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CONSOLIDATION CHARACTERISTICS DETERMINATION FOR PHOSPHATIC CLAYS

VOLUME 1: Seepage Induced Consolidation Test Equipment Description and Users Manual

Prepared By
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CONSOLIDATION CHARACTERISTICS DETERMINATION FOR PHOSPHATIC CLAYS

Final Report
(FIPR contract No. 90-02-084)

VOLUME 1: Seepage Induced Consolidation Test Equipment Description and Users Manual

Prepared for
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PERSPECTIVE

Patrick Zhang, Research Director

Phosphate mining and beneficiation produce large quantities of phosphatic clay. Approximately one ton of such clay is generated for each ton of phosphate product. Nearly 100,000 tons/day of waste clay are generated by the active phosphate mines in Florida. The waste clay creates one of the most difficult disposal problems in the mining industry.

Conventionally, the clay is disposed of in settling areas by transporting it in a slurry form, at an average density of 3 to 4% solids. The traditional phosphatic clay disposal procedure is quite simple. 20- to 60-ft high dikes are constructed around areas 300 to 800 acres in extent. The clay slurry (3 to 5 pct solids) is pumped into the impoundments at a rate of 20,000 to 80,000 gpm. During natural settling, most clays consolidate to 12 to 15% solids within 3 to 30 months. After the initial settling, surface water is drained from the settled material, which allows the solids to desiccate and form a crust. Frequently, sand tailings and/or overburden materials are used to cap the clays to promote further consolidation and compaction.

This conventional clay disposal method does have a few advantages:

(1) The impoundments can be used as reservoirs for process water.

(2) The reservoirs collect rain water so that withdrawal of deep well water is reduced.

(3) It is the most cost effective method currently available.

Although most of the mechanical and electrical dewatering processes can dramatically enhance consolidation of the phosphatic clays, none of them is economical under current economic condition. Seepage induced natural consolidation with or without addition of additives will continue dominating the disposal/reclamation of phosphatic clay in the near future.

From the Florida Phosphatic Clays Research Project to the Florida Institute of Phosphate Research, the development of a reliable numerical model has been given a high priority. As a result of two-decade extensive research, several computer programs, based on the finite strain consolidation theory, have been introduced in the phosphate industry. A few of the models have proven to be invaluable tools in planning the size of required settling area and in predicting in predicting time at which reclamation is technically feasible. However, these models have limited or no use without the input of some parameters, of which

compressibility and permeability are the most important.

In 1991, the Florida Institute of Phosphate Research (FIPR) awarded a research grant to University of Colorado to develop a rapid technique for determining compressibility and permeability of phosphatic clays. A rapid, accurate and sophisticated measurement system has been developed. The technique is based on the seepage induced consolidation test, and the analysis procedure utilizes an inverse problem solution technique for parameter estimation.

This technique offers the following advantages:

(1) Determination of permeability can be done within two to three days, which presents substantial savings in terms of time and efforts when compared to the alternate methods that may require weeks or months to obtain the same experimental data.

(2) Acquisition and processing of data are all performed by a computer.

(3) Accurate consolidation data may be obtained.

(4) The system is relatively inexpensive.

The technique has been enthusiastically endorsed by some engineering companies and the DNR of Florida. There was even "rumors" that the technique would be adopted by all the Florida phosphate mining companies. FIPR is currently using the system to supply data for a phosphatic clay consolidation/reclamation project. Except for occasional mechanic problems, the system is reliable and gives data that are comparable to those obtained by the conventional technique.

TABLE OF CONTENTS:

INTRODUCTION

The equipment required to perform seepage induced consolidation tests is described in this manual together with the step by step procedure for preparing the samples and performing the tests. The test analysis is performed using the computer program SICTA which is described in a separate users manual (Abu-Hejleh and Znidarcic, 1992). The testing procedure described herein includes a standard form in which the test parameters are input and prepared for the analysis using program SICTA. All units in this manual are consistent with the SI system of units, however, they can be converted into any other consistent system of units and used in the SICTA program. This manual relates to the specific equipment constructed for this project but any other equipment in which the seepage induced consolidation tests can be performed may be used to generate data required for the analysis using the program SICTA.

The equipment with all technical data is described in chapter two of this report. The step by step sample preparation and testing procedures are described in chapter three together with the description of the data necessary for the analysis using program SICTA.

Abu-Hejleh, A.N. and Znidarcic, D., (1992). User Manual for Computer Program SICTA,Prepared for FIPR, University of Colorado, Boulder

EQUIPMENT DESCRIPTION

The seepage induced consolidation testing system consists of five major parts.

* pressure control panel
* flow pump
* sample cell with the differential pressure transducer
* loading system
* data acquisition system

Each part of the system with all the technical data is described in the subsequent sections of this chapter.

Pressure Control Panel

A schematic drawing of the pressure control panel is given in Figure 1. The panel has a dual purpose: to provide the necessary back pressure for the sample and to provide air pressure for the loading mechanism. The two functions are separated on the panel except that they have a common air supply and a common pressure gauge. The left part of the panel controls the back pressure while the right part of the panel controls the load.

The back pressure part consists of a pressure regulator, a water reservoir and three ball valves to control the flow of water and air. The valve #1 controls the air pressure intake into the reservoir. It is a three way

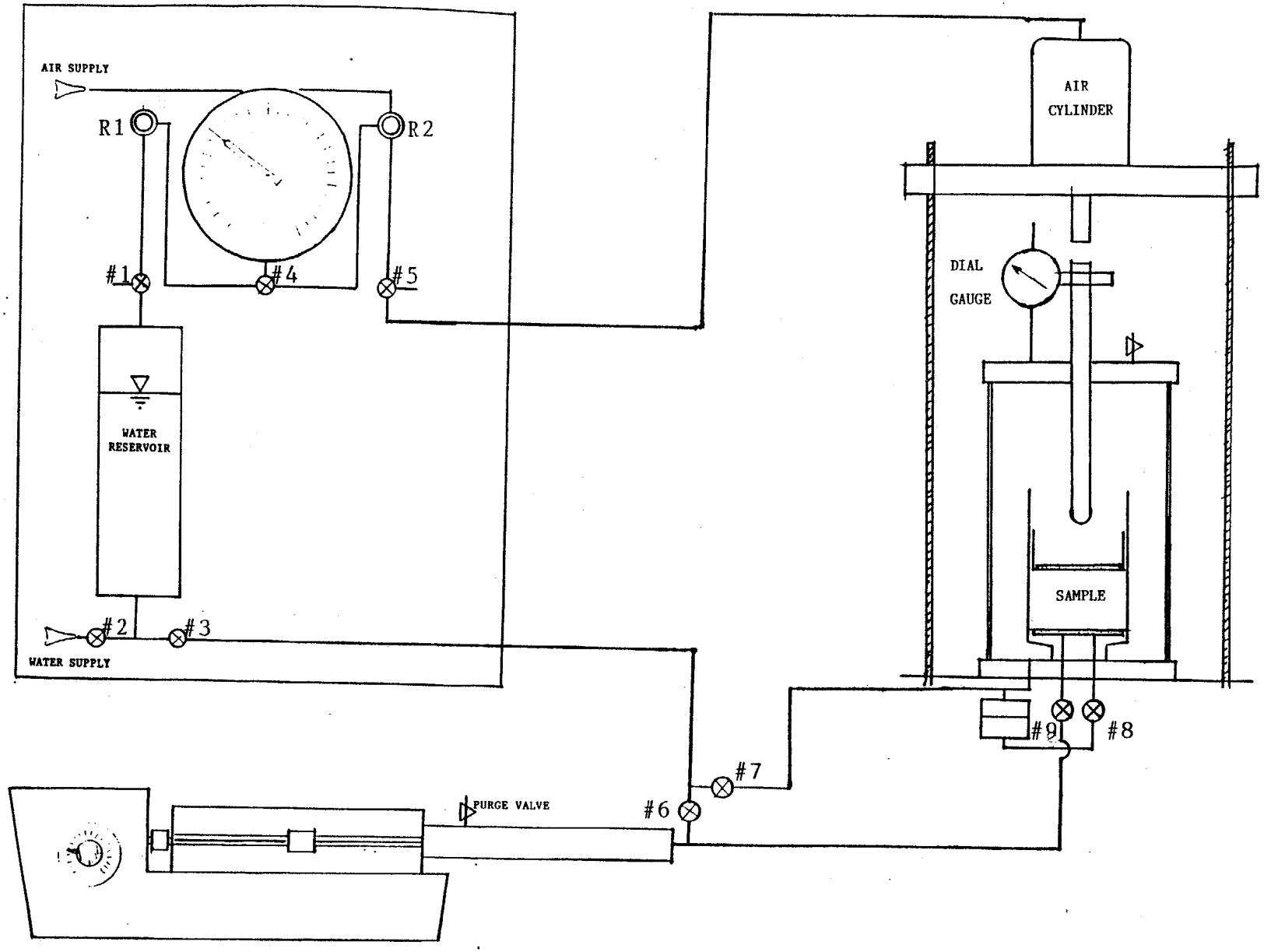


Figure 1 - Seepage Induced Consolidation System

valve which can be in the OFF position, ON position or VENT position. In the VENT position the reservoir is open to the atmosphere and it can be readily filled with water or emptied under gravity flow. In the ON position the air pressure set with the pressure regulator R1 is applied to the reservoir. In the OFF position the reservoir is isolated from the pressure as well as from the atmosphere which creates an air cushion above the water in the reservoir. This is a convenient feature when filling the sample cell with water as will be described in the step by step sample preparation and testing procedure. The valve #2 connects the water reservoir to the water supply which is usually a container located at a higher elevation than the reservoir so that the water flows under gravity. This valve must be in the OFF position when the water reservoir is under pressure during testing. The valve #3 controls flow of water from the reservoir to the flow pump and the sample cell. It is always in the ON position during testing. The valve is turned in the OFF position during refilling of the reservoir.

The load pressure control part of the pressure control panel consists of the pressure regulator R2 and the three way valve #5. The pressure regulator controls the pressure which is through valve #5 applied to the air cylinder on the loading system. Valve #5 has three positions ON, OFF and VENT. In the ON position the air pressure from the regulator R2 is applied to the air cylinder. In the VENT position the air from the air cylinder is vented to the atmosphere. This

is necessary when the air cylinder is to be repositioned in the upper position after the load application. In the OFF position both the pressure regulator and the air cylinder are separated from each other and from the atmosphere. In this position a small underpressure is created in the air cylinder under the weight of the piston in the uppermost position. This underpressure holds the piston steady during sample preparation and in the early stage of the test when the load is not applied to the sample. It is noted that the valve #5 in the VENT position does not vent the pressure in the regulator R2 and in the lines between R2 and valve #5. This pressure has to be released through the regulator R2 by turning it in the counterclockwise direction.

The valve #4 controls which air pressure, back pressure or load pressure, is displayed on the pressure gauge. The valve should be operated slowly in order to avoid a sudden large pressure change on the gauge when there is a significant pressure difference between the two sides of the control panel. Repeatable shocks on the gauge could cause damage or reduce its accuracy. The pressure gauge has a knob which controls the rotation of the scale on the gauge. This control allows for precise zeroing of the gauge and for easier control of the load applied to the sample as will be discussed in the later part of this manual.

Flow Pump

The flow pump consists of a modified driving system, a custom made stainless steel syringe and two valves to control the flow of water. The driving system is the Harvard Apparatus syringe pump Model 909. The technical details and specifications as well as maintenance instructions are given in the manufacturers literature that is provided with the pump . The driving system has twelve gear settings with a displacement rate range of 1 to 5,000. The variable speed motor provides the additional velocity control in the range of 10% to 100% of the motor speed. Thus, the range of the displacement rates is expended to a ratio of 1 to 50,000. Note that though the motor speed can be controlled from 0% to 100% the rates below 10% are not reliable and therefore not recommended. It is a good practice to control the pump displacement rates by changing the gear setting while keeping the motor speed control at 100%. The displacement rates for different gear setting and motor control at 100% are given in Table 1. Table 1 lists also the full stroke travel time for each setting. It is important to stop the motor before the piston reaches the end of the travel. A forced stop of the piston while the motor is still running could result in the damage to the driving system.

The custom made stainless steel syringe consists of a thick wall housing and a 0.625 in (1.59 cm) diameter piston giving an effective area of 0.307 sq in (1.98 cm^2). The shop

Table 1 - Flow Rates and Travel Speeds

Gear #	Speed (cm/min)	Travel Time (hours:min)	Flow Rate (ml/sec)	Darcy Velocity (m/sec)
1	6.35	0:03	2.09E-01	2.90E-05
2	2.54	0:09	8.37E-02	1.16E-05
3	1.27	0:18	4.19E-02	5.80E-06
4	0.635	0:35	2.09E-02	2.90E-06
5	0.3175	1:00	1.05E-02	1.45E-06
6	0.127	3:00	4.19E-03	5.80E-07
7	0.0635	6:00	2.09E-03	2.90E-07
8	0.03175	12:00	1.05E-03	1.45E-07
9	0.0127	31:00	4.19E-04	5.80E-08
10	0.00635	63:00	2.09E-04	2.90E-08
11	0.003175	126:00	1.05E-04	1.45E-08
12	0.00127	315:00	4.19E-05	5.80E-09

drawings for the syringe are given in the Appendix A. The flow rates produced by the driving system and the syringe are given in Table 1 for 100% motor speed setting at each of the gear position. The syringe has a purge valve on its upper face for the easy deairing of the system. Valves #6 and #7 are used to control the flow of water in the various stages of the sample preparation and testing procedure. Valve #7 is closed during the filling procedure so that the water could be directed from the reservoir through the flow pump into the bottom part of the sample holder. This valve is always open during the testing. Valve #6 is closed when the flow generated with the flow pump is directed through

the sample. At all other times this valve is open. For detailed explanation for the operation of these and other valves refer to the step by step description of the testing procedure.

Sample Cell with the Differential Transducer

The sample cell is a modified conventional triaxial cell which is fitted with a custom made sample base and an acrylic sample ring. The shop drawings for the modifications are given in Appendix A. The inside diameter of the sample ring, identical to the sample diameter, is 3.75 in (9.52 cm) giving a sample cross sectional area of 0.00712 m^2. The sample base have a groove with an O-ring which seals the contact between the sample ring and the base. Thus the flow controlled by the flow pump through the base is forced through the sample. The apparent water velocities (Darcian velocities) through the sample for each driving mechanism setting are given in Table 1. The sample base has a porous plate with a small cavity behind it. The cavity is connected with two stainless steel tubes to the ball valves #8 and #9 which control the flow of water to the base. Valve #8 is always open during testing except when the pore pressure transducer has to be protected from the excess pore water pressure that may exceed its pressure range. This could happen during the load application to the sample. The valve

#9 is open during the seepage induced consolidation test and the permeability test. It must be closed during resetting of the pump to prevent sample disturbance. The valve may also be closed if the measurement of the excess pore water pressure is required. The detailed operation of the valves is discussed in the step by step procedure for sample preparation and testing. An aluminum piston with a porous plastic plate is used in the sample cell to transfer the applied load to the sample. The piston has the same diameter as the sample and when submerged produces a surface load on the sample that corresponds to a stress of 0.1 kPa. This load is applied to the sample from the beginning of the test to prevent the creation of flow channels during the seepage induced consolidation phase. The external load applied by the loading system is transferred to the piston through the triaxial cell shaft with a dial gauge to measure sample height.

A differential pressure transducer is attached to the cell base. The transducer is a Validyne model DP215 with a replaceable diaphragm. The general operating instructions and specifications for the transducer are given in the manufacturers literature. The transducer has a 3-36 diaphragm with a 35 kPa range. Three additional diaphragms for various pressure ranges are supplied with the equipment and could easily be replaced if needed. The pressure transducer has two pressure ports and two bleed screws. One pressure port is connected to the bottom of the sample to

measure the generated pore water pressure during testing while the other is connected to the water reservoir on the pressure control panel (back pressure) to provide the reference pressure from which pressure differential is measured. Note that the back pressure acts in the sample cell throughout the testing. Thus, the differential pressure transducer measures induced pressure difference across the sample. The transducer also has two bleed screws to facilitate the deairing process for the system. The step by step deairing procedure is described in the second part of this manual. The transducer is connected to the data acquisition system.

There is a purge valve on top of the cell which is used to vent out the air during the filling operation.

Loading System

The loading system consists of a simple frame and the Bellofram air cylinder which provides load onto the sample. The air cylinder has a nominal area of 9 sq in. The air pressure for the loading system is controlled on the pressure control panel. The air cylinder area is equal to 80% of the sample area which means that the applied stress on the sample can be calculated by multiplying the pressure read on the gauge by 0.8. It is noted that an initial pressure of about 0.5 psi will be needed in the air cylinder

to overcome the uplift force acting on the triaxial cell shaft. This initial pressure could be subtracted from the gauge by rotating the gauge dial in the clockwise direction. Once the test is completed and the sample is unloaded the air cylinder piston should be pushed in the upper position while keeping the valve on the control panel in the VENT position. Upon reaching the end of the piston travel the valve should be turned in OFF position so that a small underpressure is created due to the weight of the piston. CAUTION! The piston should never be pulled out of the cylinder by force or twisted. Such operations could result in a damage to the rolling digphragm within the cylinder.

Data Acquisition System

The data acquisition system consists of a DELL 333P computer with a VGA color monitor and the Validyne UPC601-L interface card mounted within the computer. An external box with a terminal block is used to connect the differential pressure transducer to the interface card. The Easy Sense software from Validyne Engineering Corporation is used to drive the data acquisition card and to display and store the data. The documentation for the computer, the interface card and the software is given in separate volumes and detailed instructions are not repeated here. However, instructions on

how to run the data acquisition program are given in the step by step description of the testing procedure.

TESTING PROCEDURE

This section describes the step by step procedure that should be followed for equipment and sample preparation, testing and data collection and analysis.

Equipment Preparation

The first step in the equipment preparation procedure is to set the dial gauge to read the height of the sample accurately. This is accomplished by assembling the cell without any sample and placing the aluminum piston with the porous stone on top of the cell base. The loading shaft is then pressed to the aluminum piston and fixed in this position. The dial gauge is then located to give a reading of 2.000 in on the dial. This location will allow for the sample height to be calculated by the expression:

$$H = 2.000 - (\text{dial reading}) \quad [\text{in}]$$

where the dial reading is taken when the loading shaft is in contact with the aluminum piston. At the same time the position of the top. of the aluminum piston should be noted on the ruler attached to the side of the sample container. This reading will allow the height of the sample to be approximately monitored throughout the testing.

The next step in the equipment preparation phase is the filling of the back pressure reservoir and flushing of the system with water. The back pressure reservoir is filled under gravity from a container that should be located three to five feet above the reservoir. Valve #3 is closed. The valve #1 is turned in the VENT position and valve #2 is in ON position during this operation. When the water reservoir is 3/4 full, valve #1 is turned to OFF position and the further water flow is prevented by the creation of an air cushion on top of the water.

In the next step the flow pump and sample cell base are filled with water and any entrapped air is purged out of the system. Valves #3 and #6 are open and the water is allowed to fill the flow pump while the purge valve on top of the stainless steel syringe is kept open. The purge valve is shut off when water is coming out without any air bubbles. Valve #9 at the base of the cell is open and water is allowed to fill the acrylic sample confining ring inside the cell. The valve #9 is shut off when there are no air bubbles coming from the porous stone. The flushing procedure should

be repeated several times by alternately opening the purge valve on the flow pump and valve #9 at the base of the cell.

It is noted that valve #2 is kept ON and valve #1 is in the OFF position during the air purging procedure so that the higher water column from the water container could be used to flush the system.

Sample Preparation

The clay slurry should be homogeneous prior to placing it into the cell. A sufficient amount of clay should be thoroughly mixed at a consistency that will allow the clay to be smoothly poured out of the mixing container. If the initial water content is too low more water should be added until an acceptable consistency is reached. Two to three small samples of the clay should be used to determine the initial water content of the mixture. The data for these samples are entered in the test form presented in Figure 2. From these data the initial void ratio e_0 of the slurry is calculated as:

$$e_0 = w * G_s$$

where w is the measured water content and G_s is the specific gravity of the clay.

SEEPAGE INDUCED CONSOLIDATON

Project: _____

Sample: _____

Date: _____

Specific Gravity, G_S = _____

Initial Water Contents:

	natural			slurry			σ=0		
Can #									
Can weight, W_c									
Can + wet, W_{cw}									
Can + dry, W_{cd}									
Water content, $W = (W_{cw}-W_{cd})/(W_{cd}-W_c) \times 100\%$									
Void ratio, $e = (WxG_s)/100$	e_n=			e_0=			e_{00}=		

Initial height of the slurry, H_0 = _____ m

Area of the sample, A = .00712 m^2

Date	Time	Height Reading	Dial Reading	Load	Sample Height	Comments

Figure 2 - Test Form

Final Water Content:

Can # _____

Can weight, W_c _____

Can + wet, W_{cw} _____

Can + dry, W_{cd} _____

Dry weight, W_d _____

Water content $(W_{cw}-W_{cd})/W_d$ _____

Void ratio _____

Height of solids, $H_s = W_d/(\gamma_s \times A)$ _____ m

Input Values for SICTA Program

Initial Height of the sample, $H_o = H_s(1+e_{o(o)})$ _____

Void ratio at zero effective stress, e_{oo} _____

Top effective stress, σ_T 0.1 kPa

Darcian velocity, v (from table) _____

Final Height of the Sample after S.I.C.T., H_f _____

Final bottom effective stress,
$\sigma_B = 0.1 + H_s(\gamma_s-\gamma_w) + \Delta u$ _____

$= 0.1 +$ _____ x(_____ - _____) + _____

Step Loading Test Results:

Void ratio, $e_L = (H_L/H_s) - 1$ _____

Effective stress, σ_L _____

Permeability coefficient,
$k = (v \times H_L)/\Delta h$ _____

= (_____ x _____) / _____

Figure 2 - continued

In addition to the samples for the initial water content determination one or two laboratory jars should be filled with one inch thick layer of clay for the determination of the void ratio e_{00} corresponding to the zero effective stress. The clay in the jars with plastic covers to prevent evaporation is left for several days to consolidate under its own weight. Any supernatant accumulated on top of the sample is removed and few samples for water content determination are taken from the surface of the clay. The data for these measurements are again recorded in the form in Figure 2 and the zero effective stress void ratio is calculated as:

$$e_{00} = w * G_s.$$

Any excess water from the sample confining ring is removed and a filter paper is placed at the base of the cell. The remaining slurry is again thoroughly mixed and immediately poured into the cell through a funnel. The height of the sample should be between 1.5 and 2.0 in.

NOTE: It is extremely important that the prepared sample has a horizontal upper surface, or at best the central portion a bit elevated above its circumference. If the surface is uneven there is a potential for the aluminum piston to get stuck in the acrylic confining ring and to fail to follow the compression of the sample. Such a condition will lead to

flow channeling of the sample and the test will generate erroneous results.

A filter paper is carefully placed on the sample. Again it is important that the filter paper has a proper size so that any potential interference with the piston movement is avoided. A water layer one to two inches deep is carefully placed on top of the sample avoiding any disturbance. Leave the sample at rest for a couple of hours to minimize the chance of extruding the soil around the loading piston once the piston is placed on the sample. The loading piston is placed in the confining ring and allowed to rest on top of the sample. Its submerged weight produces a surface loading of 0.1 kPa. If the piston is not completely submerged the surface load would be higher but its exact value would not be known. This would again lead to erroneous results. The initial height of the sample is recorded at this time by reading the position of the top of the piston on the attached ruler. This data is recorded in the form in Figure 2 with the date and the time.

Once the sample is prepared the sample cell is closed by placing first the acrylic tube in its place and then placing the top cap and securing it with the three tie rods. The purge valve at the top of the cell should be open during this operation and the loading shaft with the dial gauge should be locked in such a position that it won't touch the sample when the cell is assembled. Connect the polyflow tube

to the bottom of the cell. At this point valve #7 is open and the cell is completely filled with water. The purge valve is closed as soon as the water starts seeping out. It is important that throughout the sample preparation and cell filling procedures the valve #9 be closed. Otherwise the water pressure would lift the sample and cause its disturbance.

After filling the cell both sides of the differential transducer should be deaired. This is accomplished by opening the bleed screws with the hex wrench. First the back pressure cavity is deaired by opening the bleed screw on the under side of the transducer. The screw is tightened once water without air bubbles start to seep. At this point valves #8 and #9 on the cell are open and the bleed screw on the top face of the transducer is used to purge the air from the transducer and the connecting tube. The bleed screw is tightened once the air bubbles are not visible in the seeping water. The procedure should be repeated a few times to insure that no air remains in the transducer. The presence of air could lead to erroneous pore pressure measurements.

Valve #9 is closed to prevent sample disturbance during the back pressure application. Valve #2 is closed and valve #l is turned in the ON position. Valve #4 is turned to BACK PRESSURE so that the pressure gauge would measure the applied back pressure. The back pressure is slowly increased with the pressure regulator R1 up to the desired pressure

level. It is recommended that a back pressure of about 25 psi be used in all the tests. Once the desired pressure level is reached the loading shaft is unlocked and allowed to be raised by the back pressure and to get in contact with the piston of the air cylinder on the loading frame. Valve #9 is open and the sample is allowed to consolidate under the back pressure overnight.

Seepage Induced Consolidation Test

The seepage induced consolidation test is usually performed after the sample has consolidated under its own weight and the load produced by the aluminum piston. However, the seepage induced consolidation test can be also performed prior to reaching complete consolidation of the sample under its own weight. The complete consolidation of the sample can be verified by closing the valve #9 and monitoring the change in the pore pressure at the base of the sample for several minutes. If there is no change,, the consolidation is completed while a pore pressure increase indicates the existence of an excess pore pressure within the sample. It is convenient to record the height of the sample in the form at this time. If this represents the height of the sample at the and of full consolidation this value could be later compared to the value calculated in the analysis. While this comparison is not essential for the

analysis, it provides a level of redundancy that can increase the confidence in the obtained results.

An appropriate Darcy velocity for the seepage induced consolidation test should be selected. While there is not a firm criterion on how to select the appropriate velocity several guidelines could be given. For more plastic clay a lower velocity is more appropriate. It is better to start testing at lower velocity and then repeat the test with higher velocity if the resulting pressure difference is to low (much lower than 1.5 kPa). If the test is started with a to high velocity and the resulting pressure difference exceeds 10 kPa, a new sample must be prepared. Reducing the flow rate would result in testing a sample that is partially overconsolidated to an unknown amount, leading to erroneous results from the analysis. A good initial velocity for testing samples of phosphatic clays corresponds to the gear setting #8 for the driving mechanism of the flow pump. The selected Darcian velocity is recorded in the form. The pump should be positioned in the forward most position at the beginning of the test. If the syringe piston has to be reset, valve #9 is closed, the gear setting #1 is selected and the motor turned on in the infusion mode. The pump is stopped when the piston reaches the end of travel. The desired gear and the withdrawal mode are selected. The timer is set to stop the pump after the travel time for the selected speed as listed in Table 1.

Prior to starting the seepage induced consolidation test the data acquisition system should be initiated. The step by step procedure for the initiation of the data acquisition program is described in the next section.

Data Acquisition for Seepage Induced Consolidation Test

In Windows menu click on Validyne icon and the Easy-Sense program will be started. For seepage induced consolidation test data acquisition follow the ensuing steps:

1. Go to **Graph** option (F7)

   -change the **Graph Rate** to 90 seconds (this will enable the display of 6 hours of data
   -Press Esc

2. Go to **Log** (F6)

   -choose **Setup** (F2)

      -change the **Log File Name** as desired - the use of a .PRN extension is preferable

      -change the **Log Update Rate** to the desired

interval in seconds - record this rate in the test form

-choose **Select Log Item**, pick Item #3 (the "Enter" key will toggle selections on and off - an item has been selected when an asterisk appears beside it)

-Press Esc

-Press Esc

-begin logging data by choosing **Start** (F3) from the main logging menu

-to see graph of data, choose **Graph** (F7) from main logging menu

* Note: Logging to disk will stop as soon as you exit the logging mode (or logging menu). Therefore, any desired changes to graph parameters must be made before you start logging data.

After the data has been collected for several minutes to provide reference reading, the flow pump is started in the withdrawal mode at the selected rate. Again several minutes should pass before the valve #6 is turned off and the seepage induced consolidation of the sample is started. The test continues until the pore pressure measured at the

bottom of the sample reaches steady state. If necessary the flow pump is reset during the test by first stopping the pump, closing valve #9, opening valve #6 and turning the pump on at the gear setting #1 in the infusion mode. This operation may need to be performed several times during a single test in order to reach the steady state under the chosen velocity. If at the steady state the pressure difference across the sample is less than approximately 1.5 kPa the seepage induced consolidation test should be repeated at a higher flow rate. Once the steady state at an appropriate flow rate is reached the flow pump is stopped and the data acquisition program is stopped as well. Valve #6 is open and the testing proceeds with the step loading phase.

Step Loading Test and Permeability Measurement

Once the seepage induced consolidation test is completed the final height of the soil sample has to be precisely measured. First the height is approximately measured by reading the position on the ruler of the top edge of the aluminum piston. The precise measurement is obtained from reading the dial gauge outside the cell once the loading shaft is brought into the contact with the aluminum piston. This operation has to be performed extremely carefully to prevent sample disturbance. First on

the pressure control panel valve #4 is slowly turned into the LOAD position so that the pressure gauge would indicate the applied load. Valve #5 is then turned into ON position. With regulator R2 the air pressure is slowly increased in the air cylinder until the uplift force on the loading shaft from the cell pressure is exceeded and the shaft starts to travel downwards. At that moment the pressure increase is interrupted and the dial on the pressure gauge is rotated so that indicates zero pressure. By doing so the subsequent readings on the pressure gauge will indicate the load applied to the sample. The loading shaft is allowed to slowly travel downwards until it touches the aluminum piston. At that instant the dial gauge is read and the height of the sample is calculated as:

$$H = 2.000 - (\text{dial reading}) \text{ [in]}$$

This number is then recorded in the test form in meters.

The load pressure is slowly increased to the desired level for the step loading test. Any load between 10 and 100 kPa is appropriate for the step loading test. It is noted that pressure gauge reads a pressure 25% higher than what is applied on the sample. Thus the pressure read on the gauge should be multiplied by 0.8 to get the stress acting on the sample. Also note that the pressure gauge reads the pressure in psi. The pressure increase should be very slow to prevent fast sample loading that could lead to the extrusion of the

soft clay in between the aluminum piston and the sample confining ring. Such material loss would lead to erroneous results. The stress applied to the sample is recorded in the test form. The load application should be done with the valves #9 and #6 open to prevent overloading the sensitive differential transducer and to facilitate faster consolidation under the doubly drained condition.

The sample is allowed to consolidate, usually overnight, under the applied stress. The sample is fully consolidated when the dial gauge indicates no further deformation of the sample and when there is no pore pressure increase when the valve #9 is closed. At the end of consolidation the sample height is read of the dial gauge and recorded in the test form.

Once the sample is fully consolidated its permeability is measured using the flow pump. The flow pump piston is moved to the forefront position and a slow flow rate (#10, #11 or #12) is selected. Prior to starting the permeability test the data acquisition system should be initiated. The step by step procedure for the initiation of the data acquisition program is described in the next section.

Data Acquisition for Permeability Measurement

In Windows menu click on Validyne icon and the Easy-Sense program will be started. For permeability test data acquisition follow the ensuing steps:

1. Go to **Graph** option (F7)

   -change the **Graph Rate** to 45 seconds (this will enable the display of 3 hours of data
   -Press Esc

2. Go to **Log** (F6)

   -choose **Setup** (F2)

      -change the **Log File Name** as desired - the use of a .PRN extension is preferable

      -change the **Log Update Rate** to the desired interval in seconds

      -choose **Select Log Item**, pick Item #2 (the "Enter" key will toggle selections on and off - an item has been selected when an asterisk appears beside it)

-Press Esc

-Press Esc

-begin logging data by choosing **Start** (F3) from the main logging menu

-to see graph of data, choose **Graph** (F7) from main logging menu and page down to Graph #2

* Note: Logging to disk will stop as soon as you exit the logging mode (or logging menu). Therefore, any desired changes to graph parameters must be made before you start logging data.

After the data has been collected for several minutes to provide reference reading the flow pump is started in the withdrawal mode at the selected rate. Again several minutes should pass before the valve #6 is closed and the permeability measurement is started. The test continues until the head difference across the sample reaches steady state. The pump and the data acquisition program are stopped and valve #6 is open.

With the permeability measurement the test is completed and the sample can be removed from the apparatus. The step load and permeability tests can be performed on the same sample under several load increments. However, only one step

load test is required for the analysis and the additional data will be redundant, though they will provide additional information on the material behavior under higher stress levels.

Sample Removal from the Apparatus

The first step is to unload the sample by reducing the pressure in the air cylinder with the pressure regulator R2. Once the pressure is released the valve #5 is turned to the VENT position and the air cylinder is pushed in the upper position. The valve #5 is turned to the OFF position. The back pressure is then reduced and the purge valve on top of the cell is open. Valve #9 is closed and the cell is emptied by disconnecting it from the system and draining it through a 1/4" O.D. plastic tube. The cell is disassembled and the sample confining ring with the sample and the aluminum piston is removed. The sample is then extruded into a drying dish and its water content and dry weight are determined and recorded in the form.

TEST ANALYSIS

Plotting the Seepage Induced Consolidation Data

For plotting the seepage induced consolidation data follow the ensuing steps:

- In Windows menu click on Quatro icon and the program will be started. Retrieve file C:\QPRO\SICT\SIC.WQ1

- With cursor positioned at column A, row 1, import the desired data file with the following commands:

  /Tools
  Import
  choose **Comma & "" Delimited File** (Validyne-generated data files will be in the C:\VALIDYNE directory)

- Change the Time Increment (column E, row 1) so that it is the same as the Log Update Rate used during data collection (recorded on the form). Enter the value in seconds.

- Run the macro in column L of the spreadsheet to convert and graph the data:

  /Tools

Macro

Execute - when asked to specify the macro block, type **L1..L32**

- To see graph, choose F10

- Save file under different name.

Plotting the Permeability Data

For plotting the permeability data follow the ensuing steps:

- In Windows menu click on Quatro icon and the program will be started. Retrieve file C:\QPRO\SICT\SL-PM.WQ1

- With cursor positioned at column A, row 1, import the desired data file with the following commands:

/Tools

Import

choose **Comma & "" Delimited File** (Validyne-generated data files will be in the C:\VALIDYNE directory)

- Change the Time Increment (column E, row 1) so that it is the same as the Log Update Rate used during data

collection (recorded on the form). Enter the value in seconds.

- Run the macro in column L of the spreadsheet to convert and graph the data:

  /Tools
  Macro
  Execute - when asked to specify the macro block, type **L1..L32**

- To see graph, choose F10

- Save file under different name.

Preparation of Input Data for Program SICTA

All the necessary input data for the SICTA program are prepared in the test form. First the initial height of the sample is calculated from the height of solids and the void ratio at zero effective stress. Note that this height does not necessarily correspond to the actual initial height of the sample but it represents a reference value for the analysis. This height should be equal to the actual initial height in the case when the initial water content and the zero effective stress water content are the same. Next the

final bottom effective stress at the end of the seepage induced consolidation test is calculated from the recorded stress difference, the self weight of the sample and the applied surface load during the test. The value for the recorded stress difference is obtained by reviewing the record and selecting an average value at steady state. The other data for the seepage induced consolidation phase are simply copied from the previously recorded data in the test form.

For the step loading test the final void ratio is calculated from the height of solids and the final height of the sample under the applied load. The coefficient of permeability is calculated from the applied Darcian velocity, the height of the sample and the steady state head difference. Again, the value for the recorded head difference is obtained by reviewing the record and selecting an average value at steady state.

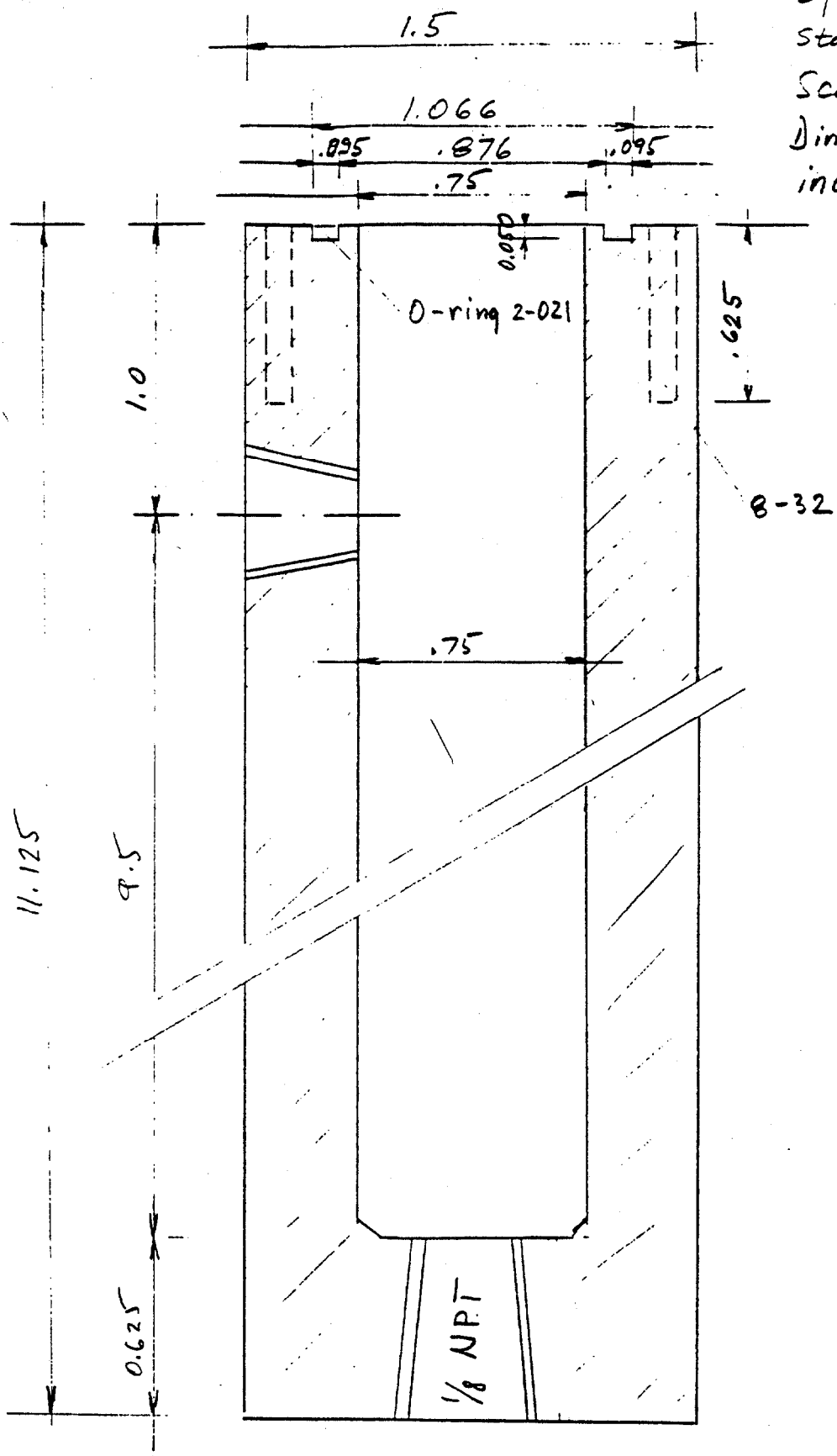
The data are then input in program SICTA and the material characteristics are obtained as the output. The effective stress - void ratio and void ratio - permeability relationships could be displayed by using QUATRO program and retrieving file C:\QPRO\SICT\E-K.WQ1.

APPENDIX A

Shop Drawings

Stainless Steel Syringe

CYLINDER
Stainless Steel
Scale 2:1
Dimensions in inches

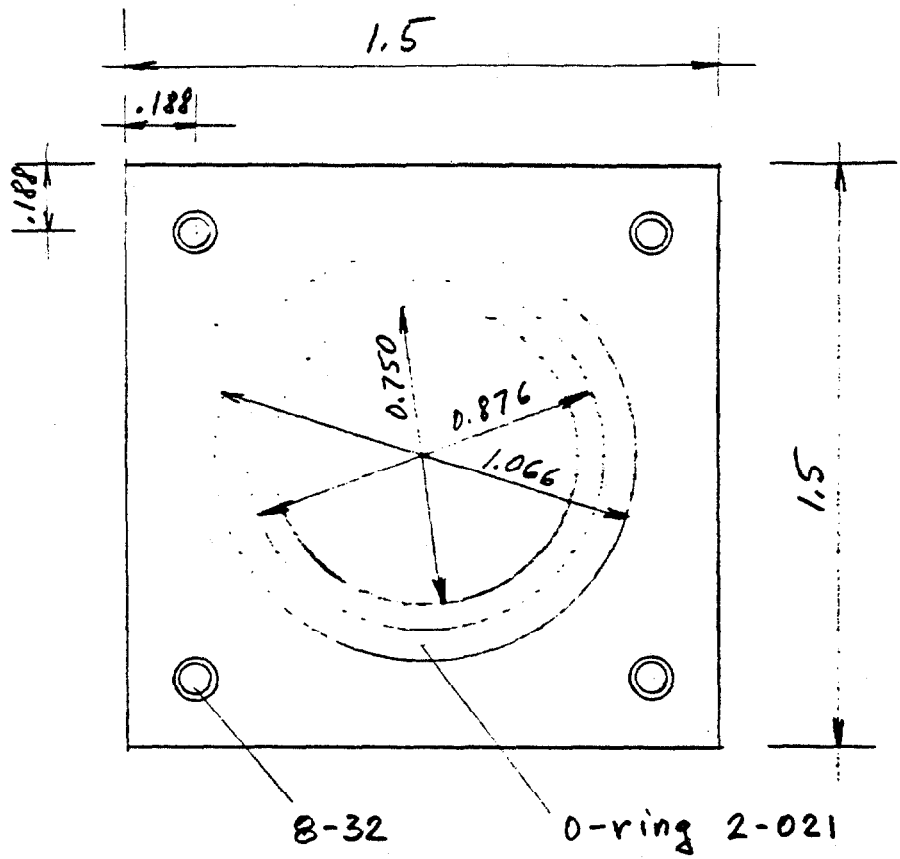


CYLINDER

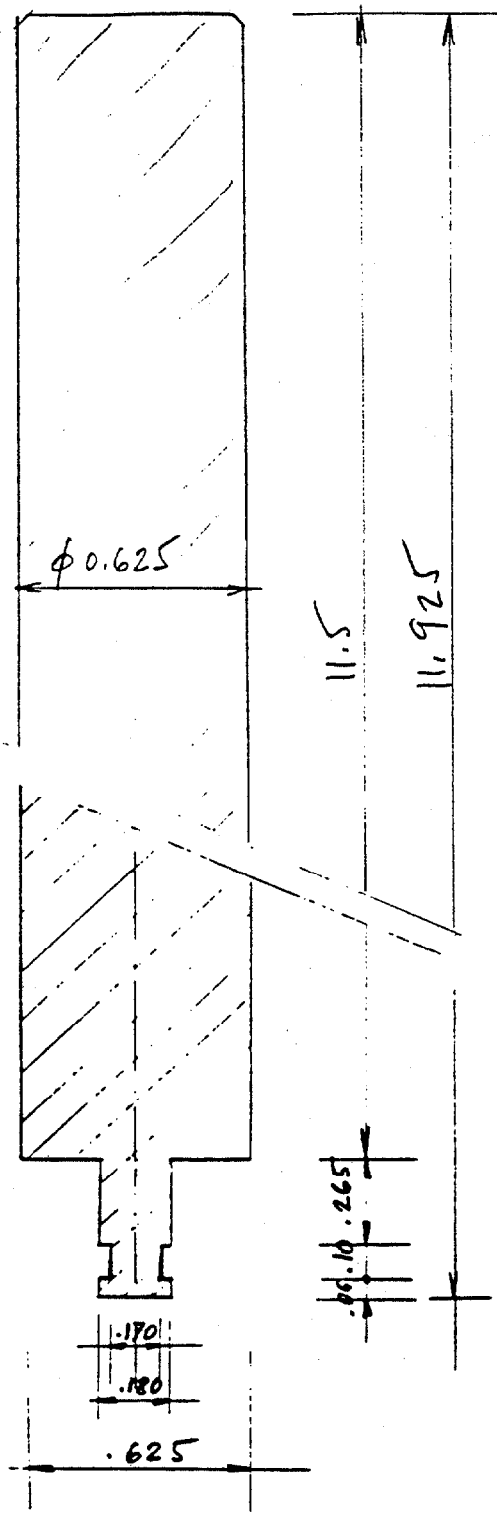
Stainless Steel

Scale 2:1

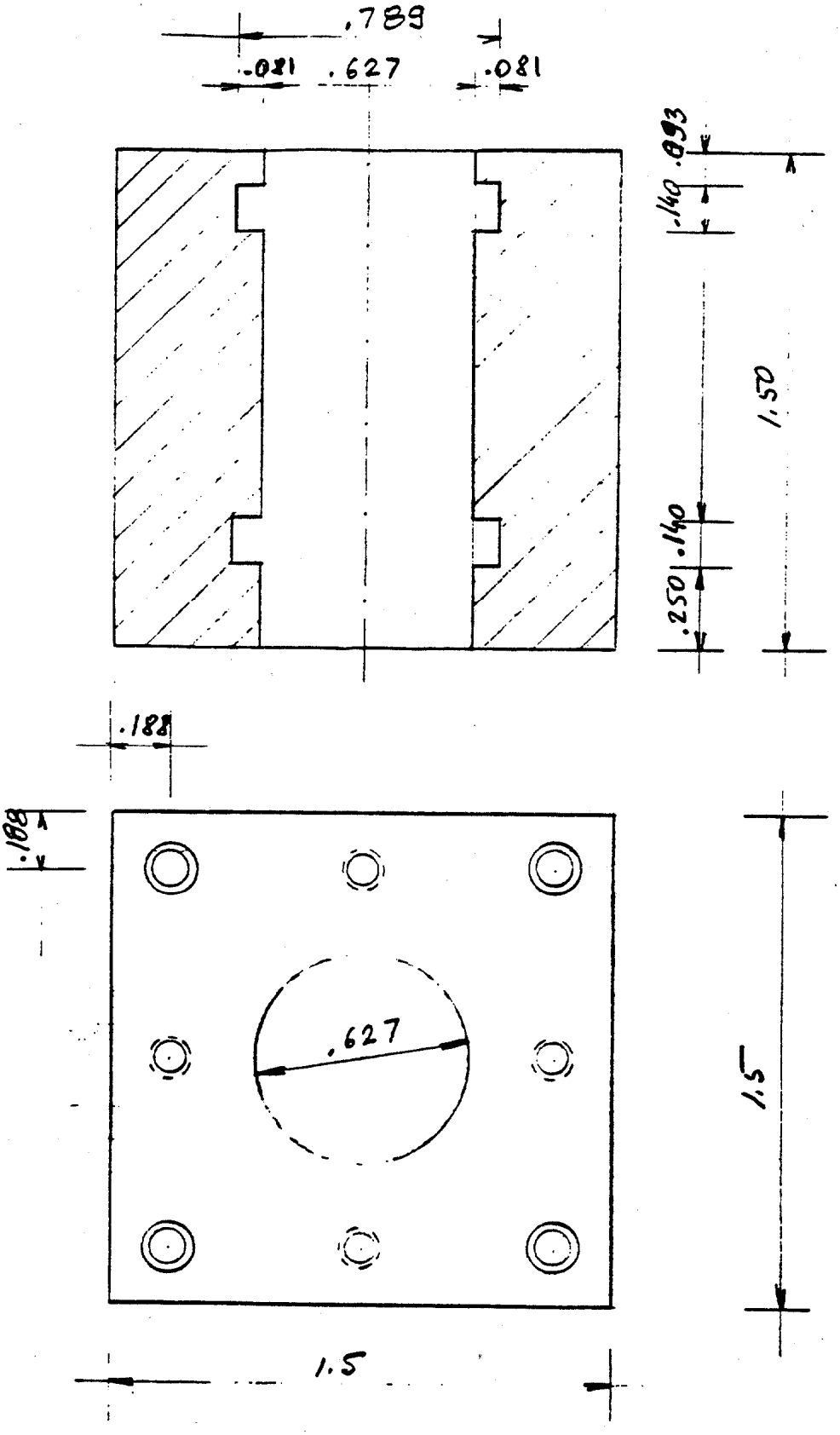
Dimensions in inches



PISTON
Stainless Steel
Scale 2:1
Dimensions in inches



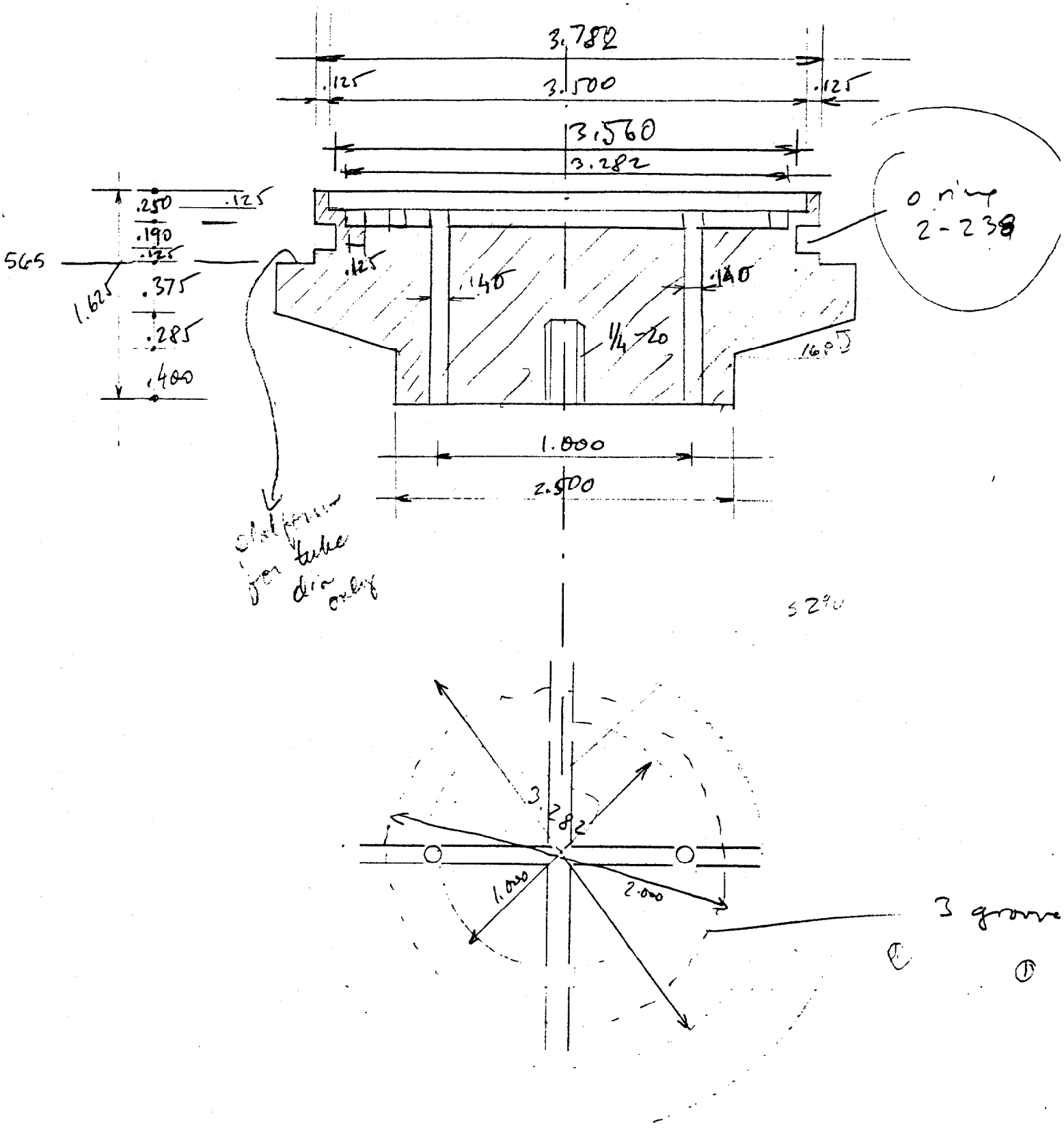
LARGE GIDE BLOCK
Stainless Steel ; Scale 2:1
Dimensions in inches



Sample Container and Load Piston

1/91 dh. 2
1-5-37361

Aluminum
Anodized, Black



cut 1/8" porous disk to press in

APPENDIX B

Testing Check List

TESTING PROCEDURE

Equipment Preparation

* Set the dial gauge to read the height of the sample accurately
    * Assemble the cell without any sample and place the aluminum piston with the porous stone on top of the cell base
    * Press the loading shaft to the aluminum piston and fix it in this position
    * Locate the dial gauge to give a reading of 2.000 in on the dial
    * Note the position of the top of the aluminum piston on the ruler attached to the side of the sample container
* Fill the back pressure reservoir and flush the system with water
    * Close valve #3
    * Turn valve #1 to VENT position
    * Turn valve #2 to ON position
    * Fill the water reservoir to 3/4 full
    * Turn valve #1 to OFF position
* Fill the flow pump and sample cell base with water and purge the entrapped air
    * Open valve #3

* Open valve #6
* Open the purge valve
* Close the purge valve when water is coming out without any air bubbles
* Open valve #9
* Fill the acrylic sample confining ring inside the cell with some water
* Close valve #9
* Repeat the last five steps several times

Sample Preparation

* Mix the clay slurry
* Take samples to determine the initial water content
* Take samples for the determination of the void ratio corresponding to the zero effective stress
* Remove excess water from the sample confining ring
* Place filter paper at the base of the cell
* Mix the slurry and pour it into the cell through a funnel
* Place a filter paper on the sample
* Add water on top of the sample (1" - 2" deep)
* Leave the sample at rest for two hours
* Place the loading piston in the confining ring
* Record the initial height of the sample by reading the position of the top of the piston on the attached ruler
* Open the purge valve at the top of the cell

* Lock the loading shaft in the upper position
* Close the sample cell
* Connect the polyflow tube to the bottom of the cell
* Open valve #7
* Fill the cell completely with water
* Close the purge valve
* Deair the differential transducer
    * Open the bleed screw on the under side of the transducer
    * Tightened the screw once water without air bubbles start to seep
    * Open valves #8 and #9
    * Open the bleed screw on the top face of the transducer
    * Tightened the screw once the air bubbles are not visible in the seeping water
    * Close valves #8 and #9 and repeat the procedure a few times
* Apply the back pressure
    * Close valve #9
    * Close valve #2
    * Turn valve #1 to ON position
    * Turn valve #4 to BACK PRESSURE
    * Slowly increase the back pressure with the pressure regulator R1 up to the desired level (25 psi)
* Unlock the loading shaft

* Open valve #9
* Consolidate the sample overnight

Seepage Induced Consolidation Test

* Reset the syringe piston to the forward most position
    * Close valve #9
    * Select gear setting #1
    * Turn the pump on in the infusion mode
    * Stop the pump when the piston reaches the end of travel
* Select an appropriate Darcy velocity for the seepage induced consolidation test (gear setting #8)
* Record the selected Darcian velocity in the form
* Select the withdrawal mode on the pump
* Set the timer to stop the pump at the end of the travel time for the selected speed as listed in Table on the pump
* Start Data Acquisition for Seepage Induced Consolidation Test
    * Click on Validyne icon
    * Press F7 **(Graph)**
    * change the **Graph Rate** to 90 seconds
    * Press Esc
    * Press F6 **(Log)**
    * Press F2 **(Setup)**
    * Change the **Log File Name**

    * Change the **Log Update Rate**
    * Record this rate in the test form
    * Choose **Select Log Item**
    * Pick Item #3 (the "Enter" key will toggle selections on and off)
    * Press Esc
    * Press Esc
    * Press F3 to begin logging data **(Start)**
    * **Press F7 (Graph)**
    * Wait several minutes to provide reference reading
* Start the flow pump
* Wait several minutes
* Close valve #6
* Continue the test until steady state is reached as indicated by constant pressure
* If needed reset the pump
        * Stop the pump
        * Close valve #9
        * Open valve #6
        * Select the infusion mode
        * Select the gear setting #1
        * Turn the pump on
        * Turn the pump off at the end of travel
        * Select the previous gear setting for seepage induced consolidation
        * Select the withdrawal mode
        * Turn the pump on

    * Open valve #9
    * Close valve #6
* At steady state stop the flow pump
* Stop the data acquisition program
* Open valve #6

Step Loading Test and Permeability Measurement

* Measure the final height of the sample
    * Read the position of the top edge of the aluminum piston on the ruler
    * Turn valve #4 slowly into the LOAD position
    * Turn valve #5 to ON position
    * Increase the air pressure with regulator R2 slowly until the uplift force on the loading shaft from the cell pressure is exceeded and the shaft starts to travel downwards
    * Rotate the dial on the pressure gauge so that it indicates zero pressure
    * Allow the loading shaft to slowly travel downwards until it touches the aluminum piston
    * At that instant read the dial gauge
    * Record this reading in the test form
* Increase the load pressure slowly to the desired level (10 kPa to 100 kPa)
* Record the applied stress in the test form (0.8 times the gauge reading)

* Consolidate the sample overnight under the applied load
* Check that the sample is fully consolidated
    * Close valve #9
    * Monitor the pressure for few minutes
    * No pressure increase indicates full consolidation
    * Open valve #9
* Read the dial gauge and record in the form
* If needed reset the pump
        * Close valve #9
        * Open valve #6
        * Select the infusion mode
        * Select the gear setting #1
        * Turn the pump on
        * Turn the pump off at the end of travel
* Perform permeability test
    * Select the withdrawal mode
    * Select a slow flow rate (#10, #11 or #12)
    * Start Data Acquisition for Permeability Test
        * Click on Validyne icon
        * Press F7 **(Graph)**
        * change the **Graph Rate** to 45 seconds
        * Press Esc
        * Press F6 **(Log)**
        * Press F2 **(Setup)**
        * Change the **Log File Name**
        * Change the **Log Update Rate**
        * Choose **Select Log Item**

        * Pick Item #2 (the "Enter" key will toggle selections on and off)
        * Press Esc
        * Press Esc
        * Press F3 to begin logging data **(Start)**
        * **Press F7 (Graph)**
        * Press Page Down to Graph #2
        * Wait several minutes to provide reference reading
    * Start the flow pump
    * Wait several minutes
    * Close valve #6
    * Continue the test until steady state is reached as indicated by constant pressure
* Stop the pump
* Open valve #6
* Stop the data acquisition program

Sample Removal from the Apparatus

* Unload the sample by reducing the pressure in the air cylinder with the pressure regulator R2
* Turn valve #5 to VENT position
* Push the air cylinder in the upper position
* Turn valve #5 to OFF position
* Reduce the back pressure with the pressure regulator R1
* Open the purge valve on top of the cell

* Close valve #9
* Disconnect the 1/4" O.D. plastic tube from the cell
* Empty the water from the cell by connecting a short 1/4" O.D. plastic tube to the cell
* Disassemble the cell
* Remove the sample confining ring with the sample and the aluminum piston
* Extrude the sample into a drying dish
* Determine its water content and dry weight
* Record the data in the form.

Plotting the Seepage Induced Consolidation Data

* Click on Quatro icon
* Retrieve file C:\QPRO\SICT\SIC.WQ1
* Position cursor at column A, row 1
* Import the desired data file from C:\VALIDYNE directory
    * /Tools
    * Import
    * **Comma & "" Delimited File**
* Change the Time Increment in column E, row 1 to the Log Update Rate used during data collection (Enter the value in seconds)
* Run the macro in column L of the spreadsheet
    * /Tools
    * Macro
    * Execute

    * type **L1..L32**

* Choose F10

* Save file under different name

Plotting the Permeability Data

* Retrieve file C:\QPRO\SICT\SL-PM.WQ1

* Position cursor at column A, row 1

* Import the desired data file from C:\VALIDYNE directory

    * /Tools

    * Import

    * **Comma & "" Delimited File**

* Change the Time Increment in column E, row 1 to the Log Update Rate used during data collection (Enter the value in seconds)

* Run the macro in column L of the spreadsheet

    * /Tools

    * Macro

    * Execute

    * type **L1..L32**

* Choose F10

* Save file under different name

APPENDIX C

Conversion Factors for the SI System of Units

Conversion factors

SI units

In these conversion tables, SI units are shown in bold blue type.

Where SI units differ from technical metric units, the conversions are given for both.

The following list details the main SI units and their symbols which are used throughout these tables.

Length:	metre,	m
Area:	square metre,	m^2
Volume:	cubic metre,	m^3
Mass:	kilogram,	kg
Density:	kilograms per cubic metre,	kg/m^3
Force:	newton,	N
Pressure, stress:	pascal,	Pa (N/m^2)
Viscosity, dynamic:	pascal second	Pa s
Viscosity, kinematic:	square metre per second	m^2/s
Energy:	joule	J
Power:	watt	W (J/s)

Length

1 km	0.621371 mile
1 m	1.09361 yd 3.2808 ft
1 cm	0.393701 in
1 mm	0.03937 in
1 μm	39.3701 μin
1 mile	**1.60934 km**
1 yd	**0.9144 m**
1 ft	**0.3048 m**
1 in	**25.4 mm**
1 milli-in (thou)	**25.4 μm**
1 μin	0.0254 μm

Volume, capacity

1 m^3	1.30795 yd^3
1 dm^3 (litre)	0.03531 ft^3 0.21997 imp gal 1.7605 pint 0.2642 US gal
1 cm^3 (ml)	0.06102 in^3 0.0352 fl oz
1 litre (dm^3)	0.21997 imp gal 1.7605 pint
1 ml (cm^3)	0.0352 fl oz
1 yd^3	**0.76455 m^3**
1 ft^3	**28.3168 dm^3**
1 in^3	**16.3871 cm^3**
1 imp gal	**4.54609 dm^3**
1 US gal	**3.78541 dm^3**
1 pint	**0.56826 dm^3**
1 fl oz	**28.4131 cm^3**

Area

1 km^2 (100 hectares)	247.105 acres
1 hectare (ha)	2.47105 acres **10 000 m^2**
1 m^2	1.19599 yd^2
1 cm^2	0.155 in^2
1 mm^2	0.00155 in^2
1 $mile^2$	**2.58999 km^2**
1 acre (4840 yd^2)	**4046.86 m^2** **0.404686 ha**
1 yd^2	**0.836127 m^2**
1 ft^2	**0.092903 m^2**
1 in^2	**645.16 mm^2**

Mass

1 tonne	**1000 kg** 0.98420 ton 2204.62 lb
1 kg	0.01968 cwt 2.20462 lb
1 g	0.03527 oz
1 ton	**1016.05 kg** 1.01605 tonne
1 cwt	**50.8023 kg**
1 lb	**0.45359 kg**
1 oz	**28.349 g**

Density

1 kg/m^3	1.686 lb/yd^3 0.06243 lb/ft^3
1 g/cm^3	62.4280 lb/ft^3
1 ton/yd^3	**1328.94 kg/m^3**
1 lb/yd^3	**0.593 kg/m^3**
1 lb/ft^3	**16.0185 kg/m^3**
1 lb/in^3	**27.6799 g/cm^3**

Force

1 N	0.10197 kgf 0.22481 lbf
1 kN	101.971 kgf 224.809 lbf
1 kgf (kilopond)	**9.80665 N** 2.20462 lbf
1 dyn	**10^{-5} N** 0.224809 x 10^{-5} lbf
1 lbf	**4.44822 N** 0.45359 kgf
1 tonf	**9.96402 kN** 1016.05 kgf

Power

1 hp (horse power)	**745.700 W (J/s)**
1 ft lbf/s	**1.35582 W**

Pressure, stress

1 Pa (N/m^2)	0.01 mbar 0.000145 lbf/in^2
1 kPa (kN/m^2)	0.01 kgf/cm^2 10 mbar 20.885 lbf/ft^2 0.2953 in Hg
1 kgf/cm^2	**98.0665 kPa** 14.223 lbf/in^2
1 bar	**100 kPa** 14.5038 lbf/in^2
1 mbar	**100 Pa** 2.0885 lbf/ft^2
1 atm	**101.325 kPa** 14.6959 lbf/in^2
1 mm Hg (torr)	**133.322 Pa** 0.01934 lbf/in^2
1 mm H_2O	**9.80665 Pa** 0.001422 lbf/in^2
1 lbf/in^2	**6.89476 kPa** 0.07031 kgf/cm^2 68.9476 mbar
1 lbf/ft^2	**47.8803 Pa** 0.4788 mbar
1 $tonf/ft^2$	**107.252 kPa** 1.094 kgf/cm^2
1 in Hg	**3.38639 kPa** 0.491 lbf/in^2
1 ft H_2O	**2.98907 kPa** 0.030 kgf/cm^2 22.3997 mm Hg

Viscosity, dynamic

1 Pa s (Ns/m^2)	0.0208854 lbf s/ft^2
1 cP (centipoise)	2.08854 x 10^{-5} lbf s/ft^2 **0.001 Pa s**
1 lbf s/ft^2	**47.8803 Pa s**
1 lb/ft s	**1488.16 cP** 1.48816 kg/m s

Viscosity, kinematic

1 m^2/s	10.7639 ft^2/s
1 cSt (centistokes)	5.58001 in^2/h **1 mm^2/s** **10^{-6} m^2/s**
1 ft^2/h	**0.092903 m^2/h** 25.8064 cSt
1 in^2/s	**645.16 mm^2/s** 645.16 cSt

Energy

1 MJ	0.277778 kWh
1 J	0.737562 ft lbf
1 kgf m	**9.80665 J** 7.23301 ft lbf
1 therm	**105.506 MJ**
1 kWh	**3.6 MJ**
1 Btu (British thermal unit)	1.05506 kJ