fast to allow the effect to be quantified, this aspect of the testing was not pursued. Since the transients generated were faster than the design specifications for the probe, and were satisfactorily registered in the laboratory testing, it was concluded that the performance of the measurement system was adequate.

The use of silicone grease as a pressure coupling medium has provided an additional practical benefit. Being adjusted by the use of suitable additives, the viscosity of the substance can be arranged to remain virtually constant over a wide range of temperatures. The particular grease chosen for the pressure coupling medium is a commonly available type designed for electrical insulation and moisture proofing applications. It is relatively viscous and has the property that it will not run off; even over prolonged periods the substance retains form. This property has been exploited to eliminate the need to seal the chamber containing the pressure sensor. The instrumented tip assembly is packed with grease by injecting it into the upper and lower sections of the transducer housing. Upon screwing the units together, the excess grease is extruded out, permeating the voids and filling the circumferential slit filter. The outside of the tip, located as a free fit in the cone section of the larger probe is surrounded by a grease film, the system relying on the static properties of the grease to retain itself within the probe. Once in the saturated soils with the instrumented tip ejected, the interface between the local pore water and the coupling medium occurs at the outside edge of the slit aperture, the external grease film on the tip being wiped off by the surrounding soils.

3.1.3 Isolating Effective Stresses from the Pressure Sensor

As with the configuration of the pressure sensor element, the design for the effective stress isolation barrier has been the subject of some change throughout the development work. It is the function of this system to allow fluid flow into or out of the chamber containing the pressure sensor, but to prevent loading of the sensor by the fabric of the in situ soils. Early on in the development work, the possibility of using a sintered metal filter was investigated. Prototype instrumented tip units were constructed using a cylindrical stainless steel element of nominal particle size 0.1 mm. As shown in Figure 4, the element was arranged to surround the pressure sensor with an exterior surface flush with that of the upper and lower sections of the instrumented tip. The configuration did not allow the filter to be subjected to driving stresses, these being carried by an internal structural sleeve. This design was proposed for use with water as the coupling medium; the assembly, as described earlier, was to be

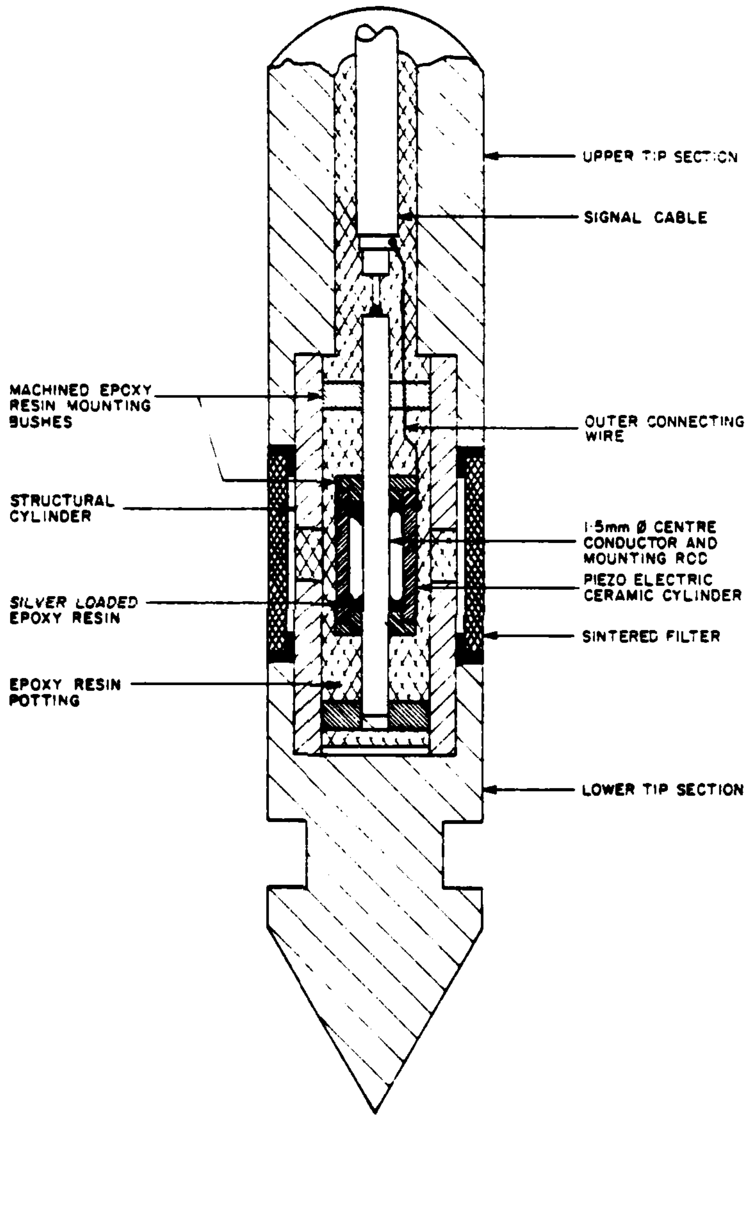


Figure 4. Early Design for the Instrumented Tip Unit.

saturated and de-aired before mounting in the cone section of the major probe.

Laboratory testing of this design for the instrumented tip yielded disappointing results. The frequency response of the system assessed in the testing by measuring the response to pressure transients, was considerably less than expected. Indeed the apparent speed of response of the sensor was so low that it was found to be influencing the determination of the calibration constant. This test, as described later, uses a rapidly vented chamber to produce a pressure step function of known amplitude. To register the step the measurement system must possess a considerably shorter hydraulic time constant (characteristic time for equilibriation of the pressures in the measurement system) than its intrinsic electrical time constant. On certain tests with the sintered filter, these conditions were not achieved and it was felt that this was due to entrained air in the system. The hydraulic time constant is directly proportional to the effective compressibility of the system, a parameter which, in liquid filled systems, can be increased substantially if air is entrained. The assumptions concerning the cause of the problem were reinforced by observations made during subsequent attempts to improve the saturation and de-airing process. It was found that even after a sustained period of high vacuum degassing, the assembly could be seen to be liberating air. Although the amount was ultimately small, at no point in the process was there any certainty that the system was fully saturated. During these efforts to de-air the sensor assembly, it was additionally noted that it was difficult to dislodge air bubbles that were attached to the surfaces of the submersed objects. While they could be made to grow substantially in the evacuated tank, the bouyancy attained, even with a special high vacuum pump, was not sufficient to clear most surfaces. It was found that brushing the submersed components was effective in clearing or wetting the surfaces, but obviously, this would be of little help in saturating the sintered filter element. The problems encountered in this early phase of testing of the sensor tips suggested that a number of fundamental design changes would be required.

The design shown in Figure 2 shows the methods evolved to overcome the problems discussed above. The principal feature of the design is the accessibility of the recesses and surface contours of the components. To achieve this, a new design for the pore pressure filter was introduced where the filter was formed by a narrow circumferential slit in the housing of the instrumented tip unit. As described earlier, the slit is formed when the upper and lower sections of the housing are screwed together. Hence, the surfaces forming the filter, and all regions of the interior of the pressure sensor cavity, can be thoroughly and conveniently wetted with the coupling medium without the need for vacuum assistance. The change of coupling medium from water to silicone grease presented no difficulties with the revised design. The unit was in fact further simplified since the O ring chamber seals used previously to retain the coupling medium could be dispensed with.

Laboratory testing of the slit aperture filter showed that it introduced no discernible effect on the frequency response of the probe even at gap widths down to 0.2 mm. It was felt that, at this dimension, the likelihood of a soil fabric penetrating the filter and stressing the pressure sensor was extremely small, particularly bearing in mind the viscous nature of the silicone grease coupling medium. Thus, the circumferential slit concept was adopted for design of the effective stress filter. The design has afforded the system a number of advantages. It is considerably simplified compared to the earlier cylindrical filter configuration and is inherently a more convenient and flexible arrangement. The procedure for mounting the piezoelectric sensor element is relatively simple, as is much of the other general assembly work on the instrumented tip unit.

3.1.4 High Frequency Response of the Measurement System

Calculation of the high frequency response of the Pore Pressure Probe measurement system is a complex matter. Even for a simplified model it is difficult to determine reasonably accurate values for a majority of the critical parameters and hence, only an estimate of the response can be obtained. The calculations presented in this report are those carried out in the early part of the development program where the porous filter design for the instrumented tip was being considered. They were used to estimate the margin of tolerance in the critical parameters and to assess the basic feasibility of the design. It was soon found that the predicted response was well in excess of that specified for the system and hence the results of the analysis did little more than demonstrate that, theoretically at least, the design concept was worth pursuing.

In estimating the high frequency response of the system, two basic simplifying assumptions are made:

a. The electrical part of the system is capable of providing a flat response over all frequencies of interest.

b. For a given design pressure transient, the wavelength in the local pore water introduced by the highest significant Fourier component of the pressure function, is large compared to the nominal dimensions of the probe. (For a velocity of sound in water of 1470 m/s, the 36 mm diameter of the probe approaches one wavelength at a frequency in excess of 40 kHz.

Given that the above conditions are satisfied, the remaining potential limit to the upper frequency response of the system is that due to the dynamic properties of the hydraulic system in the instrumented tip unit. Of particular importance are the following properties:

a. The net effective compressibility of the pressure chamber containing the pressure sensor element and the coupling medium. The higher this parameter, the higher the inlet/outlet flow required to establish a given pressure change in the chamber. For liquids and homogeneous isotropic solids, compressibility is the inverse of the bulk modulus.

b. The flow impedance of the effective stress isolation filter. At a given inlet/outlet flow rate, high flow impedance creates a correspondingly high pressure drop between the pressure outside the chamber and the pressure inside. The magnitude of this pressure drop is determined by the geometry of the filter, its permeability coefficient and the dynamic viscosity of the fluid flowing through it.

For the compressibility of the system, a value for the combined effect of the sensor and its mounting, and the surrounding coupling medium is required. It is here that the largest uncertainty exists. It can be assumed that the compressibility of the ceramic element alone will be negligible, but that the effect of the mounting of the unit will not. The epoxy resin compound used to mount the element has a low but not insignificant compliance. In addition, there is the uncertainty in the value to be assumed for the effective bulk modulus of the coupling medium. For most materials in their pure state this parameter is known. It is unlikely however that, even given a material of known and constant properties, absolute saturation of the void in the pressure chamber can be achieved. A small impurity or entrained air content can then markedly affect the net effective compressibility exhibited by the system.

The flow impedance of the effective stress isolation filter is, in contrast to the problem of compressibility discussed above, assessible with a reasonable measure of accuracy. The geometry of the system is relatively easy to define, and so too is an approximate value for the permeability coefficient (for sintered materials that permeability coefficient depends on a number of factors, nominal particle size and bulk density being of particular importance. For most materials, the manufacturer generally provides permeability data). For the coupling medium a value for the dynamic viscosity is required. This parameter is easy to obtain for water and other basic fluids, but is not so readily available for the less common materials such as silicone grease.

As mentioned earlier, the high frequency response calculations were carried out to determine the essential feasibility of the measurement system, where it was found that there was a considerable excess margin of response available for the sintered filter configuration of the instrumented tip. While the final design has departed somewhat basically from this early configuration, it is felt that the results of the calculation are still of some use. The new design does use a more viscous coupling medium which, as the calculations show, is a factor tending to reduce the upper roll-off frequency. However, by comparison with the sintered filter configuration, the revised design does feature a much higher permeability filter and a less compressible sensor element. Both these features will tend to compensate for the increased viscosity of the coupling medium.

The high frequency response calculation is presented in Appendix C. A model of the hydraulic system of the instrumented tip is given, and an expression for the high frequency transfer function of the system is derived. The upper roll-off frequency is expressed in terms of the following parameters:

a. the net effective compressibility of the overall pressure chamber, sensor and sensor mounting, and coupling medium system;

b. the effective volume of the measurement system;

c. the geometry and permeability coefficient of the filter system;

d. the dynamic viscosity of the coupling medium.

After defining the upper limiting frequency, a calculation to allow the determination of effective bulk modulus of the pressure chamber system is presented. Here the overall bulk modulus is expressed in terms of the moduli and volumes of the components of the system. Finally a sample evaluation is presented to demonstrate the order of response theoretically attainable from the early configuration of the instrumented tip. The resulting value is well in excess of the frequencies for which the basic initial assumptions for the analysis were made. Consequently, it is assumed that the design response of the probe is theoretically attainable.

3.2 THE EMPLACEMENT SYSTEM

The concept of the two-phase method of emplacement of the Pore Pressure Probe has been described in earlier sections of this report. The reasoning behind some of the design features of the instrumented tip unit have also been discussed. This section deals with the design of the remainder of the probe and presents the background of development to the more important features.

3.2.1 Emplacement Loads

A major portion of the loading applied to the probe during emplacement arises from end stress. This stress, brought about by the displacement and remoulding of the soil into which the probe is pushed, acts across the projected area of the probe and combines with the wall friction forces to produce a net push-down load. The order of push-down load to be expected is determined by the type of soil and the relative density of the deposit. In designing the system to cope with emplacement loads, use was made of the readily available data published by various companies involved in both the manufacture and operation of cone penetrometer testing equipment.

During the initial phase of emplacement of the probe, the instrumented tip section is contained within a larger protective probe. This unit prevents the instrumented tip from coming into contact with the unsaturated soils and absorbs the bulk of the loading and wear involved in reaching the desired measurement location. In order to avoid entraining air in the system and subsequently introducing it into the saturated soils in the measurement region, the case or body of the probe is designed with a minimum of surface features. By using a simply shaped pointed cylinder configuration for both the larger probe and the instrumented tip, there is least risk of trapping air. Furthermore, for the instrumented tip unit, the configuration conveniently allows saturation of the clearance space in the bore of the major cone with the pressure coupling medium. The configuration does, however, possess the drawback that the stresses acting over the instrumented tip portion of the end of the probe cannot be coupled into the major cone. Without some form of step or shoulder on the tip, acting onto a corresponding feature on the major cone, the tip stresses must be carried from within the probe. The assembly drawing of Figure A1 (Appendix A) shows how this is achieved in the final design for the probe. End load developed at the point of the lower tip, Section 11, is transmitted past the pressure measurement system by a screwed coupling. As described earlier, this coupling is used to implement the effective stress filter for the measurement system, and is arranged to bottom out to produce a circumferential slit aperature in the tip at this point. Driving loads are transmitted through this feature by a threaded shoulder which seats in a recess in the upper tip Section 10. Another screwed joint occuring at the point where the upper tip section emerges from the rear of the major cone 02 couples the load into the extension rod 09. The extension rod terminates in a cable cup arrangement 07 which is bottomed at the upper rim against the rear bulkhead 05 of the ejection pressure chamber. The bulkhead is retained against a seating shoulder in the case 03 by a special retaining nut 04. It is via the bulkhead and the retaining nut that the tip loads finally enter the probe case to join those arising from the major cone. The net push-down force for the probe due to end load and wall friction is applied from the driving rods to the upper end face of the probe case.

Having reached the desired measurement location, the second phase of the emplacement procedure is brought into action; that is, the instrumented tip is ejected. This is achieved by pressurizing the case of the probe in the region between the major cone 02 and the bulkhead or pressure chamber cap 05. This sealed cavity or ejection pressure chamber is packed with silicone grease and coupled via the rear bulkhead connector C to an uphole hydraulic tube. The system is pressurized by means of an uphole hand pump which is coupled to the probe by a length of micro-bore tubing H. Hydraulic oil is pumped into the chamber to displace the tip and the ejection force is equal to the chamber pressure times the projected area of the tip (28.3 mm^2). The hydraulic fluid in the ejection pressure chamber is retained by static O ring seals at the ends of the chamber and by an arrangement of piston seals both in the upper tip section and the extension rod of the instrumented tip assembly. The seals are located at relatively close intervals along the extension rod, and hence there is always an effective seal maintained between the major cone and the tip as ejection takes place. To pack the ejection pressure chamber with silicone grease a special grease gun has been designed. This unit, utilizing a screw driven piston, attaches to the lower end of the probe case in place of the major cone. In order that the gun can be filled with a void-free charge of grease, the unit is designed with a detachable rear cap which allows free access to the through barrel. The gun is used during the final stages of the assembly procedure for the probe with the instrumented tip unit in position. Grease is propelled into the case, past the cable cup assembly while air is expelled from the bulkhead hydraulic supply fitting (Item C, Figure A1). Further details of this procedure and an assembly drawing of the grease injection gun are given in Appendix D. Figure E5 is a photograph of the grease gun and the probe ready for the grease packing procedure to commence.

In order to retain the instrumented tip in the fully retracted position, a low strength bonded joint is made between the points of contact of the rim of the cable cap 07 and the pressure chamber cap 05. The bonding agent chosen for this application is a cyanoacrylate thin film adhesive (Loctite IS495), and just sufficient is used to achieve a joint with a reasonable strength. The object of bonding these component is twofold:

a. The assembly procedure for the probe is greatly simplified. By bonding the cable cup and pressure chamber cap together, the interconnecting cable can be coiled up and positioned in the cup while the assembly is free from the probe.

b. The instrumented tip is positively retained in the probe by the pressure chamber cap. This has the advantage of preventing the unit from moving during handling or in transit. If the tip were dislodged sufficiently far it is possible that, upon repositioning the tip, the interconnecting cable could become trapped between the rim of the cup and the chamber cap. In this position it would almost certainly be seriously damaged by the driving loads. Positive retention is also of great value in preventing this from happening when packing the ejection pressure chamber with silicone grease. Due to the viscous nature of the substance, a certain amount of pressure is developed as the grease is pumped in. At the final stage of the packing procedure the major cone is screwed home and excess grease is driven out through the bulkhead hydraulic connection. At this stage the tip is subjected to ejection forces.

To eject the tip, the chamber is brought up to sufficient pressure to break the bond (1000 to 1500 lb/in^2) between the cable cup and the chamber cap. Due to the position displacement characteristic of the hydraulic system and the damping action of the grease packing, only a slight jump or step movement of the tip occurs. Thereafter, the tip is ejected at a rate controlled by the volumetric displacement of the hand pump being used. For a properly bled hydraulic system, the tip is fully ejected by a volume of 6 cm^3 of hydraulic fluid pumped into the pressure chamber. At the limit of its travel (8.6 cm) the instrumented tip is stopped by the bottoming action of the cable cup lock nut 08 on the rear face of the major cone.

The electrical interconnection between the instrumented tip and the rear bulkhead or pressure chamber cap is a flying leadwire. This leadwire is coiled in the cable cup while the tip is in the retracted position. During ejection of the instrumented tip, this interconnection is subjected to the ejection chamber pressure and is therefore required to be sealed at both ends. A demountable seal is achieved at the cap of the pressure chamber by the cable seal plug 06. This component retains the electrical connector E and provides a back potting recess for sealing the leadwire. The plug is threaded into the chamber cap and piston sealed in a stepped seating recess. The other end of the leadwire is potted into the extension rod of the instrumented tip unit.

3.2.2 Uphole Connections to the Probe

As outlined in Section II, uphole connections to the probe are routed through the center hole in the driving rod string used to emplace and retrieve the probe. The uphole connection is comprised of a 1.5 mm (1/16 inch) diameter stainless steel microbore hydraulic pipe, and a miniature low noise (microdot) coaxial cable. The cable and pipe are contained within a tough protective nylon tube which also provides a watertight housing for the uphole connection system. As shown in Figure A1, the nylon tubing terminates in a compression fitting B which is an integral part of the connector cover component 01. When screwed home against the retaining nut 04, the connector cover and nylon tube form a hermetically sealed chamber for the electrical and hydraulic connections to the probe. This system has eliminated the need for comonents with stringent environmental specifications and has allowed the use of standard miniature connectors for both services to the probe.

This has a number of benefits from the design point of view, but also yields considerable advantages in reduced cost of components, miniaturization and convenience of handling of the system.

The selection of miniature tubing and cable for the uphole hydraulic and electrical lines was chiefly influenced by the need for a relatively flexible system. The uphole line must be prethreaded through the driving rods before emplacement of the larger probe commences and there is, therefore, a considerable amount of handling to be carried out. The need to protect the cable and tubing from damage due to abrasion or crushing was obvious, and as described earlier, this is achieved by housing them within a tough nylon tube. In order to keep this overall sheath down to a reasonably handleable size, it was found that miniature pipe and cable was required. For the cable this presented no difficulty since a suitable type was known to be commercially available. Designed primarily for working with piezoelectric transducers and referred to a microdot cable, it is tough and durable. Being approximately 2 mm in overall diameter, the cable incorporates a dense electrical screen and a special antimicrophonic conductive layer over the inner conductor.

Using miniature tubing for the hydraulic uphole line has the significant advantage from the design point of view that miniature tubing fittings can be used to connect it. The disadvantage for most applications is the pressure drop resulting from flow in the pipe. For ejection of the instrumented tip, however, this is not a problem. There is a discernible resistance at the pump due to the flow restriction effect of the tubing, but this is of no practical significance since there is no requirement to eject the tip at a prescribed rate.

In order to allow push-down loads to be applied at the top of the string of driving rods, the uphole line must be led out from the center hole. This is achieved using a driving rod adaptor unit which is, effectively, a short length of driving rod with a through slot in the wall. The uphole line leaves the rods via this slot and push-down/pull-out loads are applied to the top of the adaptor via a driving rod cap. In most commercially operated penetrometer rigs, this cap is socketed in the rig crosshead during push-down and is gripped by a slot and keyhole-plate arrangement for pulling-out.

3.3 THE ELECTRICAL SYSTEM

The fundamental design requirements of the electrical interconnection system within the probe are:

a. In order to prevent problems with ground loops, particularly with multichannel measurements, the electrical system of the Pore Pressure Probe must be fully floating. It must maintain high and preferably balanced shunt impedances to the probe case, and a high shunt impedance across the sensor element.

b. Part of the interconnection must work within the pressurized hydraulic medium used to eject the instrumented tip. The interconnection must incorporate seals to prevent loss of pressure or migration of the hydraulic medium into the instrumented tip unit or past the bulkhead connection.

c. Within the pressurized hydraulic medium, the interconnection must accommodate the full displacement of the instrumented tip assembly.

During the course of the design and development work on the instrumented tip assemblies, experiments were carried out with a number of different cable types to examine their suitability for use in the interconnection system. Ranging from twisted pair to miniature coaxial cables, the different types were potted into trial instrumented tip assemblies and pressure tested. The ease of handling, and making delicate soldered joints was noted, so too was the durability of the insulation.

The most difficult problem to emerge from this experimental work was that of pressure sealing the cable. Unless a mechanical glad or O ring type seal were to be used, it was found that cables using polyvinylchloride or teflon covering could not be used. This was so because of the difficulty in obtaining a reliable, bonded high pressure seal with these plastics. None of the bonding compounds that were tested produced an effective seal between the sheath and the inner conductors. The method of using the sheath as an overall pressure tight surround and implementing compression seals at both ends of the cable was rejected. It was thought that the sheath would not be reliably leakproof and that the mechanical seals would occupy too much space in the assembly.

The configuration ultimately adopted for the interconnection system owes its success to the uniquely suitable properties of the type of leadwires chosen. As shown in the assembly drawing of Figure A1, the interconnection is formed by a continuous twisted pair cable running from the pressure sensor element, through a central hole in the upper tip Section 10 and extension rod 09 to the cable seal plug 06. Hermetic sealing of the ejection pressure chamber is achieved by back potting the extension rod and cable seal plug units with epoxy resin. The leadwire is made up from two 0.2 mm diameter polyurethane coated copper wires of the type used in high quality transformer and coil winding applications. It was found that a high integrity bond could be achieved with the insulation using ordinary two part cold curing epoxy resin. The insulation is intimately bonded to the inner conductor, and thus the problem of leakage between the sheath and inner conductor is eliminated. The epoxy resin back potted seals shown in the assembly drawing were found to be particularly convenient to implement in the assembly work, and in the subsequent pressure testing, found to work highly consistently. Although relatively thin, the insulation is durable and tough. No problems were experienced with loss of insulation resistance due to cracking, flaking or wear. The inner conductor, being of small diameter, is highly bendable making the leadwire ideal for the delicate soldering work involved in connecting to the piezoelectric pressure sensor.

In order to accommodate movement of the instrumented tip assembly during ejection, a suitable excess length of leadwire is allowed in the run through the ejection pressure chamber. While the tip is in the retracted position, this excess length of leadwire is retained coiled within the cable cup and hence is exposed to the hydraulic medium used to eject the tip. The medium, however, being silicone grease gives rise to no problems with degredation of insulation resistance or chemical attack. The viscous nature of the grease is of additional advantage in this application in that it serves to damp any movement of the leadwires. This is a useful guard against potential problems with abrasion of the leadwire insulation.

IV. LABORATORY TESTING

4.1 DESCRIPTION OF THE TESTING APPARATUS

The objective of the laboratory testing associated with the Pore Pressure Probe development program were:

a. To derive calibration constants for the instrumented tip units to be supplied under the contract requirements.

b. To assess the frequency response of the measurement system.

Without a static or DC response, it was realized that it was not possible to use conventional laboratory equipment to calibrate the sensor units. The only method of achieving a calibration would be by introducing a transient or steady-state dynamic pressure function of known amplitude to the instrumented tips. For assessment of the frequency response it was almost certain that for the relatively high frequency of operation specified for the system, it was unlikely that any suitable testing equipment would be commercially available. It was concluded, therefore, that the design of special testing equipment would need to be undertaken.

Figure 5 is a schematic of the apparatus developed for the laboratory testing work. The apparatus is comprised of a pressure chamber system, an electronic charge amplifier and transient data capture oscilloscope, and a high pressure hand pump. The heart of the equipment is the system of pressure chambers. This unit is designed to test two tip units simultaneously, these being positioned in the base of the upper chamber. A detailed view of the arrangement of the pressure chambers is shown in Figure 6, where it can be seen that the system is comprised of two chambers interconnected by a cone seated valve. The valve is operated via a plunger and control rod by means of a rod end knob. The control rod passes through a seal in the cap of the upper chamber and is positively retained at this point by the threaded stop nut. A cone seated bleed and venting screw is located in the center of the upper chamber cap, and the underside of the cap is relieved into the screw seat. The lower chamber is thick wall pressure vessel. It is screwed into the base of the upper chamber and sealed against a seating shoulder by means of a bonded sealing washer. The throat of the lower

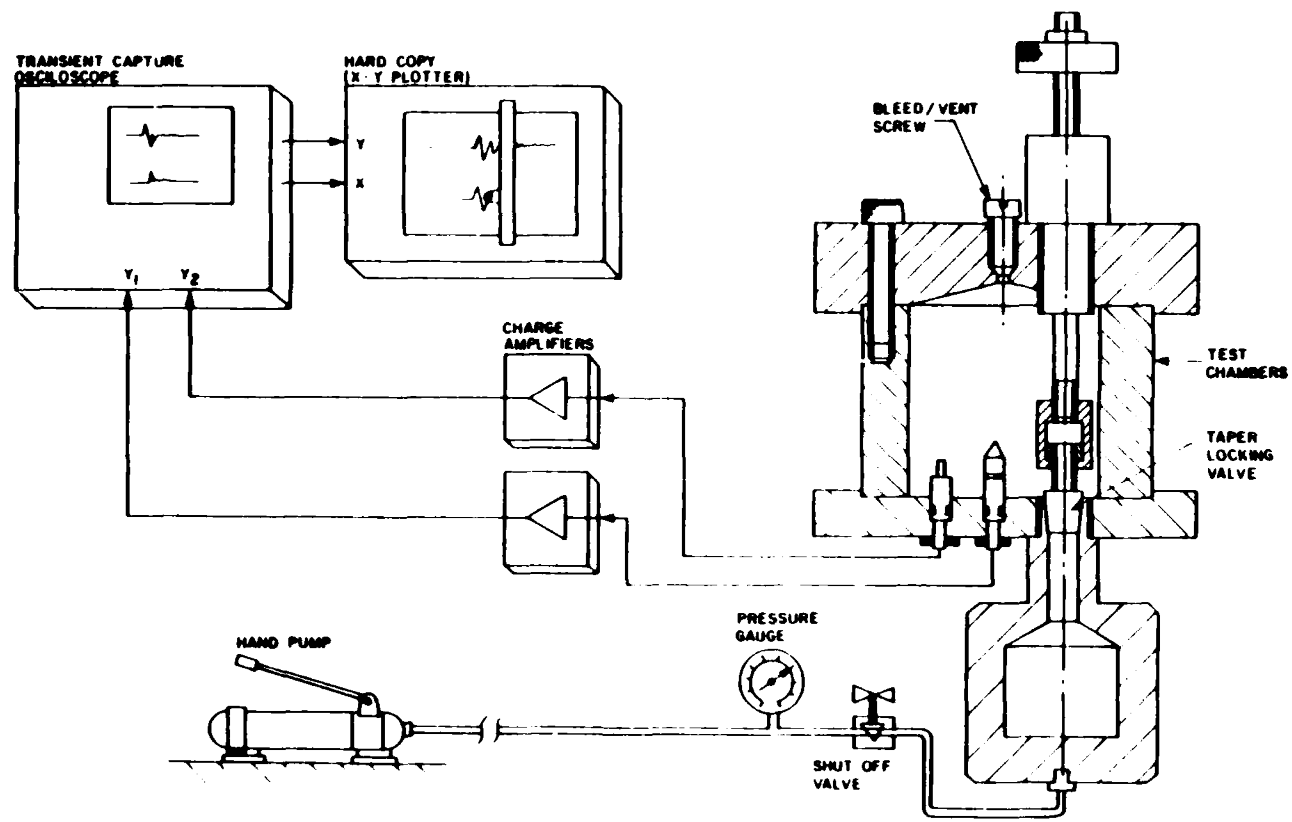


Figure 5. Schematic of the Laboratory Testing Setup

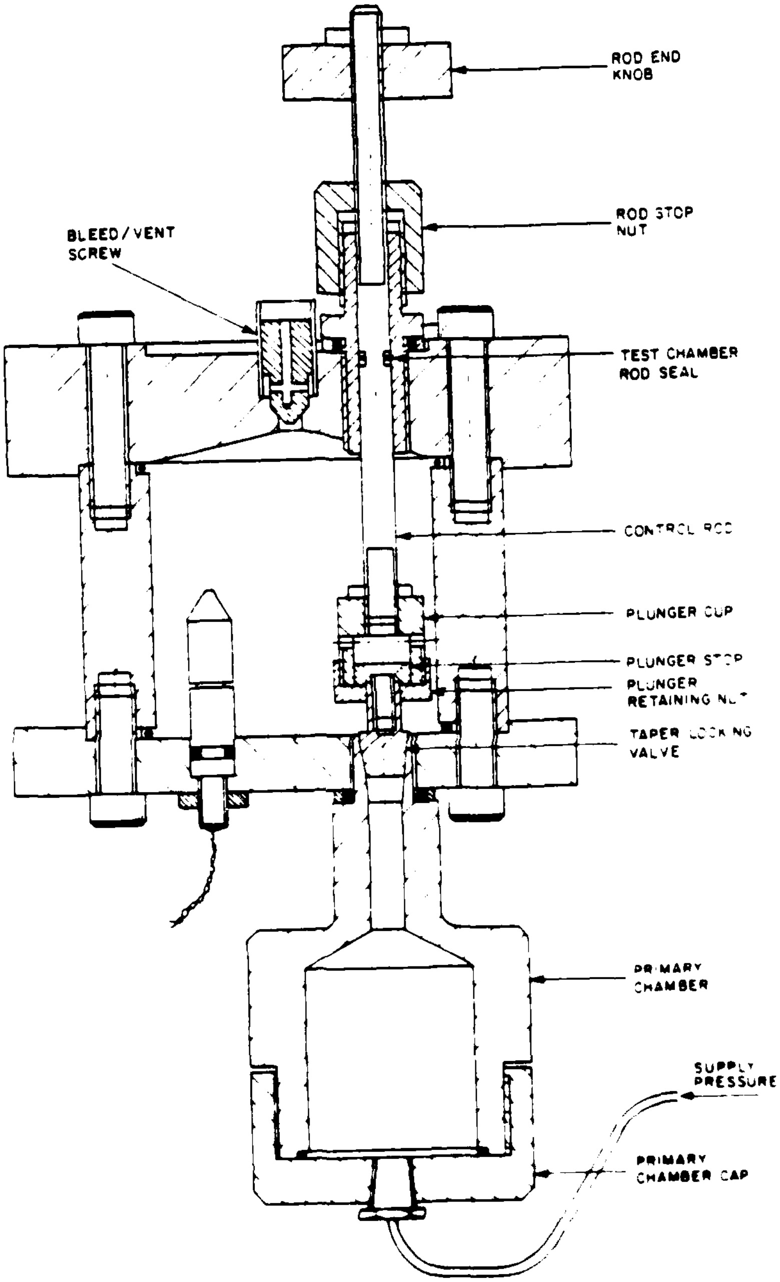
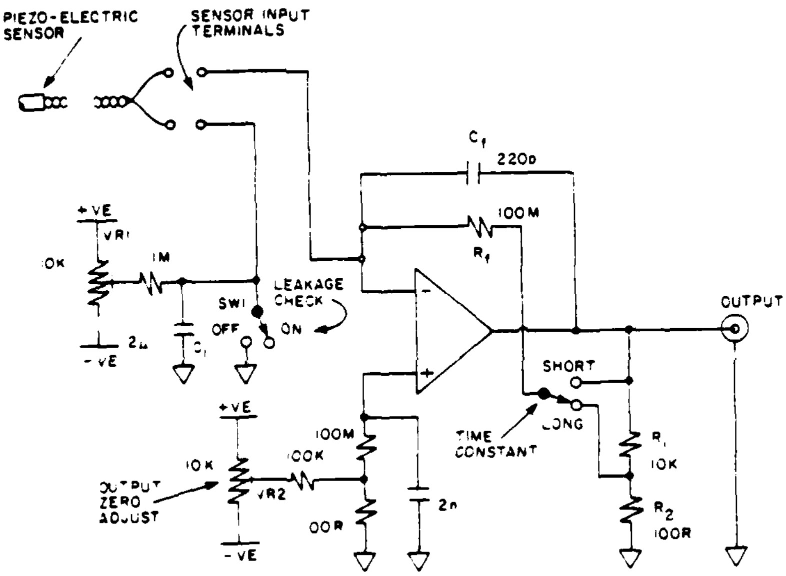


Figure 6. Detail of the Pressure Chambers in the Testing Apparatus.

chamber is machined and lapped to fit the taper locking plunger and is located in line with it in the base of the upper chamber assembly. Hydraulic feed to the system is introduced via microbore high pressure steel tubing to the cap of the lower chamber. A high pressure shut-off valve is located close to the lower chamber and is used to isolate the chambers from the hand pump and pressure gauge system.

The instrumented tip units, as mentioned previously, are located in the base of the upper chamber. Convenient use is made of the existing piston seal feature in the upper tip section of the units, and they are arranged to locate in specially machined recesses in the base plate. Testing is carried out before the tips are jointed to their extension rods, the threaded shoulder at the rear of the upper tip section being used to retain them in the upper chamber. As shown in Figure E7, the system of chambers was attached to a frame which was also used to mount the shut-off valve and the charge amplifiers. The amplifiers were housed in a screened box attached to the frame, and the leadwires were routed conveniently from beneath the upper chamber into the amplifier box. It was decided to build the amplifiers specially for the testing in order that an electrical leakage check feature could be incorporated into the system. The circuit of Figure 7 shows how this was achieved. A potential derived via VR1 from the supply rails is decoupled by C1 and fed to switch SW1. The switch allows the ground end of the sensor input to be connected to zero volts or to the potential from VR1. By noting the change in the amplifier output voltage introduced by switching in this series potential, the leakage current of the sensor can be determined. This feature was incorporated so that leakage current or sensor resistance checks could be made throughout all stages of the testing.

The buffered sensor signals from the charge amplifiers where fed into a digital oscilloscope with transient capture facility. The instrument chosen for the application (Nicolet Explorer I, Nicolet Instrument Corp.) is a two-channel unit featuring very high amplitude and time resolution (4K words of 12 bits each). A pretrigger facility which allowed capture of information prior to the point of trigger was of great use in the testing. Not also the least of the desirable features of the instrument was the hard



SHORT TIME CONSTANT, $\tau_1 \approx C_f R_f$

LONG TIME CONSTANT, $\tau_2 \approx \tau_s \left\{\frac{R_1 + R_2}{R_2}\right\} \approx 100\,\tau_s$

CHARGE AMPLIFIER GAIN, $\frac{e_0}{q_{in}} \approx \frac{1}{C_f}$

Figure 7. Circuit of the Charge Amplifier Designed for the Laboratory Testing.

copy facility. Here, the digitally stored signal could be replayed at reduced speed producing an output in analogue form to drive an X-Y plotter.

4.2 CALIBRATION OF THE INSTRUMENTED TIPS

As mentioned in the previous section, the lack of static response of the piezoelectric pressure sensor necessitated that the units be calibrated by recording their response to a pressure pulse or step of known amplitude. With the laboratory test rig described above, this was achieved by venting the upper chamber to atmosphere from a known pressure. With the sensor tips fully assembled and positioned in the upper chamber, the system was filled via the lower chamber to the point where the tips were covered. Air bubbles were brushed from the surfaces of the submersed components and a vacuum cap was applied to the top of the upper chamber to draw out as much of the inaccessibly trapped air as possible. The top plate was fastened into place on the upper chamber and the system was filled and bled via the central vent screw in the plate. With the vent screw fully home, the chamber pressure was brought up to the desired testing level as indicated on the pressure gauge and the pump isolated from the system by operating the shut-off valve. The transient recorder was armed to capture the event, and the test chamber was vented by rapidly unseating the bleed screw. Figure 8 gives a typical calibration test result.

The pressure drop function applied to the probe was a clean step resulting in a simple exponentially decaying response from the unit with the peak value being relatively easy to determine. There is a distinct advantage to venting the chamber to produce the pressure step as opposed to producing a step increase. When the chamber is vented, the effective bulk modulus of the system falls markedly. Under these conditions there is least likelihood of producing a ringing or overshooting response with the consequence that determination of the peak amplitude of the response is easiest.

The pressure drop calibration testing described above was carried out on four sensor tip units (01, 02, 03 and 04) at three initial static pressures of 0.69, 1.38 and 4.14 MPa (100, 200 and 600 lb/in^2). The calibration constants calculated from the test data for each initial pressure level are

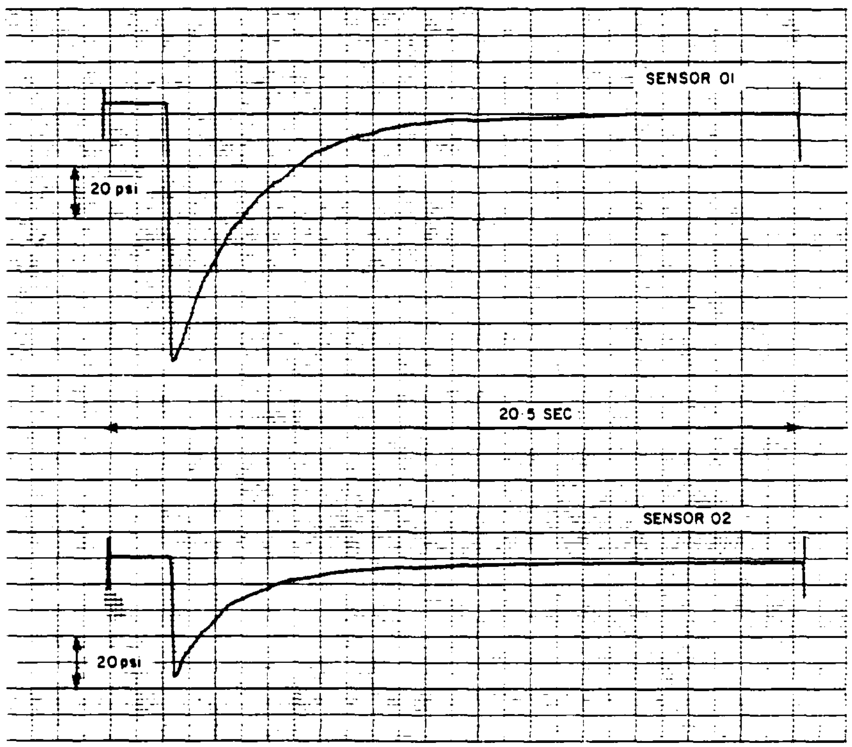


Figure 8. Typical Result from the Calibration Tests.

tabulated below, where an averaged value is given. The testing was carried out with the sensors fully assembled with the minor cone units in place (gap width = 0.2 mm nominal), and the units packed with silicone grease.

TABLE 1. RESULTS OF THE PRESSURE DROP CALIBRATION TESTS

Sensor	Initial Pressure MPa (lb/in^2)			Sensitivity pC/KPa ($pC/lb/in^2$)
	0.69 (100)	1.38 (200)	4.14 (600)	
01	24.68	24.96	29.30	26.34 (181.66)
02	8.76	9.31	9.72	9.24 (63.72)
03	16.96	18.13	20.00	18.34 (126.48)
04	20.00	21.79	22.62	21.44 (147.86)

The values in the table above indicate a reasonable consistency for the calibration constant of the sensor units. It will be noted that the apparent sensitivity increases for all cases with increasing initial pressure, and it is felt that this is probably due to greater inaccuracy in the pressure gauge readings for the lower values of the range. If it is assumed, accordingly, that the higher values in the range are likely to be most accurate, the nominal spread of the averaged calibration constant calculated from the repeated testing data is of the order of seven percent.

4.3 ASSESSMENT OF HIGH FREQUENCY RESPONSE

For assessment of the frequency response of the instrumented tip units, the features allowing the laboratory testing apparatus to generate a fast pressure step were used. The basic action of the apparatus in this mode is to rapidly couple together the two chambers in the system, having initially established a pressure difference between them. This is achieved using a taper locking valve where the frictional property of the taper is used to both provide the seal between the chambers and to withstand the seating forces due to the differential pressure. In order to achieve a sufficient speed for the transient, the special taper locking valve mechanism was used to admit high pressure from the lower reservoir into the upper chamber. The two thick walled chambers are closely coupled, and the manner of sealing the system and coupling supply pressure to it is such that a high effective bulk modulus is attained. Both chambers are filled and bled for the test, and venting does not occur. In this way, compressibility does not significantly increase and a pressure disturbance is made to act as rapidly as possible throughout the system. As shown in Figure 6 the taper valve is located at the throat of the lower pressure vessel. The taper locking plunger is coupled via a cup and stop mechanism to a control rod. The rod leaves the upper chamber through a sealed exit port and is restrained against the pressure forces from the chamber by means of a rod stop nut. In order to achieve rapid action, the plunger of the valve has been designed to be physically small. The function of the cup mechanism is to allow control of the valve from outside the upper chamber, yet not to contribute significantly to the mass of the moving parts. To achieve this the system incorporates backlash which allow free movement of the plunger and stop. This movement is sufficient for the valve to act in breaking the seal between the chambers and hence the speed of action is limited only by a relatively small mass. Once the friction retaining forces in the taper are overcome, the plunger is accelerated out of its seat by the higher pressure in the reservoir chamber.

The operating procedure for the testing apparatus used in the mode was as follows:

a. The apparatus was set up, filled and de-aired as described in the testing procedure in the previous section.

b. With the outer recess in the top cap of the upper chamber filled with water and the bleed/vent screw open, the rod stop nut was screwed home to seat the taper valve.

c. The stop nut was then backed off until a slight pull was exerted on the taper valve.

d. The bleed screw was driven home and the lower chamber was brought up to pressure (typically 1,500 lb/in^2). The shut-off valve was closed.

e. To trigger the system, the rod stop nut was turned anticlockwise to apply further pull to the taper valve.

The transient capture oscilloscope was used in a similar manner to the pressure drop testing where the mid-signal trigger facility was used to capture pretrigger information.

The results of the testing were particularly convincing. The characteristics of the pressure transient generated by the testing apparatus were well suited to the testing and were found to be very consistent. The performance of the sensors was such that they were able to register the transient with good resolution and with a high degree of repeatability. The results showed that even when comparing the simultaneously recorded outputs of two sensors, one without the slit aperture and one fully assembled, the outputs were virtually identical in detail. This verified that the sensors were responding to a truly common excitation function (i.e., the water pressure in the test chamber), and that the frequency response of the units was well in excess of that required to register the transient generated by the experimental apparatus. Examples of the test results are given in Figures 9 and 10. In Figure 9 sensor 03 (top trace) is fully assembled, packed with silicone grease with the filter gap at 0.2 mm. Sensor 02 is the lower trace where the minor cone is not attached and the sensing element is simply given a barrier coating of silicone grease. The lower set of traces show the pressure histories expanded by a factor of eight. The registration of the oscillatory response of the chamber system is identical for both channels with only a slightly perceptible loss of high frequency component in the 03 sensor output. The results shown in Figure 10 are for the same sensors but with the minor cone switched over to the 02 sensor (lower trace). The expanded traces reveal close matching of the recorded pressure function with, again, slight attenuation of the high frequency components in the output of the fully assembled sensor.

The distinctive oscillatory component of the response of the pressure chamber systems is a damped ringing of approximately 1 kHz. The sensors were able to register this function with high resolution, and the switch-over test described above indicated that the slit aperture had negligible

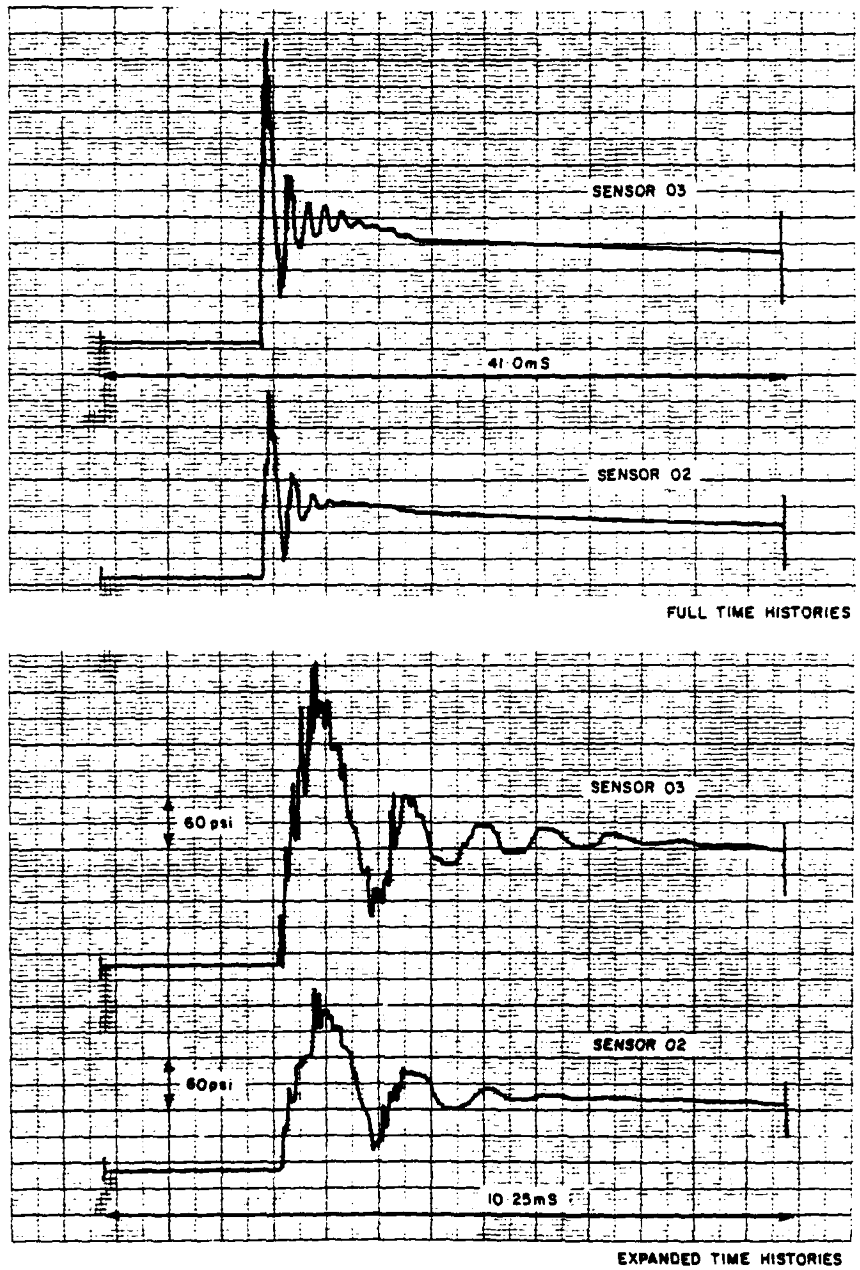


Figure 9. Record of the Sensor Outputs Taken During the Frequency Response Testing.

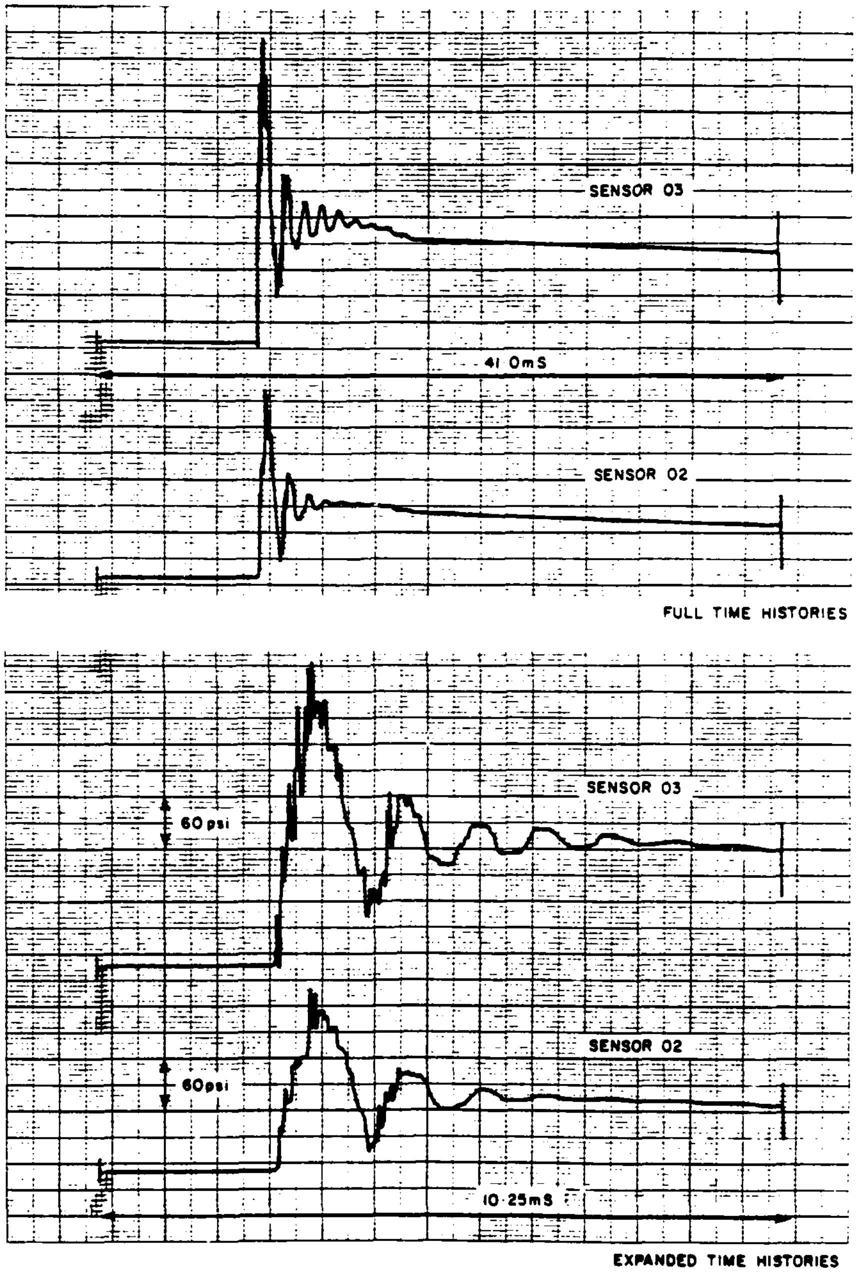


Figure 10. Repeat Test (See Text).

affect at these frequencies. It is thus concluded that the sensors are suited to applications requiring a frequency response up to 1 kHz.

V. FIELD TESTING OF THE EMPLACEMENT SYSTEM

In order to validate the design of the placement system for the Pore Pressure Probe, a field trial was undertaken. Here, the probe was driven by means of a conventional penetrometer pushing rig, and operation of the secondary ejection system was tested. The testing was carried out early in the contract work period when the sintered filter configuration for the instrumented tip was under development. The objectives of the trial were limited to assessing the survivability of the instrumented tip and to validating the working of the secondary ejection technique.

The site chosen for the test was one on which penetrometer testing was concurrently taking place. Sufficient boring log data was available for a reasonable assessment of the subsurface, and although the site was not ideal for the purpose, the tests did yield some useful results which might not otherwise have been produced. The subsurface was principally medium to stiff clay (London clay)interleaved with layers of gravelly sand. SPT blow count for the location chosen ranged between 2 to 20 for the extent of the log (6 m). Initially the probe was driven to a shallow depth into the top-soil and, as expected, no difficulties were experienced with operating the system. Upon driving to greater depth a gravel layer was encountered and driving resistance increased markedly. It was decided that rather than eject the tip into the gravel, it was better to carry on in an attempt to clear through to a layer of lower resistance. The maximum thrust encountered at this stage was 2.5 ton f. at a depth of approximately 4.5 m. During driving through the gravel the resistance could be both heard and felt at the rig as an erratic vibration. In a consequent attempt to jack out the instrumented tip, the system did not appear to respond repeatedly to ejecting pressures in the expected range. After a continued attempt at pumping, the probe was withdrawn for inspection. It was found that the cone end was considerably worn by gravel, and that the inner tip had only partially ejected. The tip was lodged firmly into the major cone, indicating that sufficient pressure had been exerted to crush the thin end of the major cone onto the inner tip. The hand pump employed for the testing utilized a pressure relief system to safeguard against excess pressures, and the maximum pressure available

(3,000 lb/in^2) was not sufficient to dislodge the instrumented tip. The tip, however, had ejected beyond the filter section and apart from a worn end, was undamaged.

It was concluded from this testing that the design was capable of withstanding the initial placement stresses provided that the major cone could be prevented from crushing and locking onto the instrumented tip. The choice of material for this component was thought to be the only modification necessary. This modification has been carried out and the major cones of the probes supplied under the contract requirement have been manufactured from tool steel which has subsequently been through-hardened by heat treatment. The particular type of steel chosen (OHNS - oil quench hardening, nonshrinking) is specially formulated to maintain dimensional stability during the hardening process.

VI. CONCLUSIONS

The product of the research and development program described in this report is a prototype design for a Dynamic Pore Pressure Probe. The feasibility of the design concepts have been explored, where possible, analytically and have been validated in laboratory and field tests. A number of changes and modifications have occurred as a result of the findings of the testing, and the final design for the device has accordingly benefited in improvements in convenience of use, and in greater inherent simplicity. It remains to see how the prototype equipment supplied under the terms of the development contract performs in actual field trials.

A number of further developments on the basic concepts of the probe have been suggested in the course of the contract work. They are thought to be essentially feasible and potentially capable of improving the measurement system described in this report:

a. A design could be produced in which the instrumented tip is fully ejected from the major probe. Here, the major probe would be withdrawn to leave behind the miniature implanted sensing system. Some form of environmentally protected "uphole" cable or line would be required to retrieve signals from the device.

b. A static response piezometer could be incorporated into the instrumented tip assembly in order to measure excess or long duration pore pressure functions. For blast monitoring applications, a hydraulic filter would be required to protect the sensor from transient overload.

In order to design these systems effectively, however, it would be appropriate to await the outcome and subsequent observations of the performance of the existing equipment.

APPENDIX A

ASSEMBLY AND FINAL DESIGN DRAWINGS

This section gives the set of engineering design drawings for the specially manufactured components of the Pore Pressure Probe. Brought-in components are identified and part designations are given in the assembly drawing, Figure A1 overleaf.

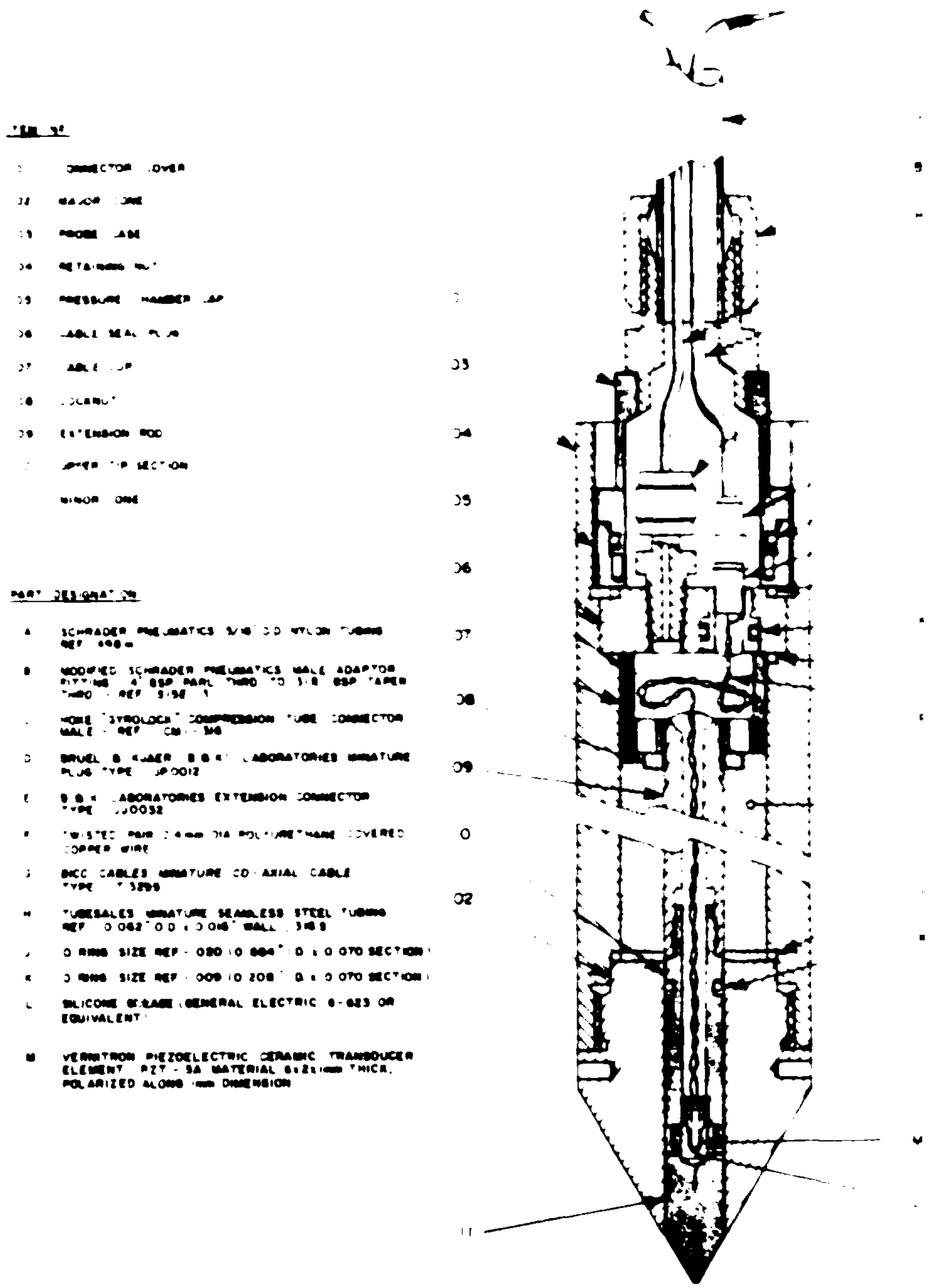
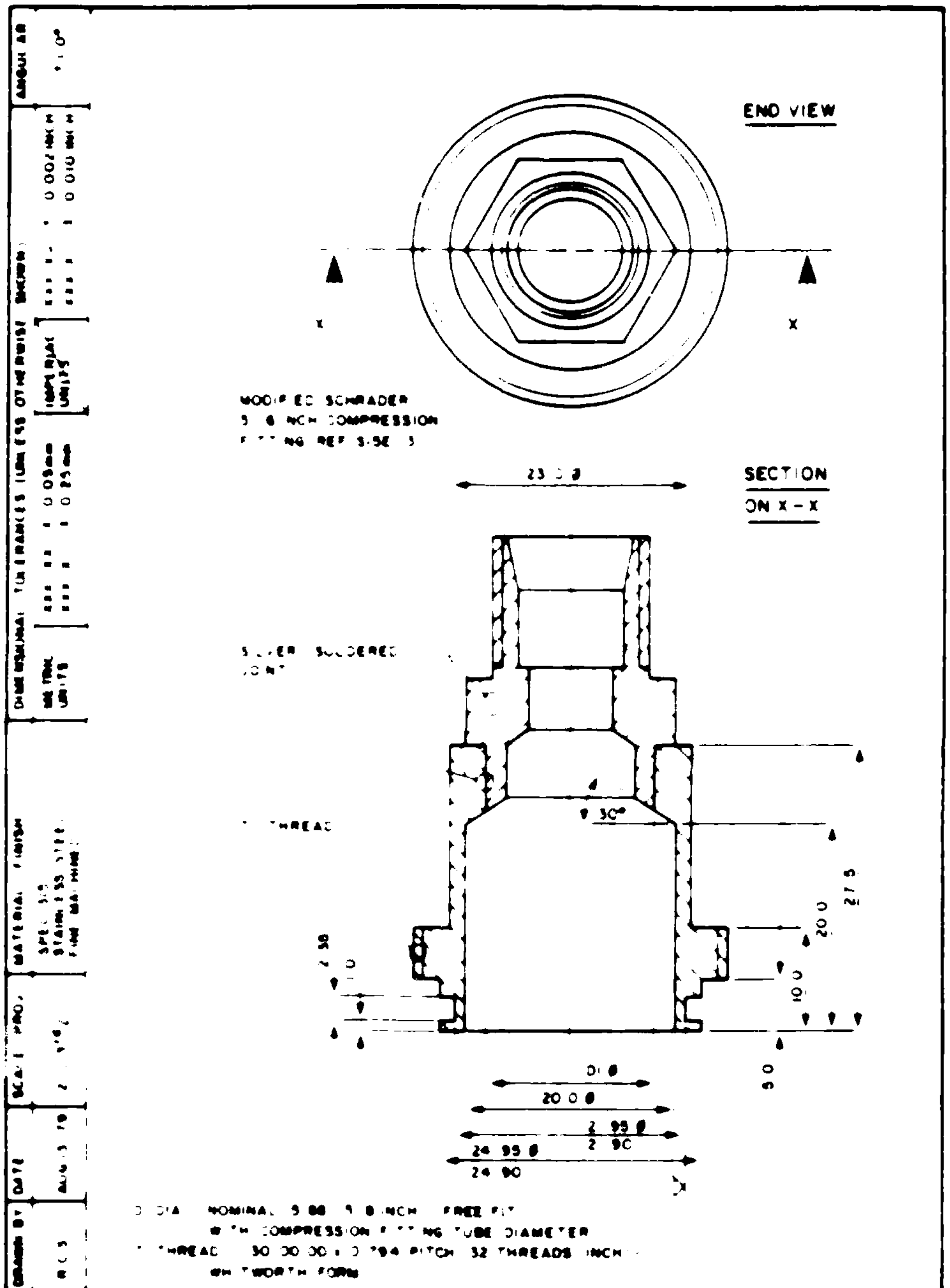


Figure A1. Pore Pressure Probe Assembly Drawing.



PROJECT PORE PRESSURE PROBE

FIGURE A2 CONNECTOR COVER

ITEM No 01

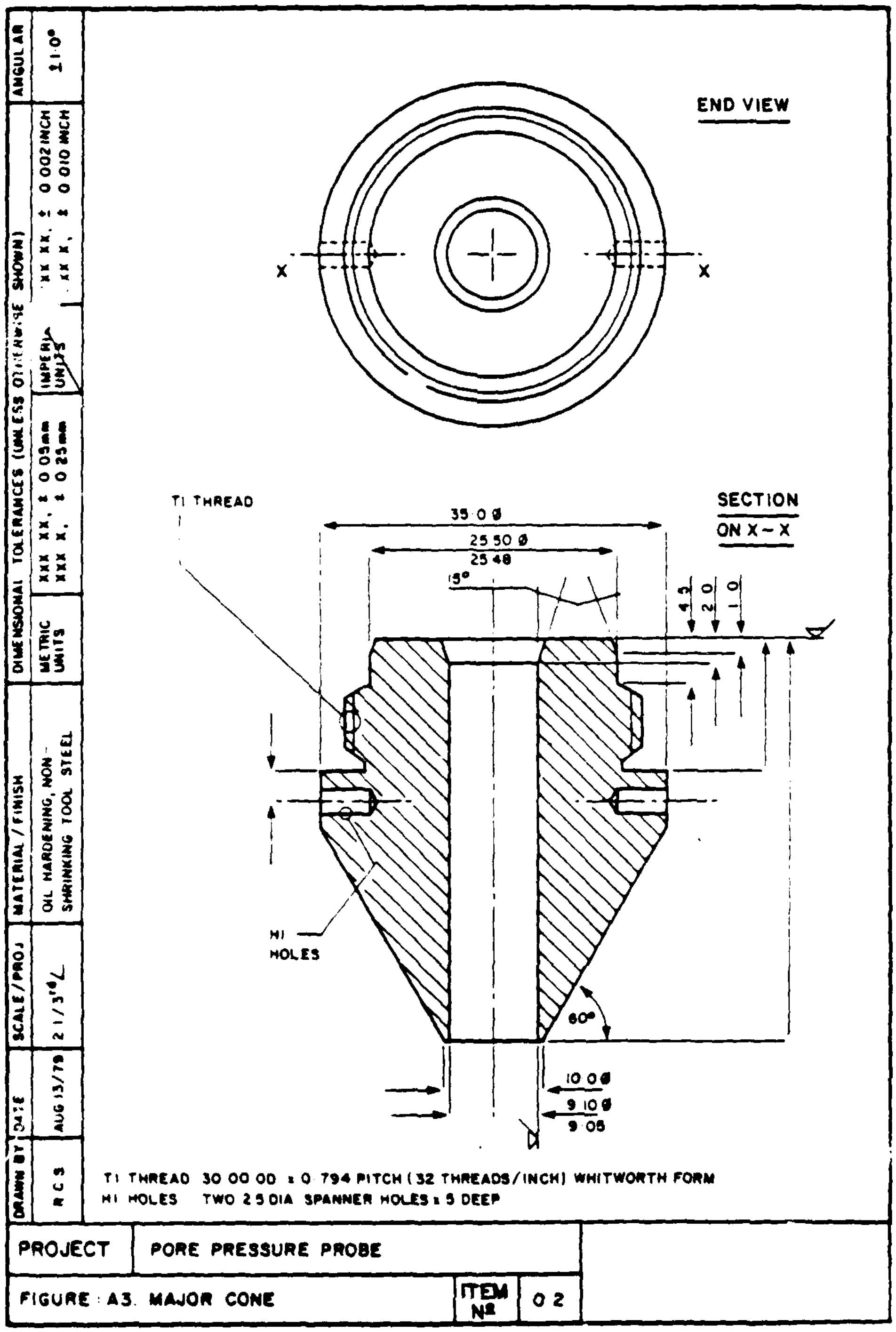


Figure A3. Major Cone

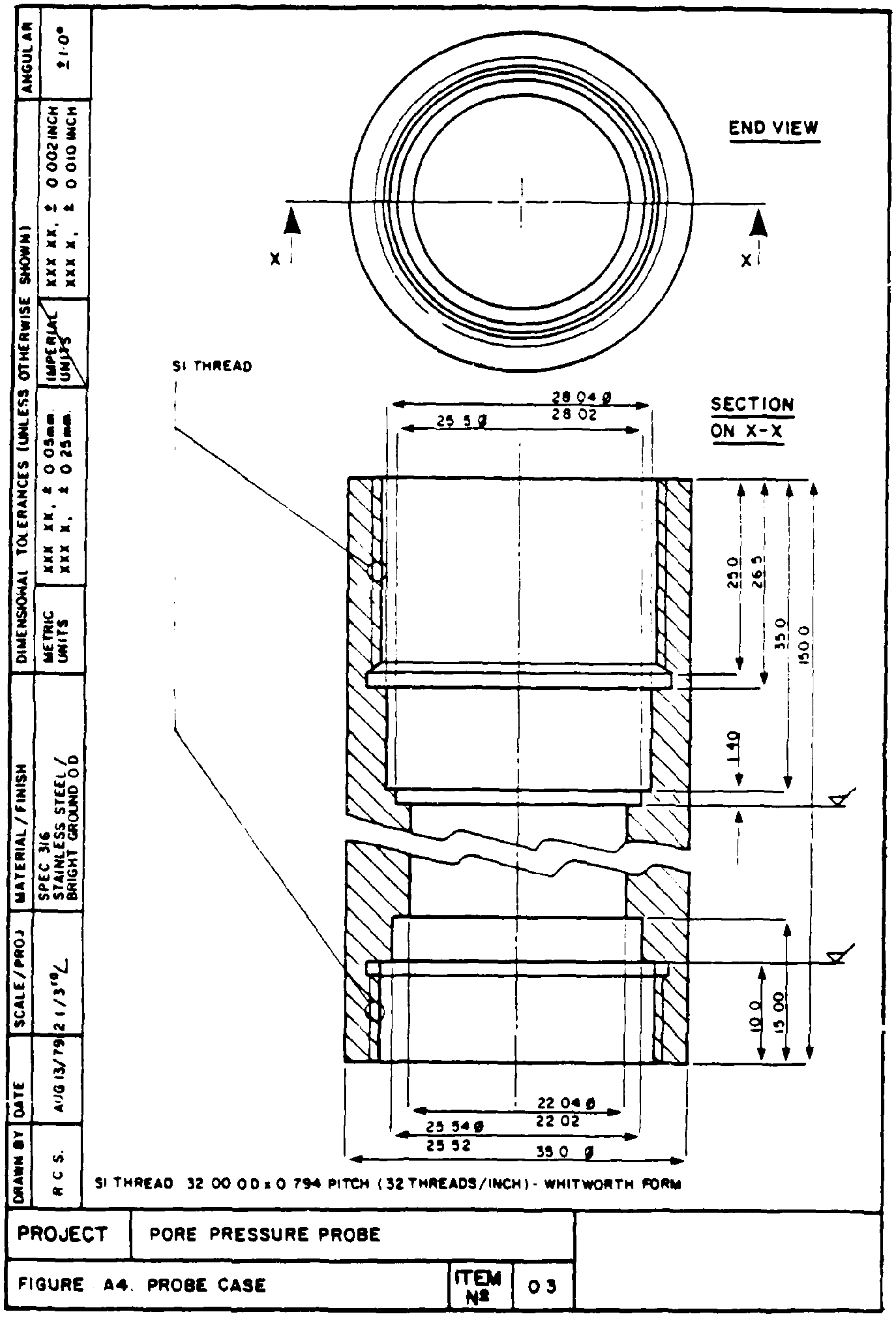


Figure A4. Probe Case

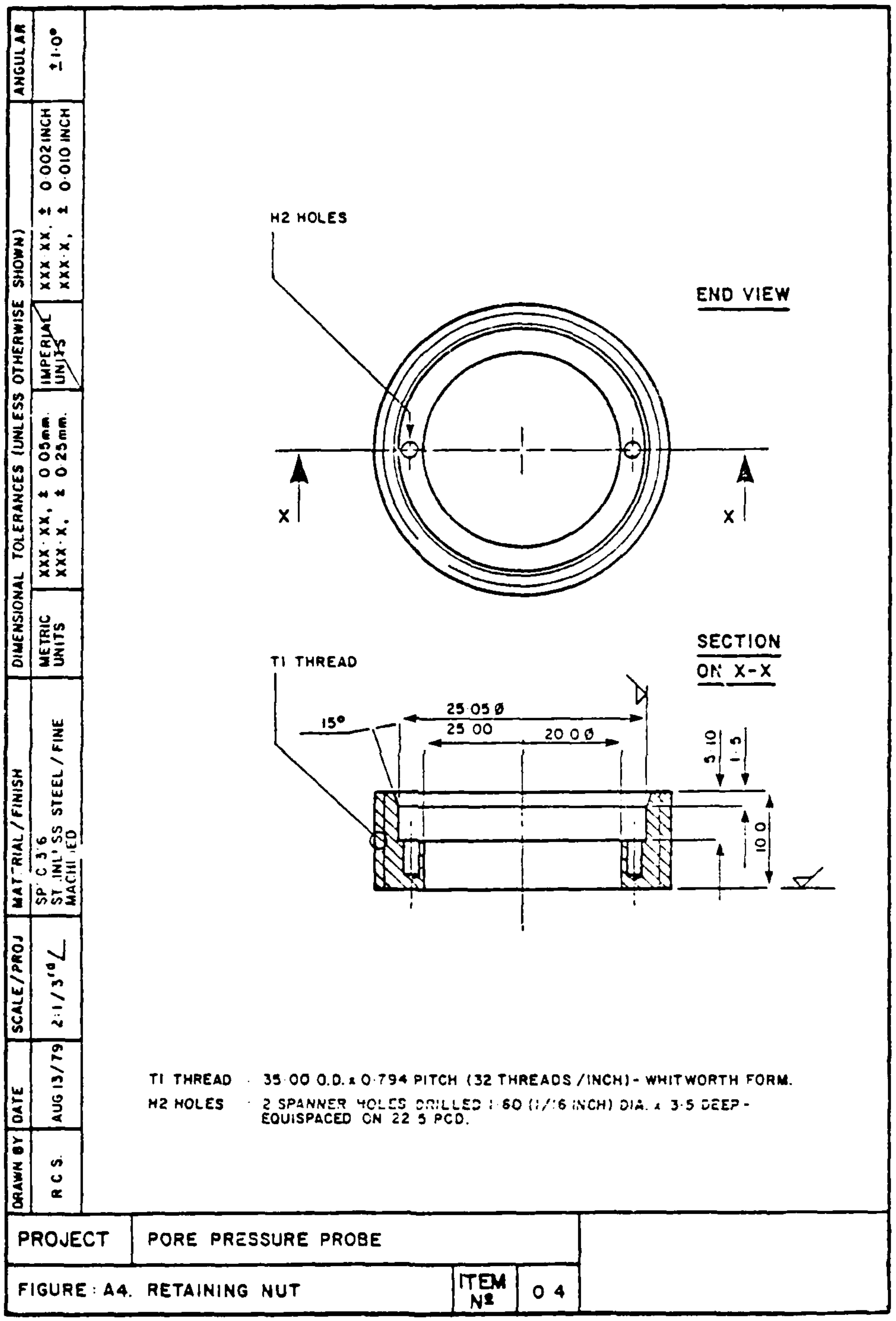


Figure A5. Retaining Nut

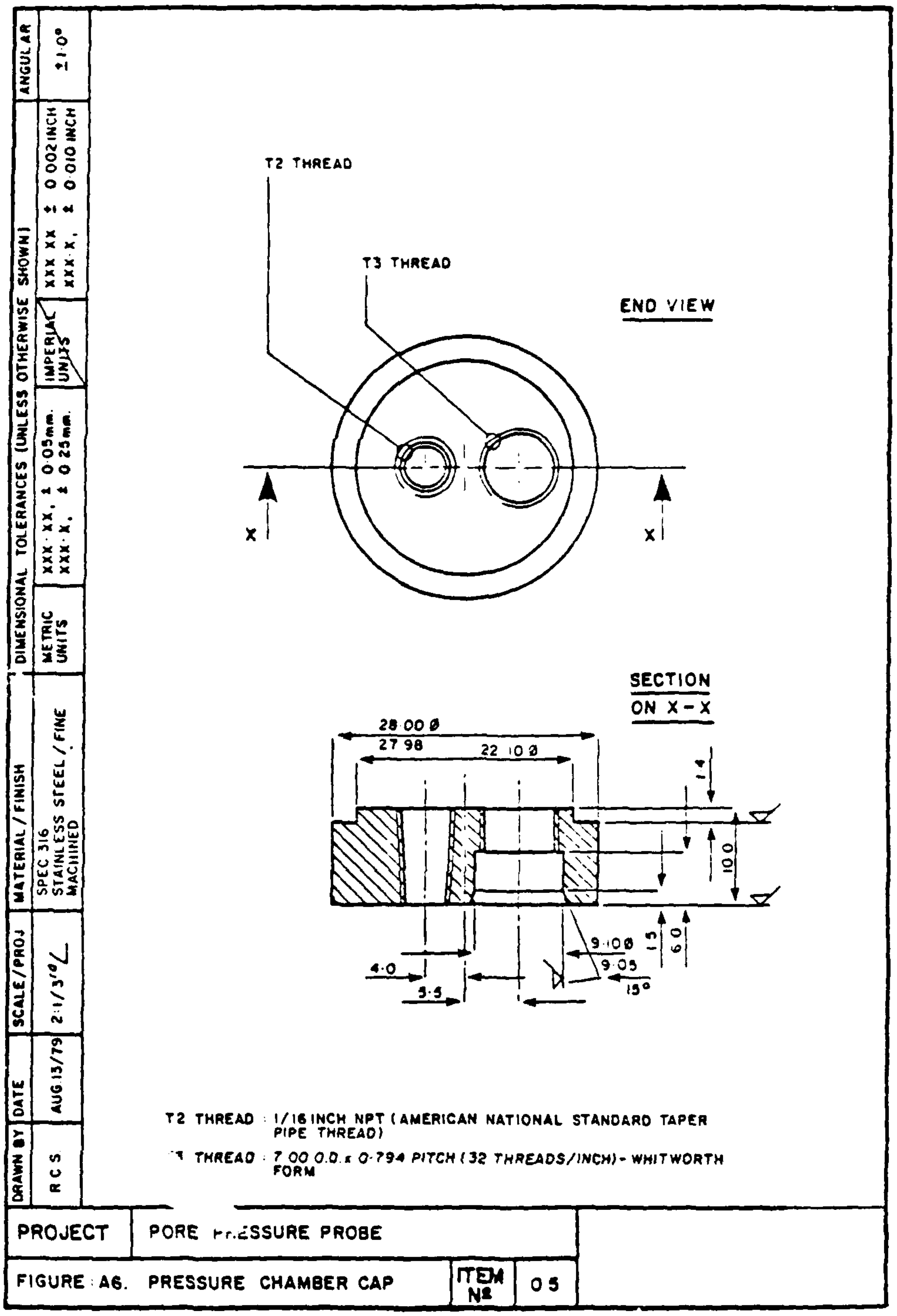


Figure A6. Pressure Chamber Cap

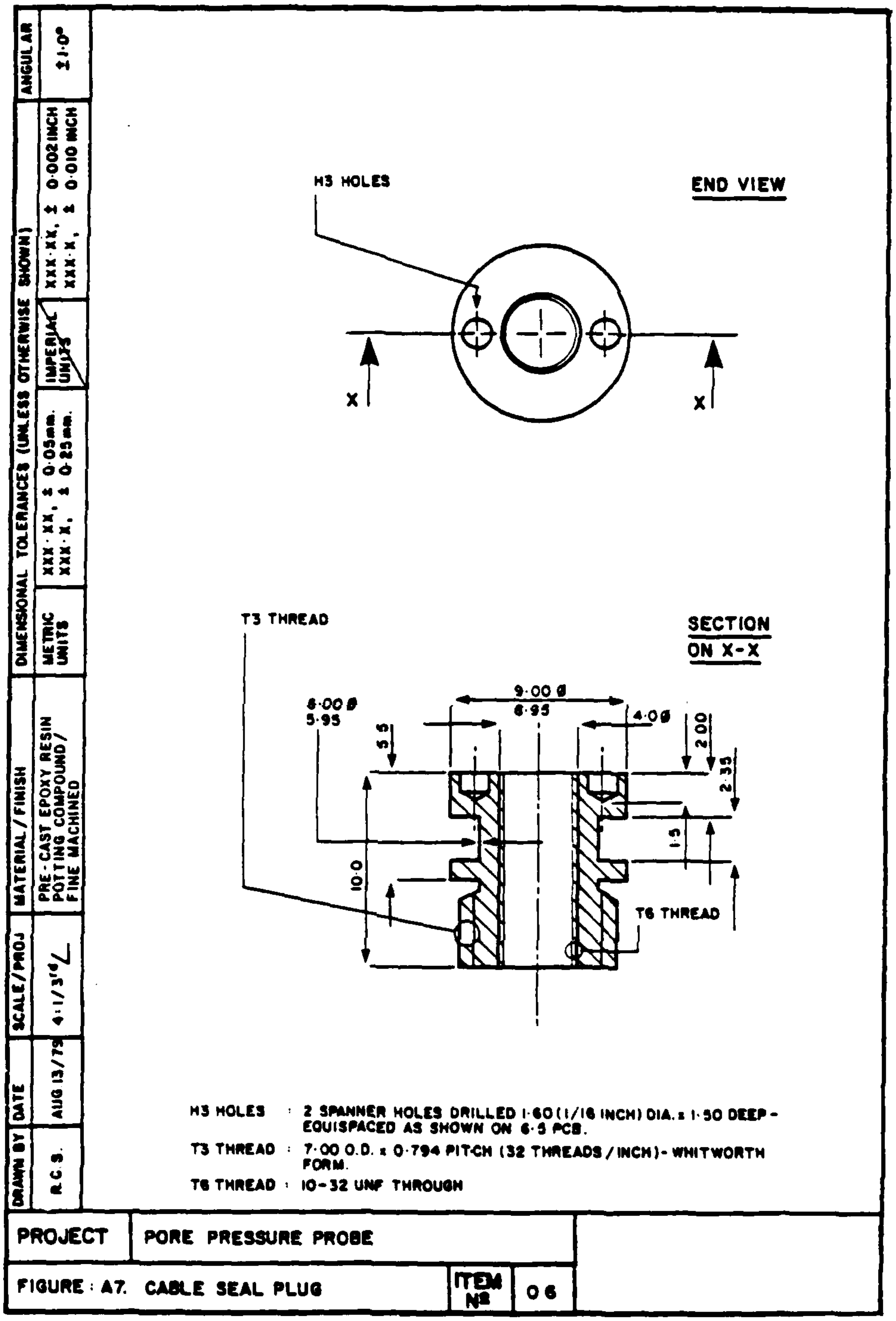


Figure A7. Cable Seal Plug

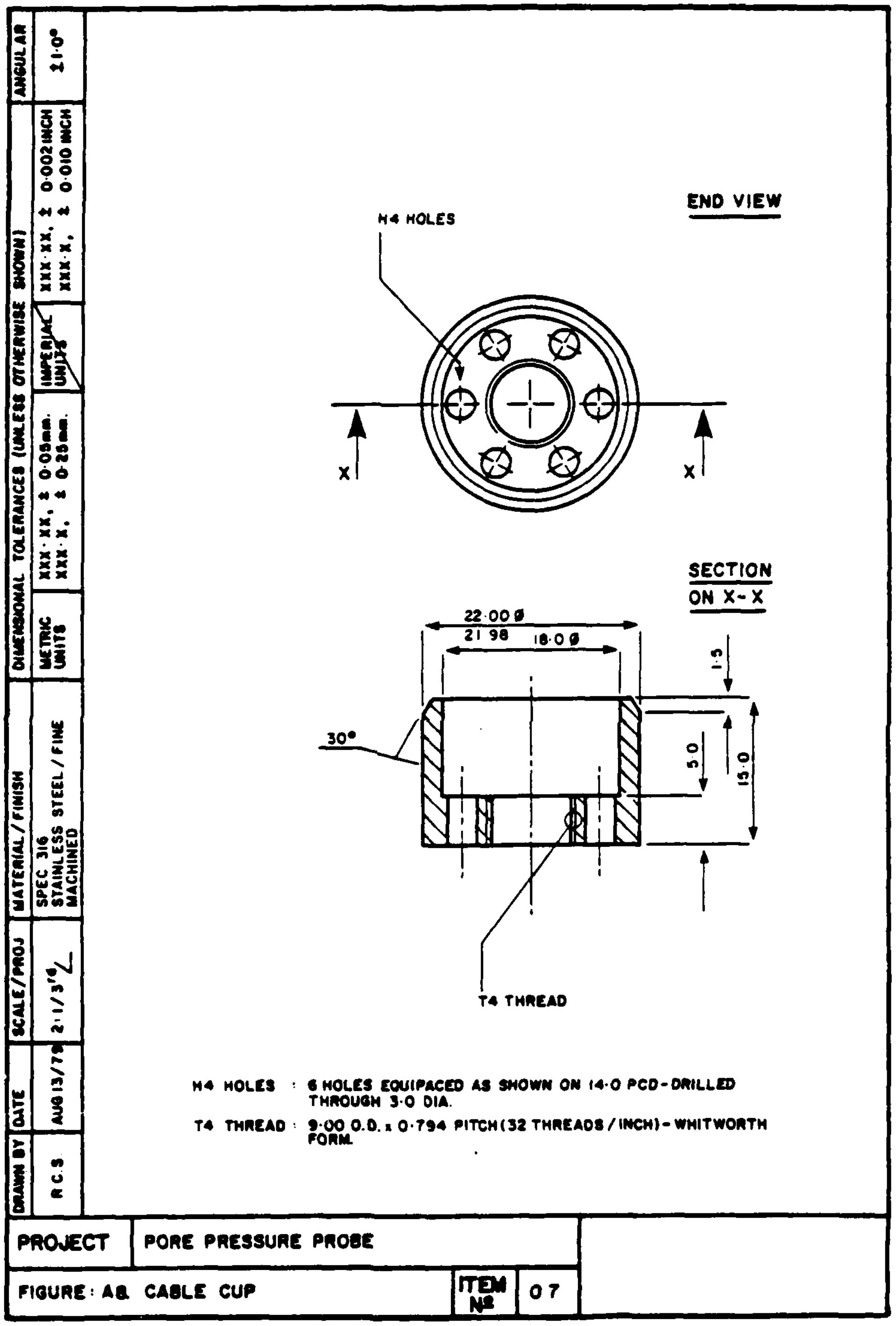


Figure A8. Cable Cup

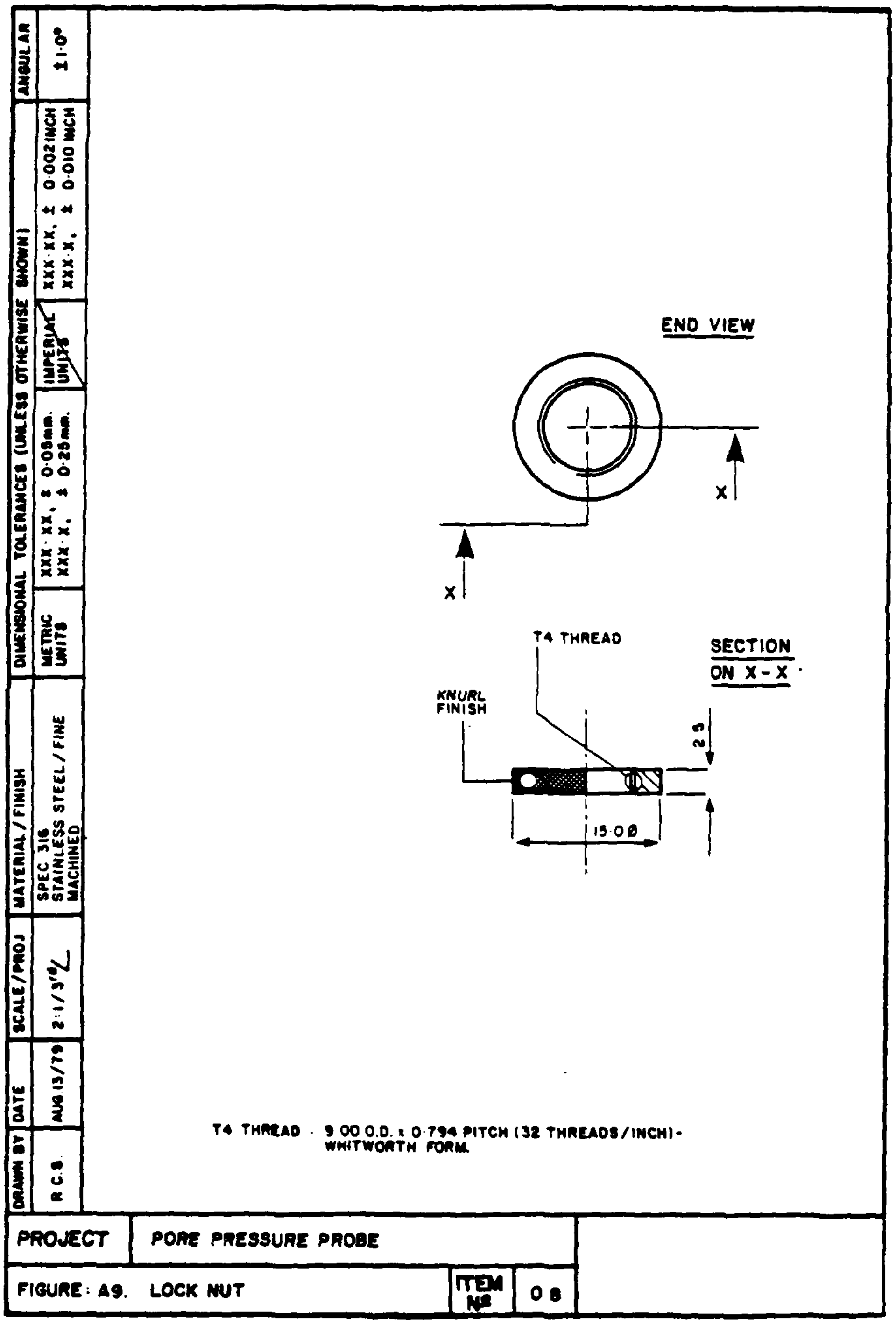


Figure A9. Lock Nut

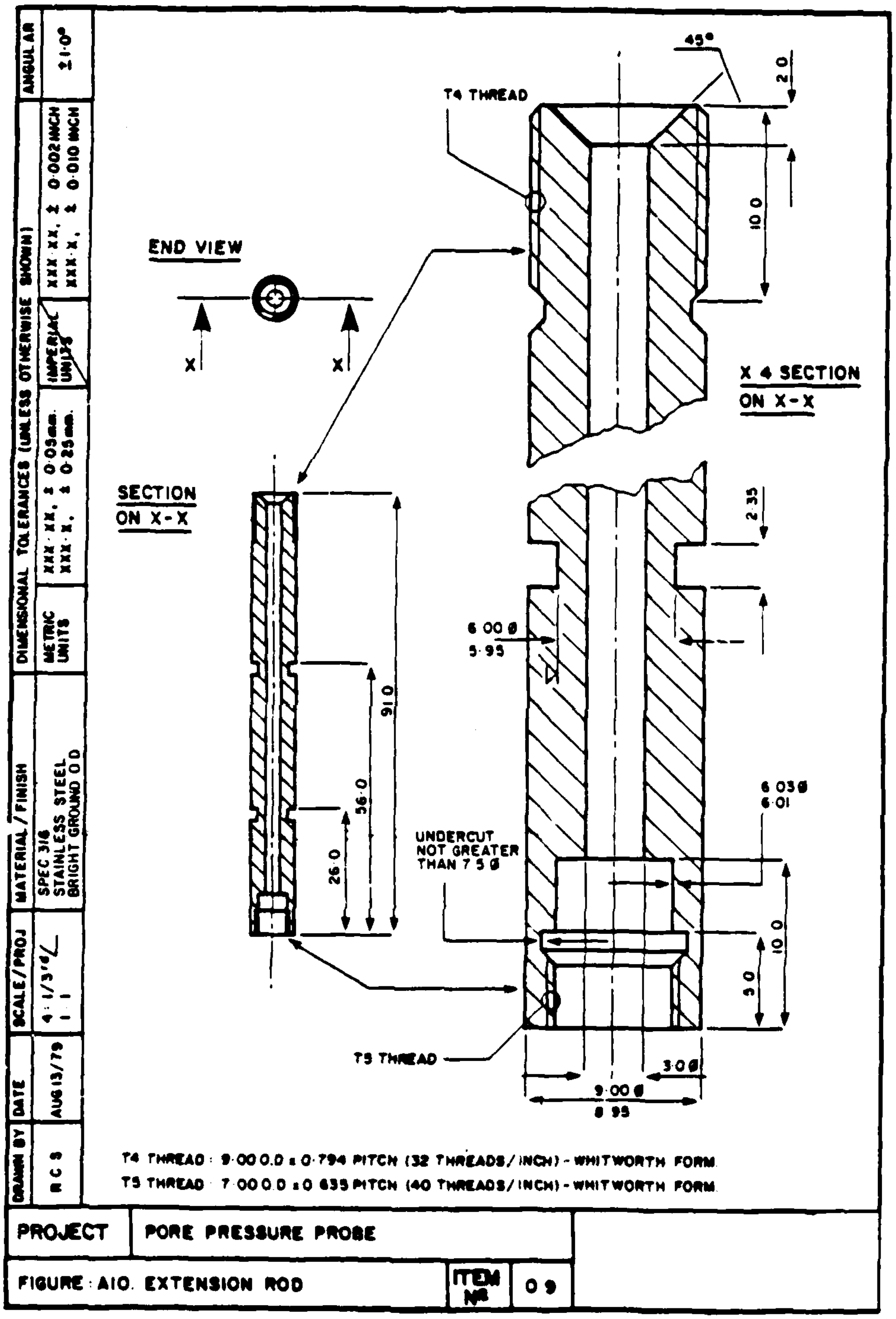


Figure A10. Extension Rod

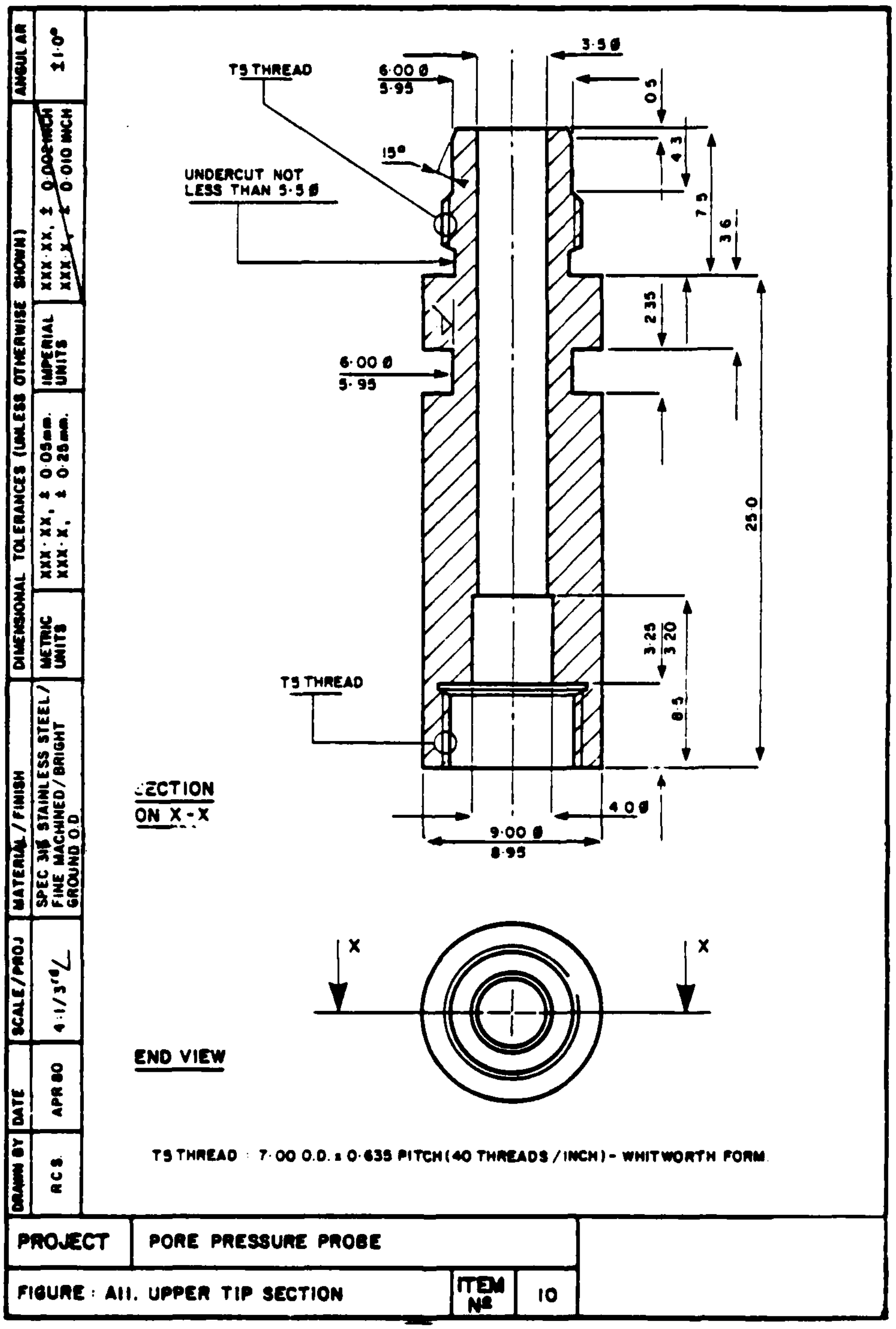


Figure A11. Upper Tip Section

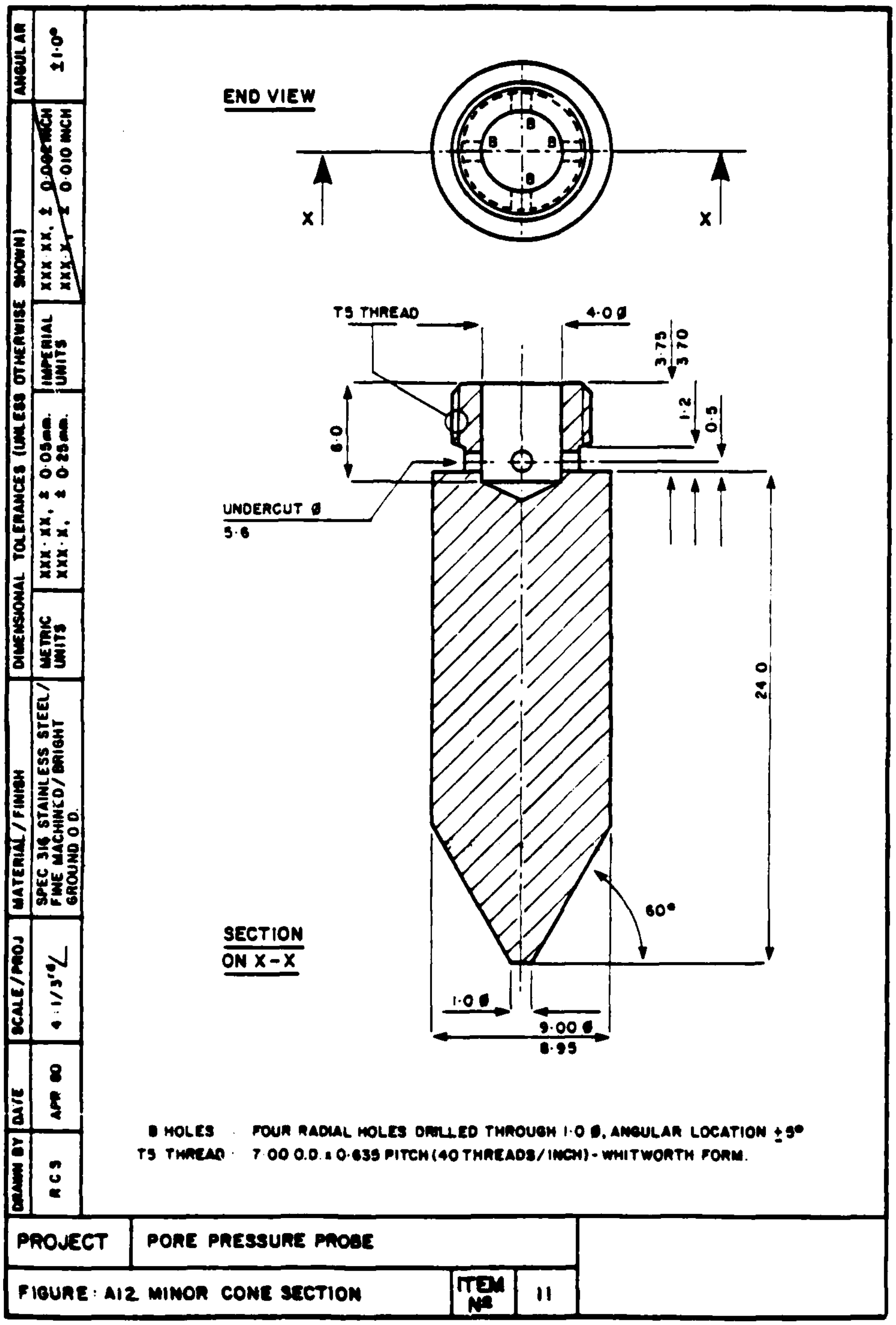


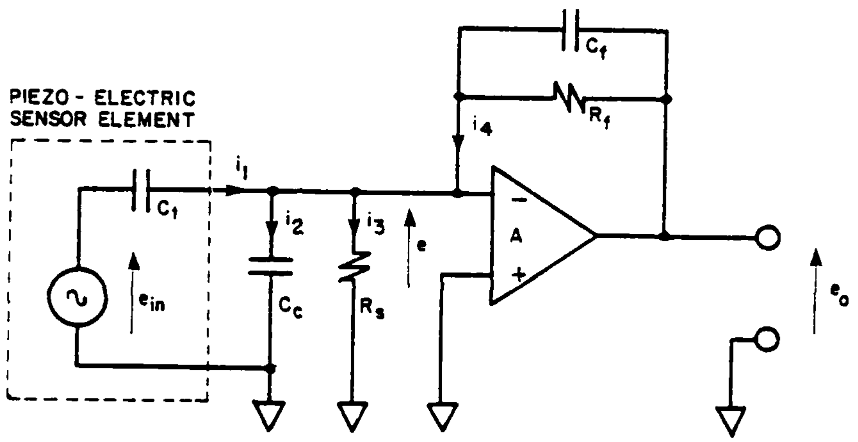
Figure A12. Minor Cone Section

APPENDIX B

CALCULATION OF THE LOW FREQUENCY RESPONSE OF THE MEASUREMENT SYSTEM

Following is an analysis of the low frequency model of the charge amplifier as used in laboratory testing. The analysis indicates the relationship of amplifier feedback components to sensor and cable parameters in establishing low frequency response.

Figure B1. Circuit for Analysis of Charge Amplification



For the above circuit let:

e_{in} = open circuit emf generated by the piezoelectric transducer

q_{in} = charge generated by the transducer, $q_{in} = e_{in} C_t$

e_o - output voltage of the amplifier

e = differential input voltage of the amplifier

i_1, i_2, i_3 and i_4 = summing junction currents

A = low frequency differential voltage gain of the amplifier

C_t = capacitance of the piezoelectric transducer

C_c = capacitance of the connecting cable

R_s = shunt or leakage resistance across the transducer

R_f = DC stabilization feedback resistance

C_f = gain determining feedback capacitor

Referring to the circuit diagram, the following equations can be written:

$$i_1(s) = sC_t[e_{in}(s)-e(s)] \tag{B1}$$

$$i_2(s) = sC_c e(s) \tag{B2}$$

$$i_3(s) = \frac{e(s)}{R_s} \tag{B3}$$

$$i_4(s) = sC_f+\frac{1}{R_f}[e_o(s)-e(s)] \tag{B4}$$

$$e_o(s) = -Ae(s) \tag{B5}$$

$$q_{in}(s) = C_t e_{in}(s) \tag{B6}$$

$$i_1(s)+i_4(s) = i_2(s)+i_3(s) \tag{B7}$$

Where s is the complex Laplace operator (note: initial conditions have been ignored, i.e.: only the steady state frequency response is required). By substituting for e(s) from Equation B5 into Equation B1 - B4 and combining according to Equation B7 the following equation results:

$$\frac{e_o(s)}{A\ R_f\ R_s}\ [s[C_tR_fR_s+C_fR_sR_f[A+1]+R_fR_sC_c]+R_s[A+1]+R_f] = -sC_te_{in}(s)$$

Substituting from Equation B6 and rearranging gives:

$$\frac{e_o(s)}{q_{in}(s)} = \frac{-Ks}{1+s\tau_\ell} \tag{B8}$$

Where τ_ℓ is the time constant of the circuit, and K/τ_ℓ is the operating frequency range charge gain.

$$K = \frac{AR_f R_s}{R_f + R_s[A+1]} \tag{B9}$$

and:

$$\tau_\ell = \frac{R_f R_s [C_t + C_c + C_f[A+1]]}{R_f + R_s[A+1]} \tag{B10}$$

The frequency response can be calculated from B8 by substituting $S = j\omega$ where j is the complex operator, $\sqrt{-1}$, and ω is the radian frequency. The response is esaily graphically determined, however, by the use of the familiar Bode plot:

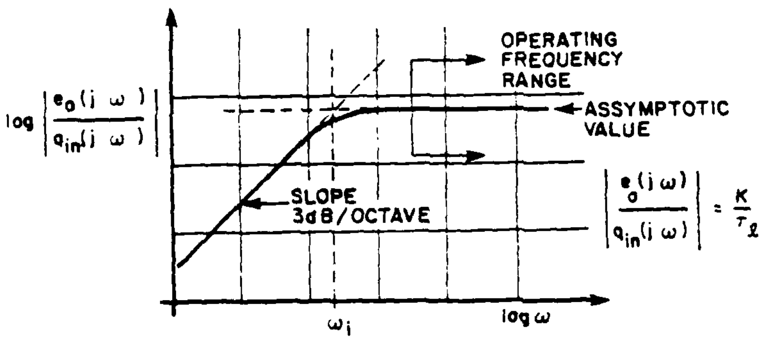


Figure B2. Bode Plot of the Low Frequency Response of the Measurement System.

From Equation B10 it can be seen that as the voltage gain A of the amplifier approaches infinity, τ_ℓ tends to $C_f R_f$, i.e., the low frequency response is determined by the amplifier feedback components. This condition holds providing $[A+1]C_f >> C_c + C_t$ and $[A+1]\ R_s >> R_f$. Given this condition, the operating frequency range gain, $\frac{K}{\tau_\ell}$ is also determined exclusively by the feedback elements in the circuit.

For the pore pressure probe, typical values for the measurement system parameters are as follows:

A, typically 10^5

C_f, typically 5×10^{-10} F

R_f, typically 10^9 (gives charge amplifier time constant of

0.5 s

C_t, 2.2×10^{-10} F

C_c = 100 pF/m, assume 20 m of cable giving C_c - 2×10^{-9} F

R_s, as measured in the laboratory testing $10^9 < R_s < 10^{11}$

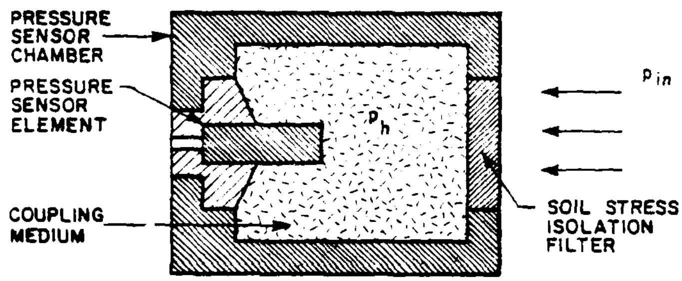
These values indicate that the above inequalities are held by a relatively wide margin, and consequently that the gain and low frequency time constant of response of the measurement system can be held essentially constant by the use of charge amplification.

APPENDIX C

CALCULATION OF THE UPPER FREQUENCY RESPONSE OF THE MEASUREMENT SYSTEM

Following is the analysis of sensor response modelled under the initial design approach for a porous sintered filter. Although a slot filter design was ultimately used the analysis serves to indicate that the sensing scheme contains nothing to limit upper frequency response to less than the required 2kHz.

Figure C1. Hydraulic Model of the Instrumented Tip.



For the above figure let:

P_{in} = external pressure applied to the system

P_h = hydrostatic pressure inside the chamber impinging on the sensor element

q = volumetric inlet/outlet flowrate

K_c = total effective bulk modulus of the chamber and its contents

V_c = effective volume of the pressure chamber

A_f = effective area of the filter normal to the flow q

L_f = effective length of the filter in the direction of q

α = permeability coefficient of thefilter

η = dynamic viscosity of the pressure coupling medi a

t = time

The following basic relationships can be written:

$$q(t) = \frac{A_f\alpha[p_{in}(t)-p_h(t)]}{L_f\eta} \tag{C1}$$

$$q(t) = \frac{dV_c(t)}{dt} \tag{C2}$$

$$K_c = V_c \frac{dp_h}{dV_c} \tag{C3}$$

the flow q, as defined in Equation C2, can be introduced into Equation C3 by writing:

$$K_c = V_c \frac{dp_h(t)}{dt} \frac{dt}{dV_c(t)} \tag{C4}$$

eliminating q between Equation C1 and C4 gives:

$$\frac{A_f\alpha[p_{in}(t) - p_h(t)]}{L_f\eta} = \frac{V_c}{K_c} \frac{dp_h(t)}{dt}$$

rearranging and writing in Laplace form (s is the Laplace operator):

$$\frac{A_f\alpha}{L_f\eta} + \frac{sV_c}{K_c} p_h(s) = \frac{A_f\alpha}{L_f\eta} p_{in}(s)$$

giving the transfer function

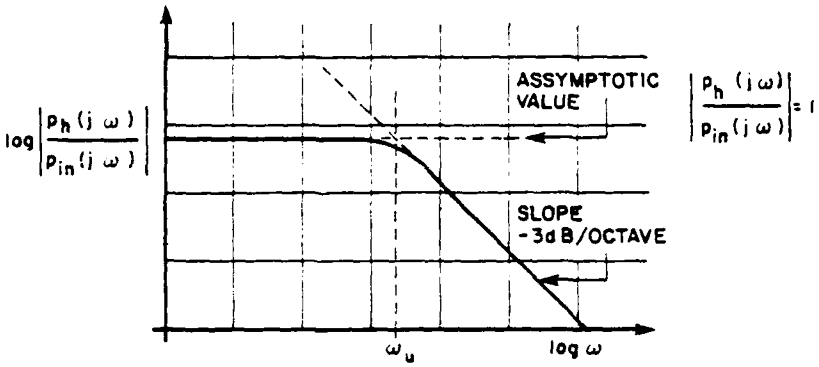
$$\frac{p_h(s)}{p_{in}(s)} = \frac{1}{1+s\tau_u} \tag{C5}$$

where the characteristic time constant τ_u is given by:

$$\tau_u = \frac{L_f \eta V_c}{K_c A_f\alpha} \tag{C6}$$

As with the analysis in Appendix B, the substitution $s = j\omega$ is used to calculate the frequency response of the system. For this simple first order analysis it is easily graphically presented. Figure C2 below is the Bode Plot of the response:

Figure C2. Bode Plot Depicting the Upper Frequency Limit of the Measurement System.



For calculating the effective bulk modulus of a system such as the pressure chamber of Figure C1, assume:

V_1 = volume of pressure sensor element and mounting arrangement

V_2 = volume of the surrounding coupling medium

K_1 = effective bulk modulus of the sensor system

K_2 = bulk modulus of the coupling medium

Hence, under an increment of chamber pressure δp_h, the corresponding incremental change in volume, δV_c, is given by:

$$\delta V_c = \delta V_1 + \delta V_2$$

which, from the definition of bulk modulus in Equation C3 gives:

$$\delta V_c = \delta p_h \frac{V_1}{K_1} + \frac{V_2}{K_2}$$

which can be rearranged to yield

$$K_c = \frac{(V_1+V_2)}{V_1K_2 + V_2K_1} \qquad (C7)$$

For a cylindrical sensing element of diameter d_1 length ℓ, in a cylindrical pressure chamber diameter d_2, of the same length, the effective bulk modulus, K_c is given by:

$$K_c = \frac{d_2^2 K_1 K_2}{d_1^2 K + [d_2^2 - d_1^2] K_1} \qquad (C8)$$

For the early configuration of theinstrumented tip the following values were estimated or derived (SI Units):

$K_1 = 1\times10^{10}$	$d_1 = 2.67\times10^{-3}$	$\alpha = 2.6\times10^{-11}$
$K_2 = 2.3\times10^{9}$	$d_2 = 6\times10^{-3}$	η (water) $= 1.02\times10^{-2}$
$L_f = 1\times10^{-3}$	$\ell = 5\times10^{-3}$	

For the above values an effective K_c of 2.71×10^{9} results. If the cylindrical filter is thin, the ratio $\frac{V_c}{A_f} \approx \frac{d_2}{4}$.

The roll-off frequency f_u corresponding to the characteristic time constant τ_u is given by:

$$f_u = \frac{1}{2\pi\tau_u}$$

which, for the above values yields a frequency in excess of 700 kHz. Many other factors, neglected in this analysis, would be apparent well below frequencies of this order. The result does show, however, that as a reasonably conservative estimate, a margin of at least two orders of magnitude is permissible in the values of the parameters used in the above analyses before the bandwidth of the system is noticeably degraded.

APPENDIX D

ASSEMBLY PROCEDURES

D1 PREPARATION OF THE INSTRUMENTED TIP UNITS FOR ASSEMBLY INTO THE PROBE

In this procedure, an assembly bush (part of the delivered hardware consignment) is required. This component is a cylindrical part with a stepped through bore. The smaller bore is a locating fit over the cable cup 07 (see Fig. A1) and the larger bore locates on the outside diameter of the pressure chamber cap 05.

a. Check that O-ring K is in place on the cable seal plug 06 of the instrumented tip assembly and ensure that the upper rim of the cable cup 07 and the lower plane face of the pressure chamber cap 05 are clean and free from oil or grease;

b. Smear a light film of silicone grease onto the cable seal plug O ring and screw the plug into the cable cap;

c. Coil the interconnecting leadwire into the cable cup such that the cup butts against the chamber cap without pinching the leadwires;

d. Apply approximately six small dots of Loctite IS495 cyanoacrylate adhesive around the rim of the cable cup. Position the locating bush over the cup and, using the bush to center the assembly, bring the cup and chamber cap together. Apply hand pressure for 1 min, leave to cure for 12 h;

e. Fill a suitable syringe* with a charge of silicone grease taking care to avoid entraining air;

f. Unscrew the minor cone section from the instrumented tip assembly and fill both the minor cone recess and the recess containing the pressure sensor element with silicone grease. This is best achieved by placing the nozzle

*The most suitable syringe for this purpose (supplied with the hardware consignment) has been found to be a moulded polyethylene type with a narrow flexible nozzle.

of the grease injection syringe at the bottom of the recesses, commencing injection, and withdrawing the nozzle while maintaining a flow of grease. For the lower tip section ensure that the rate of injection is sufficient to force grease through the radial drill holes in the threaded shoulder of the component;

g. Bring the minor cone into position and screw home, excess grease is extruded through the circumferential slit aperture.

In the above procedure, take care not to remove or misplace any steel shim (packing) washers that may be found in the instrumented tip assemblies. These washers are incorporated in certain of the tips to adjust the gap width of the circumferential slit filter.

D2 ASSEMBLY OF THE PROBES FOR FIELD USE

This section lists the steps to be followed in assembling the instrumented tips into the probes, and charging them with silicone grease as the tip ejection hydraulic medium.

a. Place the bonded instrumented tip and pressure chamber cap assembly in position in the recessed upper section of the probe case. Ensure that the lower seating O ring J is in position and that the hydraulic bulkhead fitting C is mounted in the cap. The hydraulic fitting is a taper threaded unit. To ensure sealing use PTFE tape or penetrating adhesive (Loctite hydraulic sealant 542 or equivalent) on the thread.

b. Place the seating O ring J in position over the shoulder on upper face of the pressure chamber cap. Using the special pin spanner tool (see photograph Figure E4), screw home the retaining nut 04. Before bottoming, compression of the upper and lower chamber cap O rings should be felt on the last one or two turns of the nut. Ensure that the O rings and all surfaces contacting them are smeared with silicone grease. Note: Stainless steel to stainless steel threaded systems can pick-up and jam if care is not exercised. Ensure all threads are free from grit or other solid matter and smear with silicone grease before assembly;

c. Fill the grease injection gun as follows:

(1) Detach the rear cap, remove the piston assembly and retract the piston back to the cap.

(2) Take nominal 100 g tube of silicone grease, cut off the nozzle section to produce a large opening from which the grease can be discharged.

(3) Hold the barrel of the grease gun in a bench vice and press the tube of grease to the cap end of the barrel, extrude the grease into the barrel taking care to maintain contact between the barrel and the shoulder of the tube.

(4) Refit the cap and piston unit and screw in the piston until a void free slug of grease emerges from the free end of the barrel.

d. Position the lower case seal O ring J and attach the grease gun to the probe. Check that the hydraulic fitting in the pressure chamber bulkhead is uncapped and commence filling. When grease emerges from the hydraulic fitting, continue operating the grease gun until the discharge is free of voids.

e. Remove the gun and check that the lower case seal O ring is still in position. Heavily smear the bore of the major cone with silicone grease and screw the unit into place using a tommy bar or hook spanner on the radial holes in the component. This stage of the assembly procedure takes time due to the viscose nature of the silicone grease. Do not try to force the cone home, allow time for the excess grease to be expelled via the bulkhead fitting.

f. With the major cone fully home, cap the hydraulic fitting and screw in the connector cover O1. This component provides protection for both the internal case thread of the probe and the service fittings on the bulkhead.

APPENDIX E

PHOTOGRAPHS OF THE PROBE AND ASSOCIATED EQUIPMENT

The following pages are a selection of photographs of the Pore Pressure Probe and of the associated equipment designed during the couse of the development program.

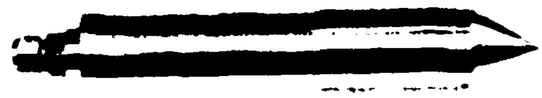


Figure E1. General view of the Pore Pressure Probe.

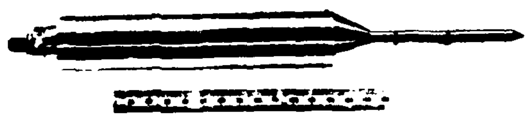


Figure E2. Ejection of the instrumented tip.

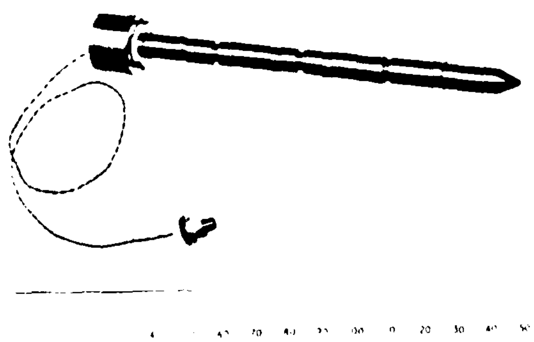


Figure E3. The instrumented tip assembly.

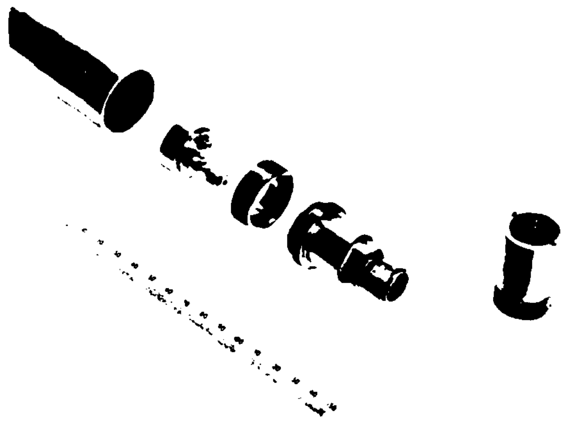


Figure E4. The upper case section components and the pin spanner assembly tool.

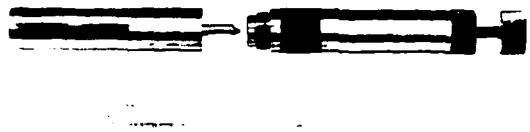


Figure E5. Grease gun and probe prior, to attachment.

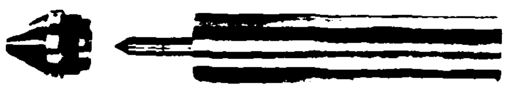


Figure E6. View of the probe with the major cone removed.

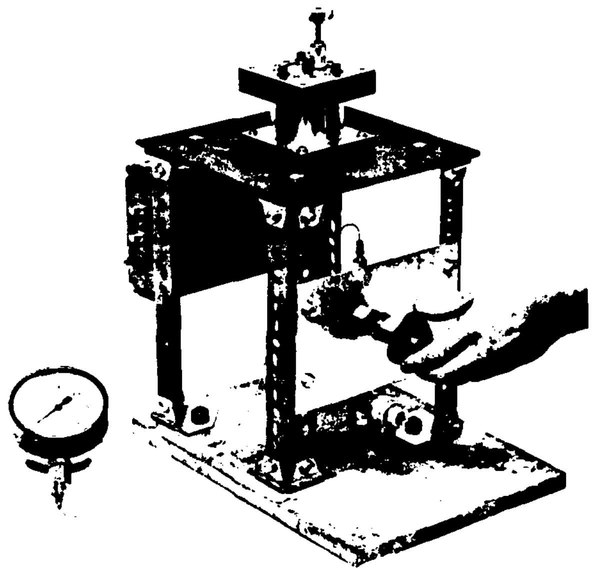


Figure E7. View of the pressure chamber system test rig.

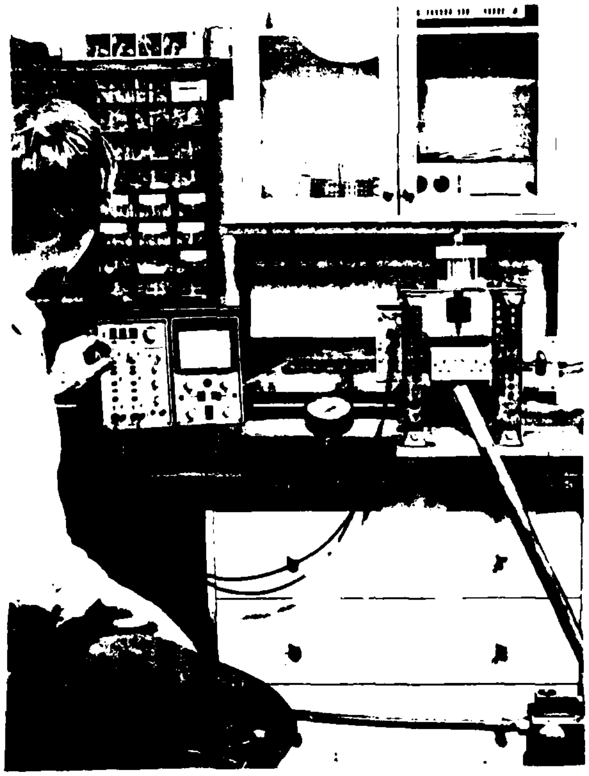


Figure E8. The laboratory equipment set up.

DATE
ILMED
– 8