ARIZONA DEPARTMENT OF TRANSPORTATION

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SATURATED SURFACE DRY TESTING MACHINE

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Final Report

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16. Abstract

The purpose of this project is directed towards developing a test method to replace the cone test CASTM (128-73) which is used to determine the bulk specific gravity and absorption of fine aggregate in the Saturated Surface Dry (SSD) state. A machine, was designed and built to have good control over process parameters and to use a parameter to measure the SSD state which would be highly sensitive to changes in moisture content on the surface of the particle. After the machine was designed and built, certain process parameters were varied and evaluated. In the final phase of the project approximately 200 tests were performed with the SSD machine and the cone test in order to make a statistically significant comparison between the two methods.

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INTRODUCTION

The Cone Test (ASTM C128-73) is used to determine the bulk specific gravity and absorption of fine aggregate in the Saturated Surface Dry (SSD) state which is then used to calculate the volume occupied by the aggregate in either portland cement concrete or asphalt concrete. The need for a new test apparatus to determine these parameters has been repeatedly demonstrated because of the difficulties incurred with the cone test. These difficulties include poor repeatability, variability, and excessive test time. The primary characteristics of an alternate technique would be simplicity of operation and short testing period. A desirable test period would be 15 minutes or less versus the current, several hours to a full day, using the traditional apparatus. It should also be usable with a range of materials (varying percentage of minus 200 mesh material), clean sands, and blend sands.

An approach used to measure the SSD state in another ADOT study was differential thermal analysis. A test material was placed in a 6" diameter drum and rotated while hot air was passed over the sample. The temperature was measured at the inlet and outlet sides of the drum. The difference in these temperatures would provide an indication of the amount of moisture being added to the air passing through the drum. This differential temperature was plotted on a chart recorder and gave an indication of the point at which SSD would occur. Six different test materials were selected: Andesite, Sandstone, Limestone, Basalt, Granite, and Schist, and thirty tests were performed on each material using the developed SSD machine.

During the tests, it was quickly observed that the SSD machine evaluation of the various materials tested produced variable results. This was due to several problems: 1) minus 200 mesh material adhering to the drum causing uneven drying and noticeable jogs on the recording chart; 2) as the material approached the SSD point, fine particles of dust would be blown out of the drum due to the air passing through it; 3) different size particles had a tendency to dry at different rates which caused great variations in the shape of the curve recorded; and 4) the heating apparatus used was not temperature controlled, hence, variations in line voltage and air velocity caused variations in inlet temperature. Although the machine included an electronic circuit to determine a change in slope which would indicate the SSD point, the problems encountered made it difficult to detect this specific point. It was necessary to reconsider certain parameters before an effective machine could be produced.

THEORY OF OPERATION

The rigorous analysis of a problem of this sort is difficult, but some simplifying assumptions were made which allowed analysis using conventional mathematics (a detailed description of this will be provided upon request). Since the actual parameters which describe a real soil are very difficult to establish, a theoretical "soil" is a useful tool which can help quantify the relationships which are involved in the drying process. For the purpose of this analysis it is assumed that the "soil" consists of a large number of particles comprising a statistically significant population. Furthermore, these particles are rigid semi-spheriodal in shape and contain a number of pores which vary in size and depth. A macroscopic view of such a soil might appear as in Figure A. The moisture contained in such a soil has different characteristics than those of bulk water due to its relative proximity to the soil particles themselves, so the effects of gravity and surface tension become important in the analysis.

Figure B shows an idealized particle containing macropores and micropores. A macropore (pore radius - r_1), as defined here, is a pore in which the mean diameter is large with respect to its depth. A micropore is of a smaller radius (r_2) and has a depth greater than or equal to its mean diameter. Since the macropores obviously have lower gravitational forces and surface tensions, it is expected that surface moisture will evaporate with a much lower energy input than micropores. Assuming that this is the case, a further simplification can be made in which the particle is modeled (Figure C). These two pores shall have a common depth L, a distance from the surface to the surface of the meniscus in the pore X, and a distance which is located an incremental finite distance above a pore shall be Xo.

Theoretically, the moisture which is held in a pore of radius r_1 is held less vigorously than moisture contained in a pore of radius r_2. Therefore, an amount of moisture will evaporate from the r_1 pores (surface irregularity pores - Figure B) until a certain condition occurs and then moisture will begin to be removed from the tighter r_2 pores.

It may be concluded that the evaporation rate during the critical drying phase which is chosen to be prior to the SSD state, will start high initially and decline rapidly to a steady state condition. Subsequently, at the point defined as SSD, when the moisture starts being removed from the r_2 pores, a phase two drying condition will begin and will exhibit an exponentially declining rate of evaporation (Figure D). The absolute value of the steady state evaporation function should be an indicator of the ratio of large pores (surface irregularities) to total pores in the sample. Also, the second phase of the drying condition should be readily discernable by observing the change in drying rate.

Proof of this analysis can be seen in a reproduction of testing performed in Russia by Nerpin and Chudnovskii (1) (Figure D). The existence of the two theoretically predicted drying states is shown graphically in two soil samples exhibiting differing drying characteristics due to their ratios of large pores to total pores(n). The first stage drying is an essentially flat line and the second stage drying can be an exponential curve. This is exactly as predicted in theory.

In order to observe this change from linear to an exponential drying rate, the drying conditions must be closely controlled. This is the reason for closely controlling the process in the SSD machine. Further, a direct indicator of a change in drying rate is the relative humidity of the outlet gases from the drying chamber.

CONSTRUCTION OF MACHINE

After the theoretical analysis was completed, machine design was begun. The machine was designed to have good control over process parameters and to use a parameter to measure the SSD state which would be highly sensitive to changes in moisture content on the surface of the particle. The machine has easily set feedback-type controls so that repeatable tests can be run.

It was decided that the aggregate would be dried by passing warm air through it and that the source of warm air be precisely controlled. The method for producing warm air is a variable speed blower that passes cool air through a closed duct over a resistive heating element, then through a duct past a thermacouple sensor, which senses the temperature of the air coming out of the heating element and passes an electrical signal to a proportional controller. The proportional controller provides the current signal to a burst-fire power regulator which, in turn, controls the amount of energy delivered to the resistive heating element. A temperature can be set on the controller to vary the air velocity over a wide range while maintaining a constant temperature output. This procedure worked well. It was insensitive to variations in line voltage and/or changes in ambient temperature.

Once the air flow was established, the technique of drying the sample in a controlled manner was approached. In the original machine, the drum was 6" in diameter. However, for proper treatment of a sample in the 1000 gram category, a large drum (10" in diameter) was deemed more appropriate. To resolve the problem of the particles being ejected in the exhaust end of the drum, the inlet side of the drum was changed to 2" and the outlet 6"; thus reducing the velocity of the exit air.

The problem of sticking material was resolved by trying several different drum configurations and/or coatings. The most efficient coating found was ceramic teflon impregnated by air-brushing and baking of silicone oil into the surface of the teflon. The mixing of the soil in the drum is critical. The material should tumble continuously through the warm air stream and yet be isolated from the ends of the drum to prevent the particles from egressing. The final configuration of the drum includes six individual vanes, which have a high slope near the ends of the drum and a lower slope near the middle of the drum which proved to be effective.

Humidity measurement equipment normally responds to relative humidity, not absolute humidity. This is an important consideration, as the detection of absolute moisture changes in the drum exhaust air is the parameter which needs to be measured. Since the humidity parameter is so sensitive to the temperature, it is important to keep the temperature constant during humidity measurements. In order to make accurate measurements in the absolute humidity, a heat exchanger was needed. This heat exchanger is an air over air type which uses a single axial flow fan to both extract air from the sample scavenging tube and to circulate cooling air over the finned aluminum heat exchanged tube. Near the exhaust end of the heat exchanger, a machined plastic (dielectric) measurement cell is inserted in the cooled gas stream. Inside this cell is a 250 micron sintered bronze filter which is designed to remove particulates from the gas stream before reaching the humidity sensor. The humidity sensor is a special hydroscopic dielectric with a gold grid on either side. This grid allows slight changes in moisture content in the hydroscopic substrate to significantly change the capacitance of the sensor which, in turn, causes a frequency change in a solid state oscillator that is compared with a standard frequency and registers on a meter on the front panel of the machine. This method of humidity measurement responds to 90% of a new reading in one second. A completely new reading takes a few seconds. This response time is adequate to register changes in the absolute humidity. The machine design was thus complete.

PARAMETER EVALUATION

Once the machine was designed and built, all of the process parameters could be varied, which allowed great flexibility in testing. The variables include:

1. air flow rate,
2. drum input temperature,
3. drum rotation rate,
4. drum preheat temperature,
5. setting of SSD indicator offset setting,
6. size of sample, and
7. initial moisture content of sample.

For preliminary testing, the air flow rate was set at 500 ft^3 per minute (CFM) (0.24 m^3/sec.) with an inlet temperature of 200°F (93°C) to promote rapid drying of the 1000 gram saturated soil sample. The drum was rotated between 40 and 50 revolutions per minute (RPM). The use of such a 'high' input enthalpy led to both a desirable and an undesirable result. The sample did dry quickly; however, the humidity rose to a very high value, thus distorting the test curve which gave misleading indications of the progress of the process. It became apparent that since the humidity parameter was so sensitive, a less intensive drying approach could be used. Furthermore, pre-heating of the drum significantly shortened the time required for drying process since heat was no longer required to heat the drum prior to and while heating the soil. The temperature was reduced from 200°F (93°C) to 130°F (54°C) and the air velocity to 375 cfm (0.18 m/sec.). This combination of inlet heat flux parameters would allow a more precise drying curve to be traced.

Also the drum was pre-heated to 125° (52°C) which aided the drying process. Unfortunately, it also helped to overshoot the SSD point - the problem being timely removal of the hot soil from the drum. As testing proceeded, it was obvious that a pre-heat to 110°F (43°C) would be better. This became the standard to be used in subsequent testing. Later, it was discovered that if the drum temperature setting was not strictly monitored, some additional variance would be intorduced due to pre-heating.

The operating parameters for the initial correlation testing were:

1.	Air Flow	375 $feet^3$/minute (cfm) (0.8 $meter^3$/second)
2.	Drum Input Temperature	130°F (54°C)
3.	Drum Rotation Rate	40-50 rpm
4.	Drum Pre-heat Temperature	110°F (43°C)
5.	Size of Sample	1000gr

The initial moisture content of the sample originally was dependent upon the amount contained therein after draining which occurred after soaking in water for 24 hours. Normally, the appearance of the sample was so wet that it was "slushy." In order to reduce the propensity for adhesion to the inside surface of the drum, the sample was partially dried prior to insertion into the machine for testing. The method chosen for doing this was to drain the sample after the soaking period, spread it out on "release" paper, and circulate a current of air over it. From time to time, a gentle mixing was accomplished either with a large laboratory spoon or by hand. An empirical method was used to evaluate the sample prior to placing it in the machine. When the sample reached the point where it held together when squeezed in the palm and crumbled slightly when released, it was deemed to be an appropriate moisture content for insertion into the test drum. Preparation of the sample by the above method made a large difference in the overall drying by the machine, and the sample dried in a more controlled manner. The removal of the sample from the machine at the conclusion of testing was also facilitated.

STATISTICAL COMPARISON TESTING

As testing proceeded, the testing of a standard sand and gravel was initiated. Enough tests were performed with the SSD machine and the cone test to make a statistically significant comparison between the two methods.

The material used was from a pit located in the Agua Fria River west of Phoenix. This material source was chosen because it has a significant amount of -200 mesh material (over 6%). The gradation of the material is shown in Figure E.

The preparation of material for testing involves several steps:

1. The samples were screened to ensure that no material larger than -8 mesh was in the sample material.

2. Each sample was weighed out in a 1000 gram sample size and placed in a paper sample sack.

3. The samples were readied for testing by pouring them 10 at a time into 10 rust-proof soaking pans. The samples were then wetted with enough water to cover them and allowed to soak at room temperature for 24 hours.

4. The samples were then drained and spread out on release paper for preliminary drying.

5. The sample was then loaded in the poly-vinyl-chloride sample loading chute for insertion in the SSD machine.

The testing program consisted of an initial set of tests not intended for analysis and then the test series. In all, approximately 200 tests were performed.

The initial group of tests was performed to give an indication of the efficiency of the machine. These tests were performed under close supervision and with a small population of tests (15 SSD - 15 Sand Cone). It was noted that the time required to perform 15 SSD tests (about one hour) differed substantially from the amount of time required to perform the cone tests (about two days). This was a good indication of the time differential involved in the use of this automated apparatus. The results of the testing are summarized below:

	Cone Test	SSD Machine
Moisture Content Average	1.15%	1.22%
Standard Deviation (@)	0.117	0.100
Variance	0.013	0.010

It was interesting to note that the preliminary indications were that the SSD machine has a very promising performance with respect to the cone test. The results justified a more ambitious program and a series of tests were initiated to confirm these preliminary results.

Figure F and G summarize the results of these additional tests and as can be seen these results do not reflect the initial testing. Apparently, the laboratory personnel performing the tests failed to realize the importance of controlling the drum pre-heat temperature which was determined by running a series of tests to determine the sensitivity of possible error sources.

The results of this small series of tests are as follows:

	SSD Machine
Moisture Content Average	1.514
Standard Deviation	.060
Variance	.002

Obviously, the results are very dependent upon control of the testing conditions. It was noted that if one exercises reasonably close control of the test parameters, the machine gives accurate results.

The results from the larger test program indicate that the SSD machine has a higher variance than the cone test but it is the author's opinion that these results do not reflect the entire picture. Control of the process parameters is critical; without it, the variance and standard deviation will be adversely affected.

The results of the tests with and without -200 mesh materials are plotted on two histograms, Figures F and G. The mean values for the materials which had no -200 material were lower both for the SSD machine results and the cone test results. The difference was approximately two-tenths of one percent. This reflects approximately a 17% difference between the material with the -200 mesh material removed and the material that still contains the -200 mesh material. Based upon these numbers, it is recommended that the -200 mesh material not be removed before the SSD test is run.

Further, the variance of the cone test with the -200 mesh material is .0146; with the SSD machine .0440. This does not reflect the same results that were obtained in the other experimentation. Apparently, it is important to perform additional testing to determine the sensitivity of the control parameters and the effects they cause on the final results. Additionally, the mean obtained by the SSD and cone test are different in the samples containing -200 material by 0.19%. This is an amount that can be accounted for by changing the offset control in the SSD machine. As the material is drying, the offset control stops the machine at a present point on the drying curve. Since the SSD machine is indicating a higher moisture content, it may be necessary to increase the offset value as this relationship is inverse.

CONCLUSIONS AND RECOMMENDATIONS

Results Obtained

The results obtained in this project are promising but the differences between preliminary results and the larger testing program indicate that more control needs to be exercised in the running of the tests. The initial testing of the samples indicate that the machine is capable of fast and accurate testing. It was designed to take approximately fifteen minutes to perform a test; it actually takes from two to three minutes.

Recommendations

Based upon the results of the testing and the experience gained through conducting the tests and developing the machine, it is apparent that the operation of the machine can be improved by making two changes in the machine.

First, a heating element should be wrapped around the drum which will be used to maintain a constant temperature ($\pm 2^{o}F$) ($\pm 1^{o}C$) during the test. Provisions will have to be made to supply power to the heating element through a pair of slip rings or a commutator so that the heat can be maintained during testing. This will have a profound effect on the results obtained by the machine. Also, it would be prudent to make arrangements to measure the temperature of the drum at several points to maintain a constant temperature in the surface of the drum. It is possible that an additional set of slip rings would be required to take the temperature measurements. The sensor should be a thermistortype which would require no special metals used in the slip ring connections. Either the above methods could be used, or as an alternative, an infrared sensor could be used to monitor drum temperature. Regardless, this condition has a very definite effect on the accuracy of results.

Second, as the machine operates now, the person running the machine must observe the level obtained during the first drying stage. This is indicated by a leveling of the graph, Figure D, when the first stage drying is occurring, the operator then sets the offset control to a value (usually 4%) which has been preestablished. This portion of the test requires operator competency to be the highest. It would be more desirable to use a microprocessor to acquire the readings from the humidity indicator, which could be acquired through a digital converter. The digital word would be stored in a memory and updated every 100 milliseconds. When the maximum value is obtained, the microprocessor would save the peak value and start looking for a declining value. Once this occurs, the microprocessor will jump out of its loop, activate another circuit, and close a solid state relay which stops the test.

It is believed that if the above two changes are made, the SSD machine will not only be much quicker and easier than a cone test, but also produce more accurate and repeatable results. Further, the author feels that it would be wise to actually compare the field absorption rates for various aggregates before making changes in the SSD results. It is quite possible that the actual absorption may be more accurately measured by the SSD machine than by the time-honored cone test.

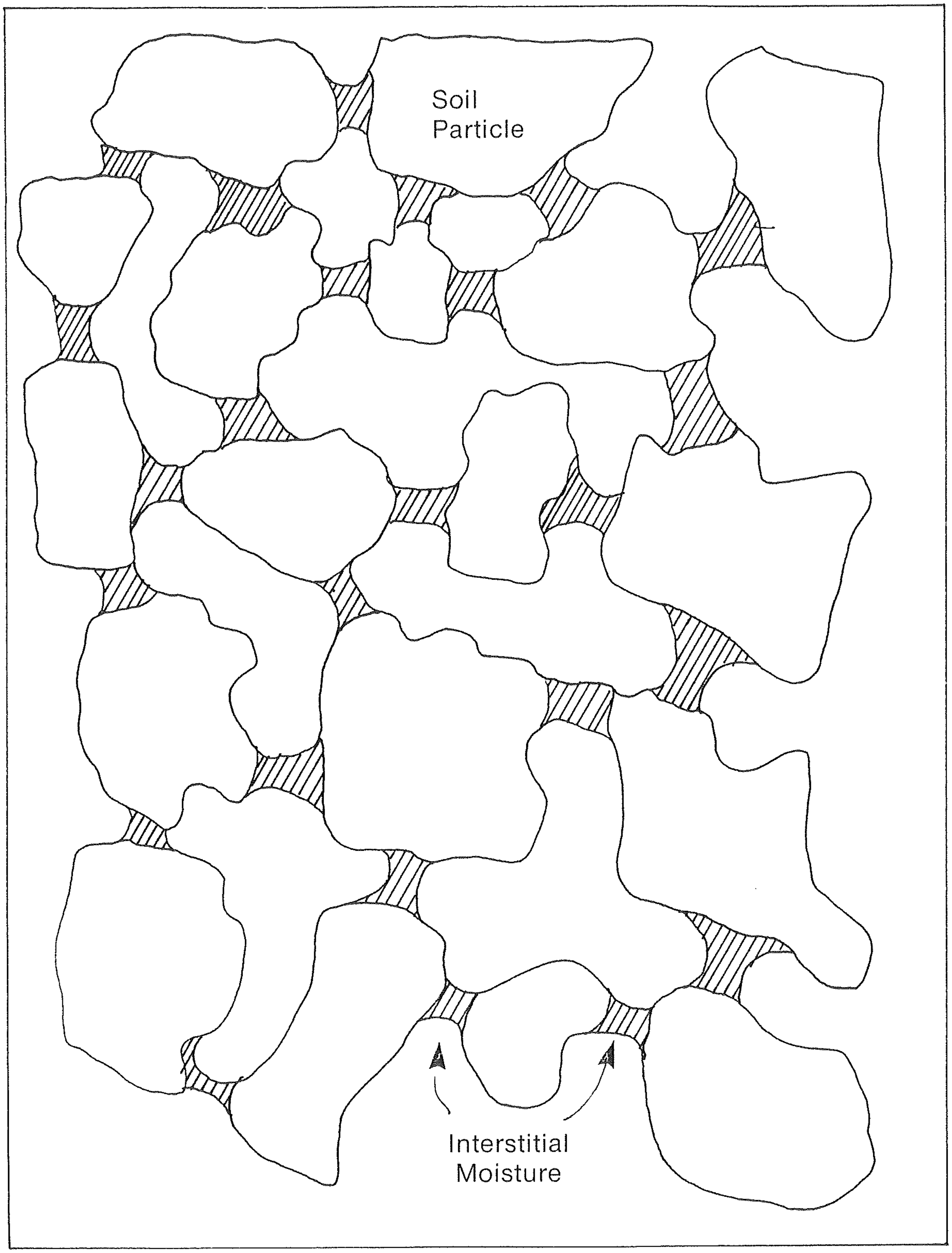


Figure "A" Illustration of closely Held Soil Moisture

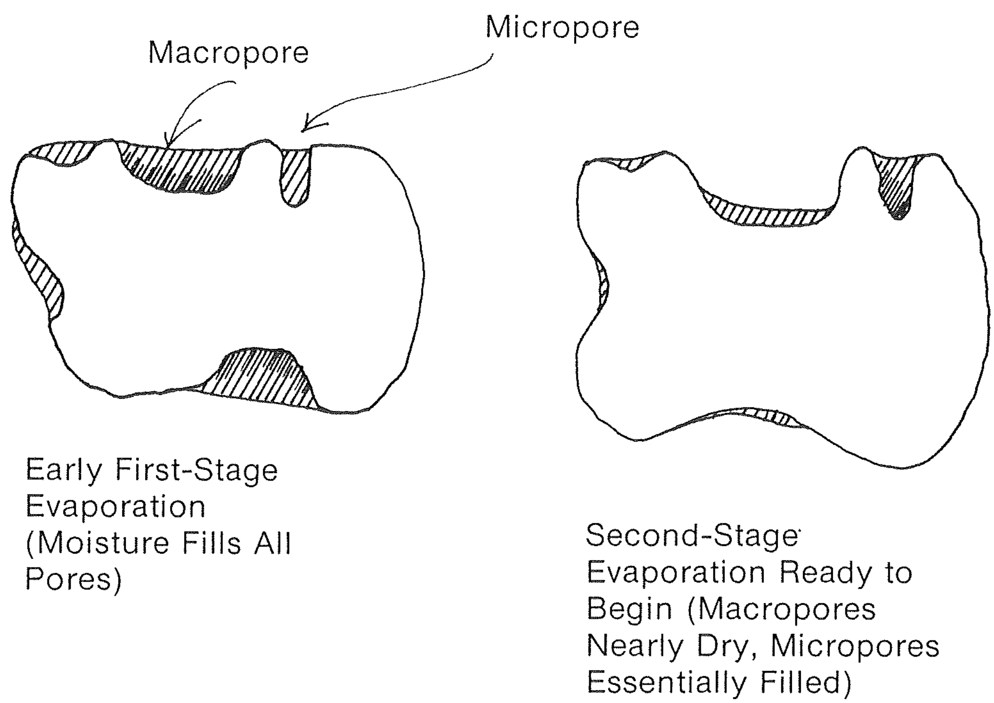


Figure "B" Illustration of Two Soil Particles Showing Propensity of Evaporation from Macropores Vs. Micropores

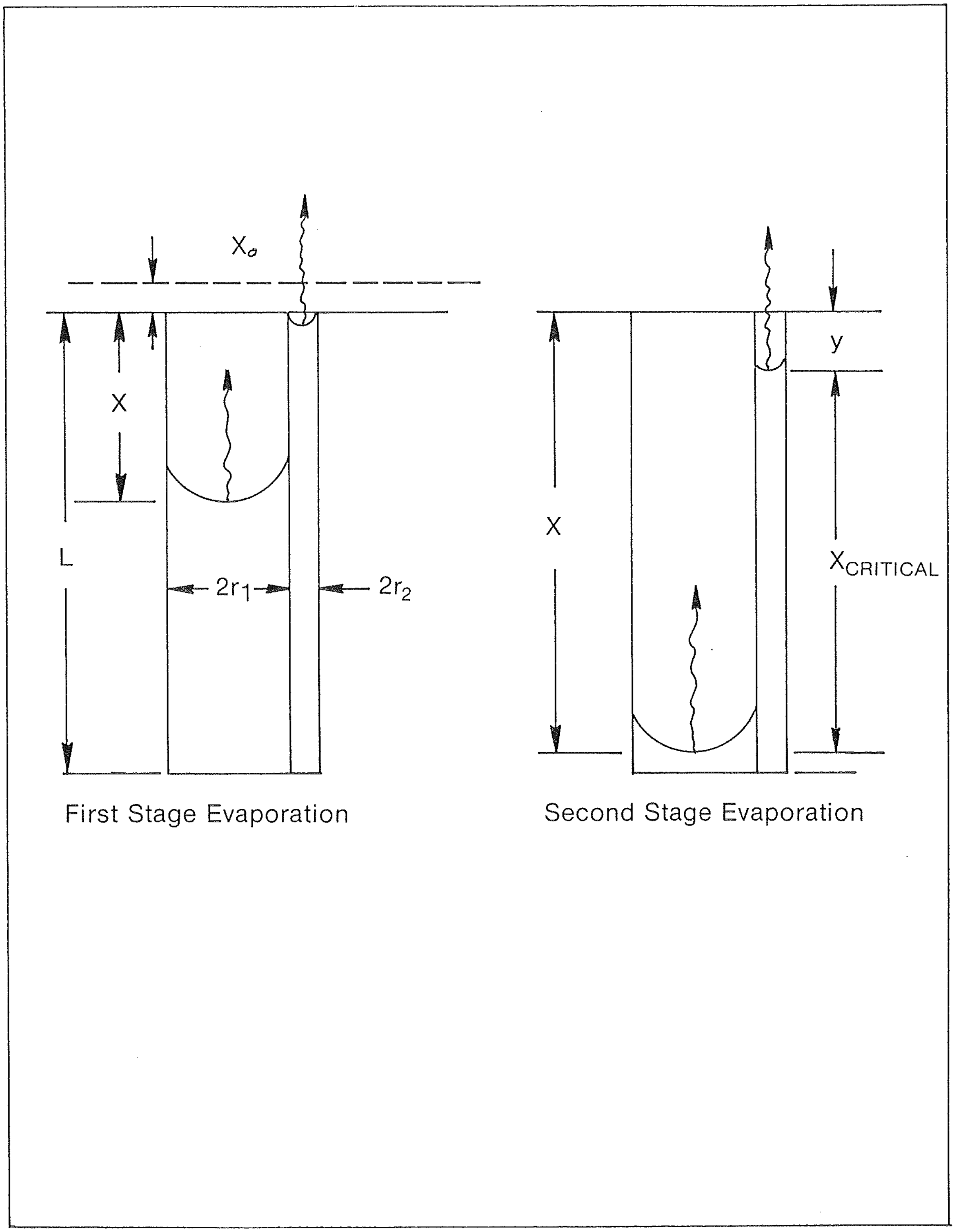
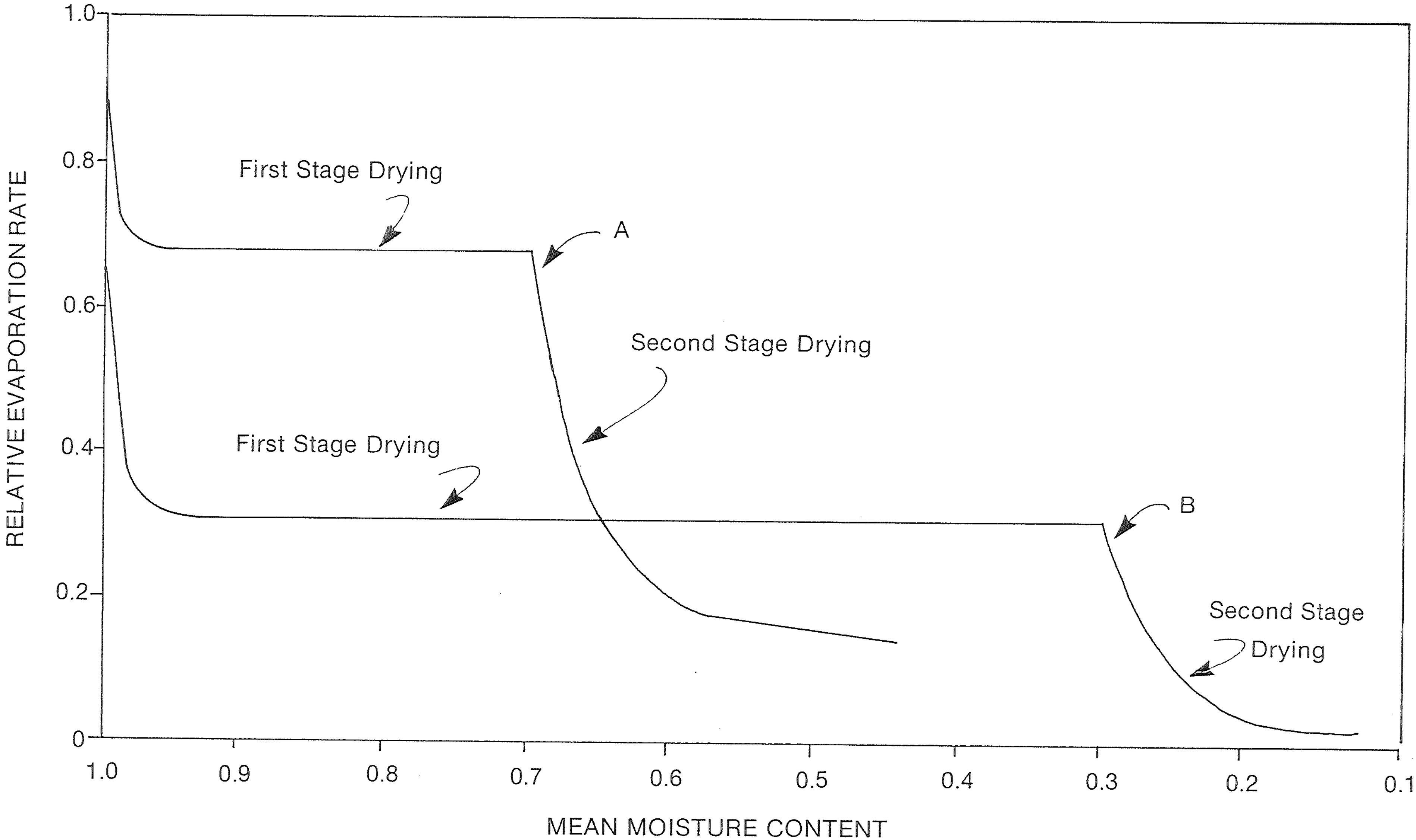


Figure "C" Mathematical Models of Idealized Soil Capillaries of Two Radii



Curve A: Π = 0.3
B: Π = 0.7

Figure "D" Relative Evaporation Rate Vs. Mean Moisture Content for a Capillary Model

FIGURE "E"

ARIZONA DEPARTMENT OF TRANSPORTATION

MATERIALS DIVISION — AGGREGATE WORK CARD

White ☐
Yellow ☐
Blue ☐

Received May 2, 1980 Test Commenced May 2, 1980 Material ______

Identification ______ Sampled May 2, 1980 Lab. No. ______

Submitted by Research Sampled by ______ Project No. HPR-1-18(163)

Source of Sample Tanner Co. Quantity 20 Sacks

Location of Supply Agua Fria Materials Pit Contractor ______

Project Name HPR-1-18(163) S.S.D. Project

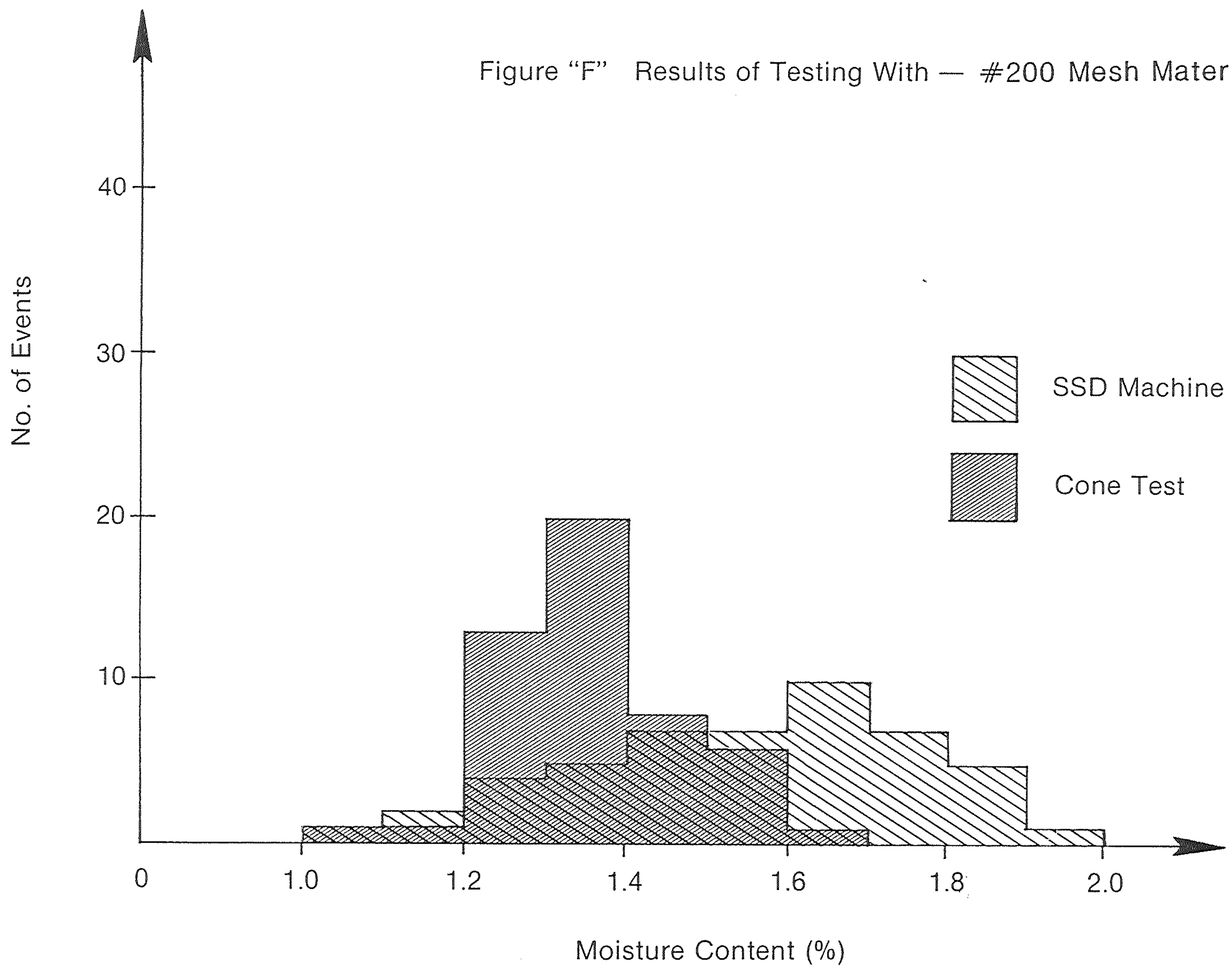
Specifications Governing ______

Remarks Materials used for statistical testing

Sieve	Weight	As Received % Ret.	As Received % Pass	Composite Grading % Ret.	Composite Grading % Pass	Specifications % Pass
3" Slot						
3" ☐						
2½"						
2"	.					
1½"						
1"						
¾"						
½"						
⅜"						
¼"						
No. 4	0					
Pass No. 4						
TOTAL						
Sieve No.						
8	36	9	91			
10	13	3	88			
16	44	12	76			
30	96	25	51			
40	59	15	36			
50	47	12	24			
100	49	13	11			
200	14	4				
Pass 200	0	7	7.01			
TOTAL	358					
Elutriation	27					

Test	Unit	Result
Liquid Limit	%	
Plastic Limit	%	
Plasticity Index		
Soil Classification		
Density by		
Maximum Density, Dry Wt. per Cu. Ft.	Lbs.	
Optimum Moisture	%	
Specific Gravity		
Moisture	%	
Abrasion 100 Rev. %, 500 Rev.	%	
Organic Impurities (Colorimetric)		
Absorption	%	
Fineness Modulus		
Soundness (Sodium Sulphate) Alternations	%	
Sand Equivalent		
Ash Correction	Gms.	
Bitumen	%	
"R" Value (300 psi Exudation)		
"R" Value Dry Weight/Ft^3		
"R" Value Exudation Moisture	%	
Expansion Pressure	Lbs/Ft^2	
Percent Swell #Lb./Ft^3		
Soluble Salts	PPM	
pH		
Minimum Resistivity	Ohms per Cu. Cm.	
Estimated Time to Perforate Culvert Pipe	Yrs.	

Figure "F" Results of Testing With — #200 Mesh Material



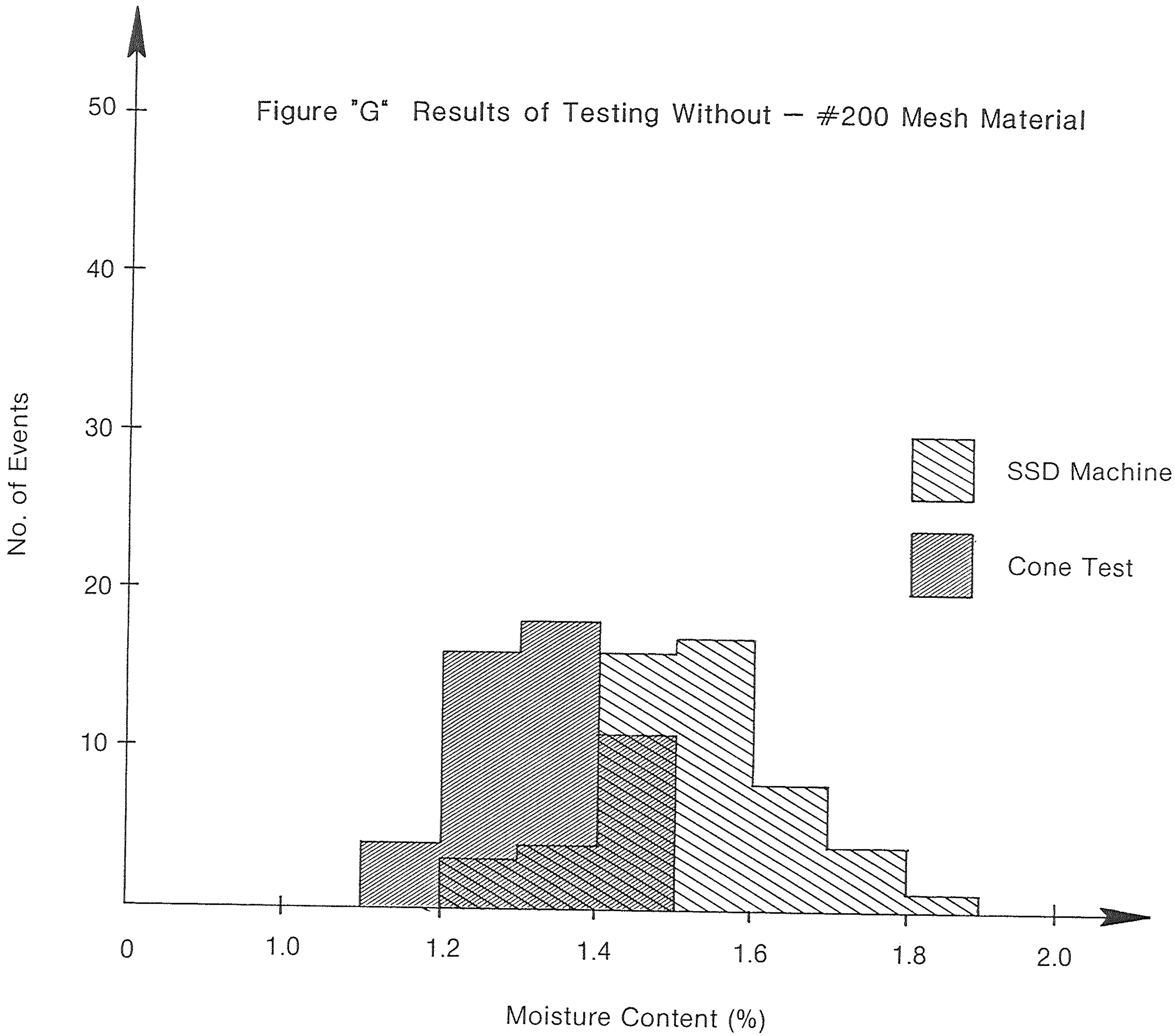
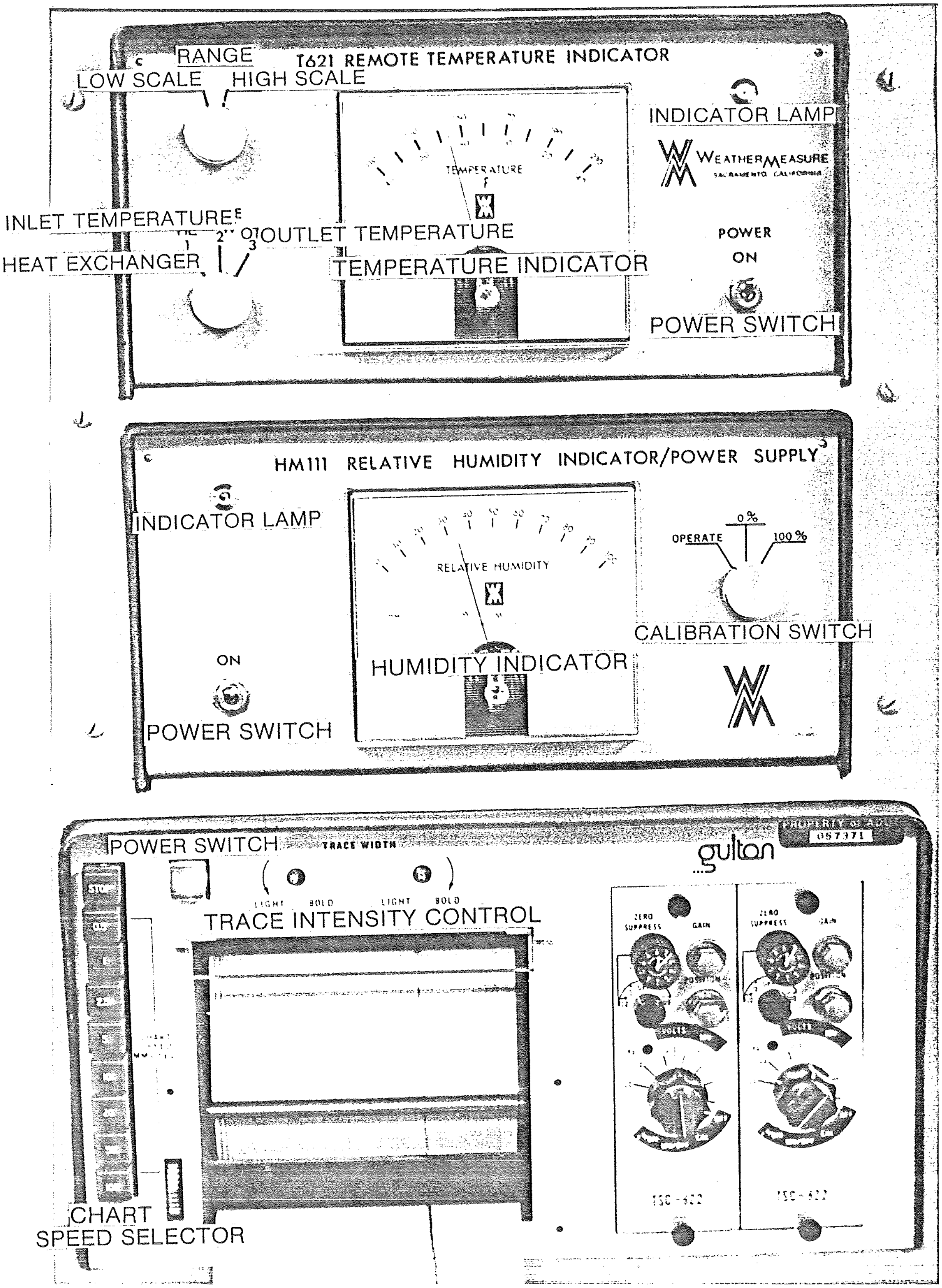
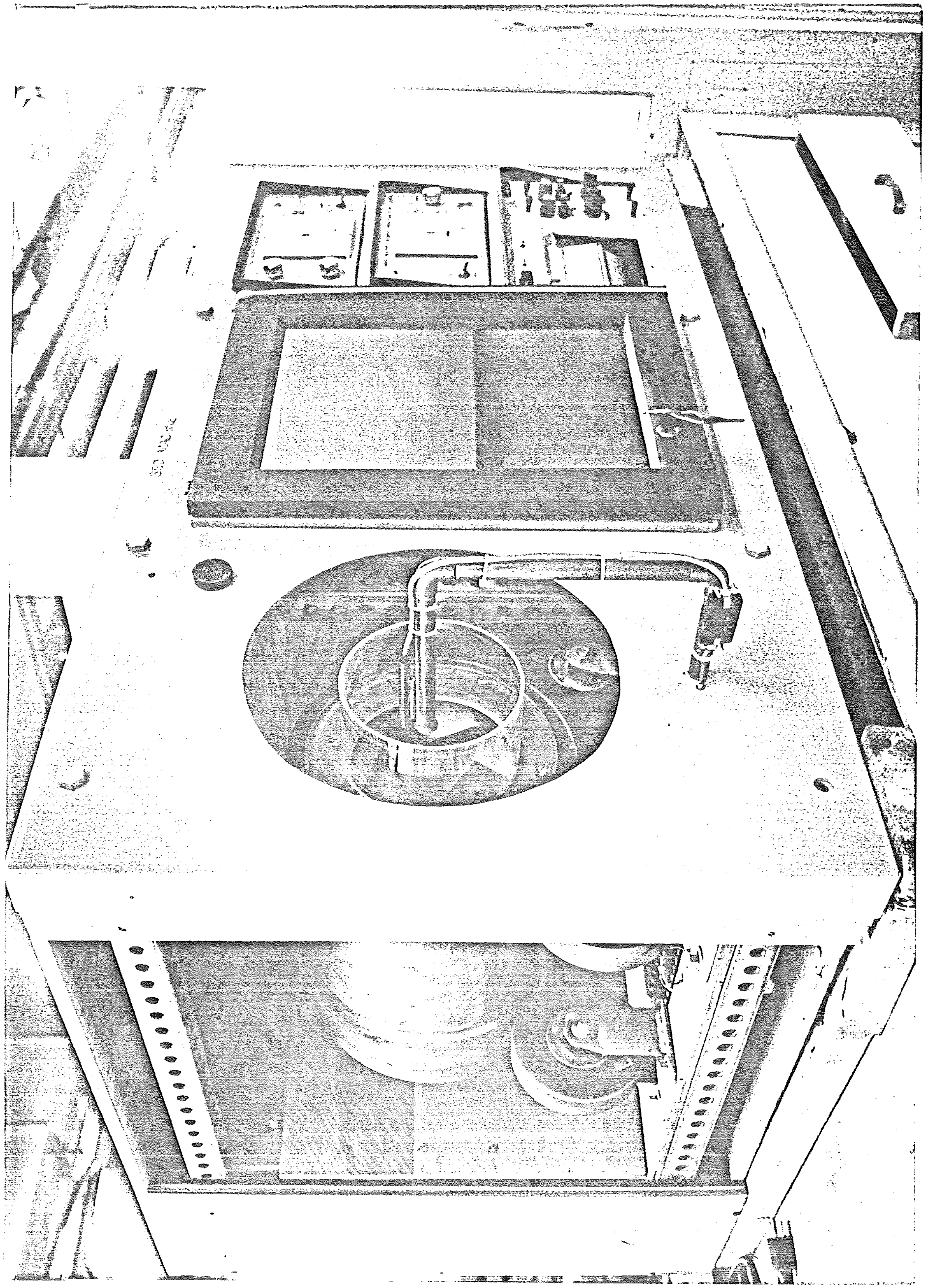


Figure "G" Results of Testing Without — #200 Mesh Material

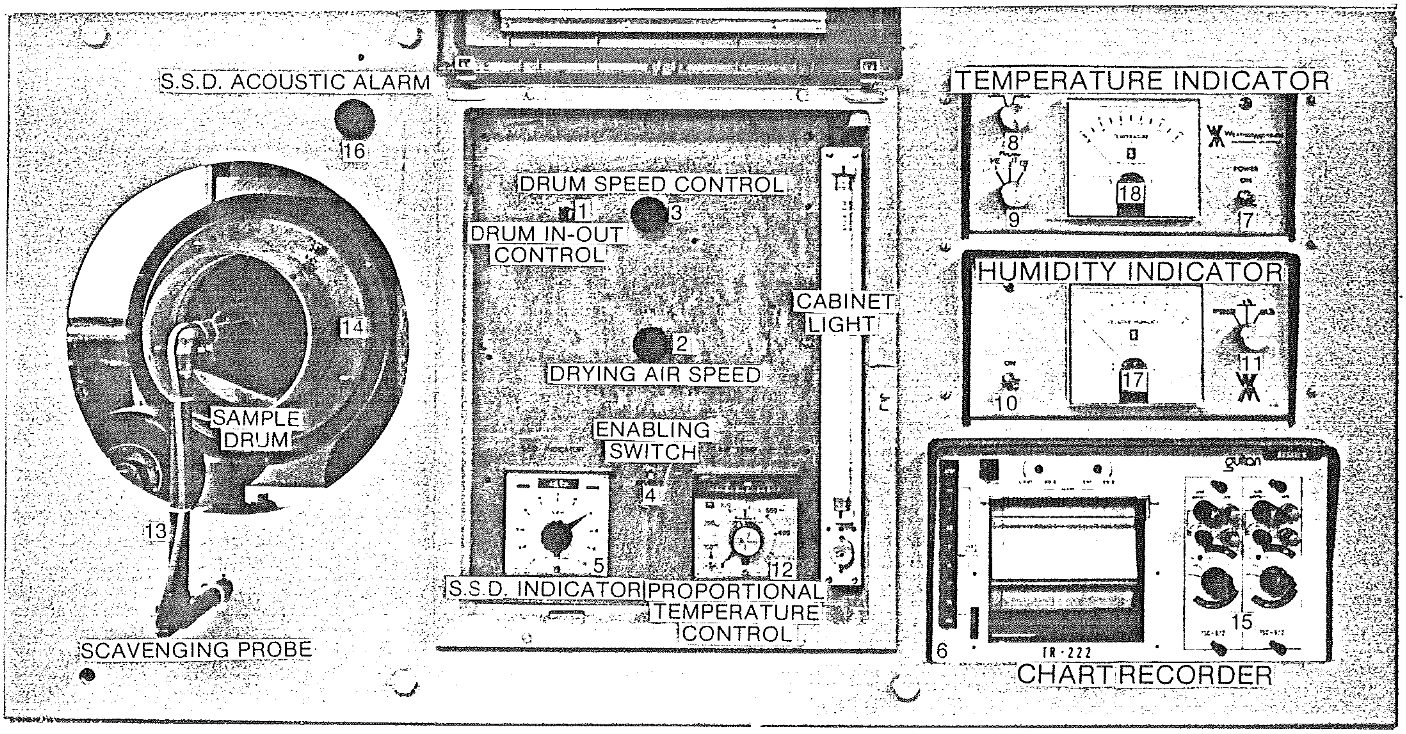
APPENDIX A



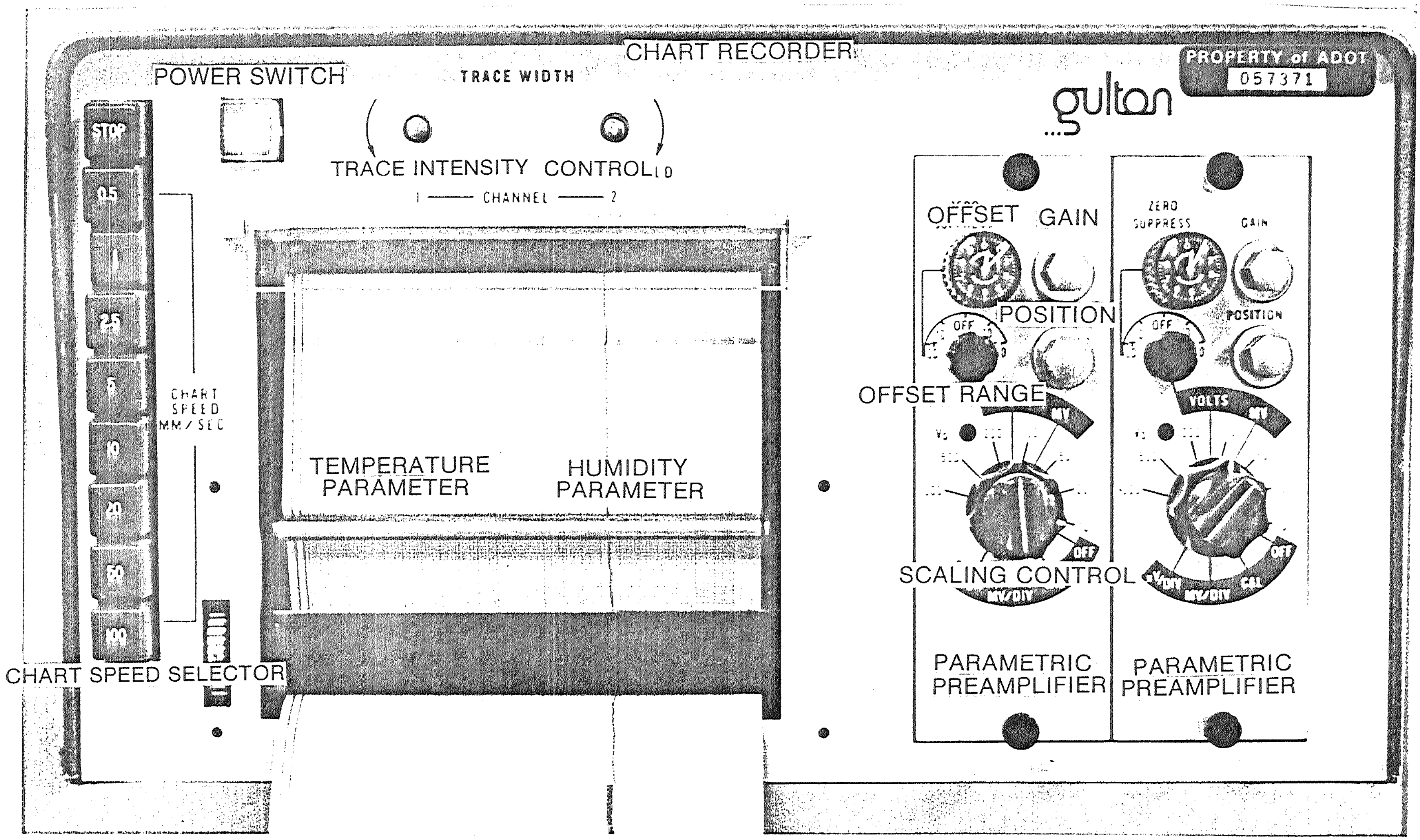
MONITORING INSTRUMENTS



VIEW OF COMPLETED SSD MACHINE



SSD MACHINE CONTROL LOCATIONS



CLOSEUP OF ANALOG DATA RECORDER