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The Effects of Wet-Pressing upon the Strength Properties of Recycled Corrugated Shipping Containers

Ted E. Dornbos
Western Michigan University

THE EFFECTS OF WET-PRESSING UPON THE STRENGTH PROPERTIES OF RECYCLED CORRUGATED SHIPPING CONTAINERS

by

Ted E. Dornbos

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Ted E. Dornbos

April 19, 1979

ABSTRACT

Tests verified the increases of strength characteristics with increasing solids content of the sheet. The rate of water removal from the sheet into the felt, involving hydraulic pressure, directly influences the compressibility of the felts and the sheet and appears to greatly determine the extent of crushing effects, which have the potential of occurring at any particular solids content region irregardless of loading.

Mention of water content interacting with the press load is suggested as an important parameter of efficient wet-pressing. Hence interest in profiles incorporating multiple wet-pressings utilizing one or two felts to increase the percent solids has an obvious financial potential.

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INTRODUCTION

During these times of energy-conscious decision-making in the paper industries, wet-pressing, the first stage of water removal after sheet formation on the wire, is quickly becoming an acute consideration in further process development to enhance its drying capabilities. The behavior of sheet strength characteristics from the wet-pressing stage, with all its many parameters, is coming under increasing scrutiny in relation to its gel (free) water content.

Also, the hydraulic pressure and the mechanical pressure, and their corresponding interactions involving the function of compression upon the sheet are of viable interest.

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GEL WATER:

Gel water, or "free water" as presented by Carlsson (1), empirically represented the water inaccessible to a polymer-dye with a specified relative molecular weight. Thus the amount of gel water present in any pulp stock is dependent on the size of the chosen polymer molecule. Parameters affecting the amount of gel water obtained include the degree of refining, the amount of fiber-fines present, and the fiber material itself.

Carlsson and his co-workers established a definition of gel water through the incorporation of a high-molecular weight dye, "Blue Dextran" dye (M_w = 2.0×10^6). Where the Blue Dextran dye could not permeate the water within the small cavities of the fiber-water suspension due to its molecular size, this water is defined as the "gel water."

Under progressively heavier loads, it is theorized that the concentration of dye decreases when the water inaccessible to the dye molecule, located for the most part within the fiber walls and the smaller fiber cavities, is expressed from the "gel matrix" of water and fiber and successively dilutes the dye solution. This concentration is determined via the use of a Beckman grating spectrophotometer set at 620nm (6200 Å).

Carlsson observed that the Dextran dye concentration does not influense the outcome of results in the experimental range of 1-10 grams/liter. However the effect of beating, with direct correlation to the fines content, indicated an increase in the amount of gel water with increased beating time.

Wet-pressing, in practice, usually approaches a 40% solids level out of the press section, but Carlsson did his work in the higher ranges of solids content. However it is hoped that by careful analysis within this frame of reference, one will be able to evaluate the influence wet-pressing will have upon the physical strength characteristics of the paper.

FIBER BONDING:

According to Marton (2), the strength of paper depends to a great extent on the number of bonds formed between the surfaces of the adjacent fibers. The number of bonds formed is determined chiefly by chemical composition and physical characteristics of the outer layers of the fiber cell wall. These factors can be altered by delignification, beating, wet-pressing, and other processes.

According to the text, THE PULPING OF WOOD, during the beating of chemical pulps, fibers are reduced in length, and their primary and secondary layers are damaged (3). The partial and/or complete removal of these layers makes the underlying layers more accessible to swelling. Hence the main action of the beating process is the disintegration of residual fiber bundles into individual fibers. At the same time the stiff fibers are made more pliable. The high-yield pulps, or semi-chemical pulps, such as linerboard and corrugated medium, which contain hemicelluloses in large amount, are not yielding to unrestrained swelling. Lignin itself not only resists swelling, but it also acts as an inhibitor for the swelling of these hemicelluloses.

Marton also studied the cross-sections of some pulp specimens. Those fibers with high lignin content (approx. 19%) appeared to be loosely arranged and only small amounts of surface areas were engaged. Fiber bundles were evident. With increasing beating time, the outlines of fibers were no longer well-defined. Instead they exhibited signs of removal of the outer layers. These exposed areas were seen to stick closely to each other with more frequent surface-surface contacts. Greater compactness (or density) and increased contact surfaces were obtained by pressing the sheets in the wet condition. With increasing wet-press, the shape of the cross-sectional areas became flatter (i.e. more oval in shape). The lumen space was squeezed to a minimum at very high wet pressures.

Photo-microscopy studies were also done by Marton and observations of highly lignified pulps and unbeaten pulps indicated that increasing degrees of wet-pressing induced more splitting of the wall, with many cracks perpendicular to the axis of the fibers. The effects of mechanical treatment imparted to the rigid, high-lignin content fibers were more pronounced than those observed on the delignified fibers. And it was shown that these specimens responded only slightly to the swelling action of water. The effect of pressure on the cell wall became less distinct in the delignified pulps as compared to the high-lignin content pulps.

Wet-pressing is generally regarded as an effect similar to that obtained by increasing the beating time. Both actions accomplish the closer contact of fibers in paper, or in other words, increased density. Doughty (4), on the basis of his work, proposed that the apparent density is one of the best indices of the interfiber bonding. As revealed by his investigation, large changes in density and breaking length occur with relatively small increments in swelling for wet pressing. However spontaneous density increases do not follow with increased "swellability" until sufficient lignin has been removed.

For the unbeaten, higher-lignin content pulps, the increased density and breaking length can be produced only through the action of increased wet pressure.

The summary of Doughty's results revealed that wet-pressing had little effect on the removal of the primary and the first of the secondary fiber walls in all cases studied. However, its application promoted strength development to a significant degree. Its effects varied depending upon the product derived from the parent pulp. For the parent pulp, wet-pressing of the fibers produced hardly any effect on the swellability of the fibers. Upon removing more and more of the lignin, and after some limited beating, wet-pressing was observed to produce a change in the fibers similar to that obtained through ball milling.

MECHANICS OF BONDING:

Van Den Akker (5) had written "that the most exciting fact about paper - known and appreciated over the eighteen-and-one-half centuries since the invention of the product by Tsai Lun - is that a tough, strong sheet of material is obtained when cellulosic vegetable fibers are mechanically beaten in the presence of water and are felted together from an aqueous suspension by the forming on a screen and then dried." When we consider the mechanism of bonding of cellulose fibers in the making of paper, we find that there are three fundamental factors involved. First we have to think of what surfaces are to be brought together, next we have to consider what surfaces are to be bonded, and, finally, how they are to be locked in position.

From "THE PULPING OF WOOD" et al, the fiber surfaces are important where beating and/or refining increases the amount of surface area available for bonding via the production of fibrillar membranes which comprise the walls of each fiber. The fiber wall is typically comprised of four layers commonly labeled S1, S2, and S3. These layers are concentric around a central cylindrical cavity called the lumen. During beating, the primary wall is usually pealed (or "beaten") off the fiber exposing the secondary layers. Increased mechanical action on the fibers releases "fibrils" or a fraying of these layers into their composite fibrils. As these fibrils are released and projecting out from the parent fiber suspended in water, a mechanical interlocking comes about, establishing close clearances between the fibers. Thus structural strength is enhanced via interfiber bonding and a corresponding increase of surface contact area. These secondary layers, especially the S1 and S2 layers, are the layers that are subject to water penetration and the subsequent swelling of the fibers.

Van Den Akker also pointed out that wet pressure enables the "bringing together" of the available bonding sites of the fiber mass where the load has to be carried by the interfiber contact areas. Since these areas are much less than the total area of the sheet, the pressure per unit area is many times greater than the load pressure, especially when there are voids present. Obviously, the pressing operation has an importance other than water removal.

Further water removal by drying enhances the "bringing together" of these bonding sites as noted by Van Den Akker. Evaporation of this water is accompanied by shrinkage. Cellulose itself, which makes up the fiber bundles, does not shrink. It is the tension force of the water that further enhances the degree of bonding and the resultant strength of this paper. One component of this strength is due to the bonding of hydrogen bonds; that is, to regions where the hydrogen atom of a chemical group such as hydroxyl (OH^-) finds itself in close proximity to an atom of oxygen or some other element possessing one or more pairs of unshared electrons (6). This mechanism occurs as soon as the amount of water in a cellulose fiber or a mass of cellulose fibers such as paper pulp becomes low enough to be in equilibrium with the relative vapor pressure (less than 100%). This tension force (the surface tension of water) comes into dominance to draw the solid surfaces together. That is, provided the solid surfaces are already close enough to each other so that the space between the solids is filled with water when the humidity goes below the one-hundred percent point.

WET-PRESSING:

According to Bliesner (7), the basic principle of wet-pressing a sheet of paper involves the compression of the sheet to squeeze water from the interior of the web. The more the paper sheet is compressed, the more water is removed.

This simple definition becomes more complicated as one reviews the dynamics. Wahlstrom (8) pointed out that the total press load is counter-balanced by other forces generated within the nip, all expressed in pounds per lineal inch (pli). This counter-pressure can be divided into two parts: the hydraulic pressure involving the water present in the felt and the paper, and the mechanical pressure. The total pressure at any point in the nip is equal to the sum of these component pressures.

Wahlstrom further establishes and defines four specific regions or phases describing the interaction of these two component pressures (figure 1). Phase 1 is represented by the entrance of the sheet and felt into the nip. Here only mechanical pressure is present and continues to increase until the web voids are filled with water, that is, are completely saturated with water. Thus the onset of the hydraulic pressure commences, introducing phase 2. Phase 2 proceeds now to the point of maximum pressure at or near the midpoint of the nip. As the hydraulic pressure increases, water is squeezed from the web into the felt. Phase 3 continues from the midpoint to the point of maximum paper dryness. Mechanical pressure on the sheet continues to increase as long as the dryness of the sheet increases (phases 1 & 2), hence maximum mechanical pressure corresponds to the maximum sheet dryness. Phase 4 represents the rewetting region where the expansion of both the paper web and the felt causes water to move along the interface and readsorb back onto the sheet. This phase continues until the final physical separation of sheet and felt.

Wahlstrom continues to discuss the factors which influence wet-pressing. 1) The Press Load, which is under direct control of the papermaker. However in high-moisture sheets, crushing can result, hence limiting the press load. The loss of caliper and/or bulk are a couple of the quality parameters one must consider when increasing the press load. Press roll covers can be a limiting factor due to the heat buildup. This cover, usually rubber, also influences the nip length which determines the amount of time the sheet and the felt are in the nip; the "residence time." With hard rolls the felt (other than the sheet) is the only compressible material in the nip.

2) The Drainage Forces, also referred to as the hydraulic pressure diference, or its pressure uniformity across the sheet, will improve water removal.

3) Sheet Quality Factors, such as formation, fines retention, and furnish components are believed to be major considerations. Unfortunately, no published research exists in this area.

4) Paper Compression Properties, as summarized by Han (9), is the best literature available to date. It is shown that for static compressibility of synthetic fiber mats, the data can be represented by a simple power function over a wide range of compacting pressures (i.e. the mat density is proportional to the applied pressure^n). Also for woodpulp fibers, which are viscoelastic in nature, irreversible factors become important; loss of absorbed water at contact points has an effect along with the time-dependent variables. Finally since the flow of water is involved in wet-pressing, wheet moisture content into the press has a direct bearing on the compression of the web.

5) The Flow Resistance of Paper, is the major resistance to sheet-water removal, where its primary determinants are the basis weight and the degree of refining as indicated through the Canadian Standard Freeness (CSF).

Nilsson and Larsson (10) commented that except for very light-weight papers (e.g. tissue) it is quite likely that the flow resistance of the paper web itself is the major deterrant to higher sheet dryness. And Busker (11) concluded that one major controlling factor is the resistance to water flow out of the paper.

6) The Time Duration of Pressing, is coming under greater scrutiny. The variables here involve the nip residence time which is a function of machine speed

and nip length, where the nip length is a function of rubber cover hardness and/or felt compression properties and the applied stress load.

Briefly, rewetting mechanisms (12) are also parameters of wet-pressing which are now only beginning to be understood. Recent developments to offset rewetting problems includes the advent of grooved rolls, two-felt presses, and the incorporation of vacuums inside the press to aid in water removal.

Mention is now given to D. J. MacLaurin and J. F. Whalen of the Institute of Paper Chemistry, Appleton, Wisconsin, concerning their work involving wet pressing (13). In their research, they cite Doughty et al about an extensive study of relationships between wet-pressing of handsheets and the properties of the dried sheets, using unrefined spruce sulfite pulp. They showed that dry sheet density, tensile, fold, and burst increased with increasing pressure. Doughty, through subsequent research, showed that at the same wet pressure, sheets of shorter fibers were denser and had higher tensile strength than sheets of longer fibers. The amount of shrinkage increased rapidly to a maximum at relatively low pressures. Sheets from short fibers showed greater shrinkage than those of long fibers at any particular pressure. These studies led to the generalization that wet pressing has the same kind of effects on dry sheet properties as typical refining.

Another author cited by MacLaurin and Whalen is Campbell as well as Lindman, Campbell saying that if the fibers are sufficiently flexible and fibrillated, bonding is not increased by wet-pressing. Lindman made an extensive study of the strengths along the drier section of a paper machine. He concluded that excessive wet-pressing could give a lowering of dry sheet strength. He also found that the sheet had a higher fold and density immediately after the wet presses than after the first few driers. Arlov and Ivarsson (other authors cited) showed how stretch could counteract the effects of wet-pressing.

MacLaurin and Whalen theorized that because of the general relationships between wet sheet pressing and dry sheet strengths it was predicted that the dry sheet burst could be raised by additional wet-pressing alone, thus avoiding slowing the stock through refining. Their experiments indicate that repeated pressings at lower pressures are not as effective in raising burst as a single pressing at higher pressures. Other conclusions include the appearance that a sheet can be compacted so far and no further, unless perhaps very high pressures are used which are sufficient to crush the fibers and remove internal water. It is interesting to note that sheet density-strength relationships are not independent of refining. It is quite apparent that refining is more effective than wet-pressing in raising burst. Lastly it was concluded that for purposes of increasing the bursting strength through wet-pressing, two or possibly three pressings at pressures not over 300 to 400 pli, but otherwise as high as possible, would give maximum gain. Pressing to a moisture content of about 50% appeared to be optimum.

LINERBOARD AND CORRUGATED MEDIUM:

As communicated to me by Dr. R. B. Valley (14), linerboard characterizes the flat wall of corrugated shipping containers. Raw stock is unbleached softwood Kraft produced in high yields (60%+) made from standard Kraft southern pine. Its function is to offer resistance to puncture and tearing, and to offer good stiffness. Ten to twenty percent of total board is comprised of waste paper, waste wood, and hardwood of standard basis weight of 42 lb/100ft^2.

Corrugated medium is comprised of 50 to 60 percent NSSC (Neutral Sodium Sulphite) hardwood with subsequent high refining. Forty to fifty percent of the total product is comprised of recycled box or refined Kraft commonly referred to as "bogus." Also included in the furnish is that this product is 7 - 9 percent long fiber (from the recycled box). The major distinction is that this product is unsized and produced in an alkaline pH and may contain a wetting agent to prevent self-sizing. Caution must be exercised in pH since lower pH may cause self-sizing to commence.

STATEMENT OF OBJECTIVE

The objective of this investigation is to establish interrelationships of the degree of wet pressing, as indicated through the "gel water" expressed from the sheet, to the strength characteristics of the resultant paper. The gel water, which is a parameter of wet pressure, is also directly related to the solids content of the sheet; hence moisture relationships can be utilized.

Theoretically, it would be ideal to assume a smooth curve relationship between the two wet-pressure endpoint extremes. That is 1) not enough wet pressure is applied to the web to remove a sufficient amount of water (thus the strength quality is poor); and 2) too much wet-pressure is applied resulting in the crushing of the web fibers - again resulting in poor strength quality.

This study will attempt to elucidate the functions of wet-pressing upon final sheet strength properties of recycled corrugated shipping containers with emphasis on the solids content as well as the applied pressure.

STOCK PREPARATION

Three 400g ADF valley beaters of pulp were required to supply enough stock for this investigation.

Refining of 400g of brown stock comprised of corrugated shipping containers was done in a valley beater with 23.6 liters of tap water under a loading of 5650g upon the bed plate. The resulting suspension was then refined for 10-15 minutes to a freeness within the range of 400 - 450 CSF. The initial freeness approx. 660 CSF, and the final consistency was 1.5%. The stock was allowed to age not less than twenty-four hours before use. Storage was facilitated via the use of 40 milliliters of formaldehyde.

HANDSHEETS

Handsheets were made, utilizing the Noble and Wood Handsheet Machine, to a constant humidity room basis weight of 50 lbs. This criterion required a handsheet weighing about 2.8 grams immediately after drying upon the drying cylinder.

The weight increments, 3, 4, 5, signify the number of weight increments (1 increment ≐ 4500 g.) applied to the arms of the Noble and Wood wet-press. In all cases, the first pass of the handsheet through the nip was done with the handsheet screen involved between two layers of felt. Subsequent passes through the nip were as follows: 1) the felt press with the screen - The sample was not removed from the screen, but merely sandwiched between the layers and passed through again; 2) the felt press without the screen - The sample was removed from the screen and sandwiched between the layers of felt and passedthrough the nip; 3) the blotter press with the screen - The sample on the screen was sanwiched between two 9" X 9" blotter sheets and passed through the nip; 4) the blotter press without the screen - The sample sheet was peeled off the screen and sandwiched between two blotter papers (9" X 9") and again passed through the nip.

The moisture determinations were calculated by weighing either the combined mass of the handsheet and screen or the damp handsheet and subtracting the mass of the dry screen (where necessary), and weighing the final dryer dry weight of the handsheet.

SPECIALLY PRESSED HANDSHEETS

To get the Noble and Wood handsheets to fit in the Carver press, a British Sheet Mold drying ring was placed on the forming wire of the Noble and Wood Handsheet Machine before the sheet was formed. The drying ring permitted a circular section of paper to be formed in the regular square sheet.

Each sheet was then pressed in the Noble and Wood wet press (@ 3 wt.) and the circular section was peeled off of the wire screen. It was then placed between two blotters with six additional circular sheets, with a blotter between each, topped with a British Sheet Mold chrome plate, placed in the Carver Press, model B, and pressed at the desired pressure at which it was held constant for five minutes. After the five minutes, one sheet was removed and placed in a weighing can for moisture analysis, while the others were dried on the dryer can of the Noble and Wood Handsheet Machine.

THE GEL (OR FREE) WATER TEST

Carlsson's basic procedure was followed (outline for procedure - refer to Appendix I).

The test sample was prepared by measuring the consistency of the stock. After the consistency determination, the amount of stock required to yield 20 grams ODF was calculated. The stock then was thickened up to 100 g wet by draining the stock through a 100 mesh screen. The resultant moist fiber was weighed and the additional water was added to yield a final mass of 100g stock @ 20% solids. 150 ml of a high-molecular weight BLUE DEXTRAN DYE (@ 5g/liter) was added, mixed and permitted to stand for one hour. Meanwhile, the oil on the apparatus (figure 2 and figure 3) was wiped off, the screen put into place, and the cylinder was securely tightened. The bottom half of the assembly was put into the carver press. A 50 ml beaker was then placed under the drain-hole to collect the liquid expressed from the pulp mass. The pulp and dye sample was then poured onto the cylinder, the piston put into place, with the gaps of the seal rings opposite each other. The cover portion of the Carver press was then lowered to the top of the piston so as to permit free fall into the cylinder. The press was pumped until the needle on the pressure gauge started to move. Pressure was held at this point for 10 minutes. The amount of liquid expressed during this time was collected and measured in a graduated cylinder, from which a sample was set aside for measurement in the spectrophotometer. The pressure was then increased to 5000 pounds of force and held for ten minutes during which the expressed liquid was again collected and measured and a sample reserved for the spectrophotometer. This procedure was followed for 10, 15, and 20 thousands of pounds of force. Once the last sample was obtained, the wet pad was removed from the apparatus and weighed on a single-pan balance. The pad was dried overnight in an oven set at 105 celsius degrees. The dry pad weight was also taken upon the same balance.

Standard spectrophotometric procedure was followed to determine the dye concentration. The wavelength used for the analysis is 620nm (6200 Å). The free water endpoint is determined from a plot of dye concentration vs pad consistency. The pad consistency at a point was determined from the dry weight of the pad and the total weight of the material present at that point. The total weight was found by subtraction of the amount of water removed up to that point from the original wet weight of the pulp suspension.

TESTING

Tensile, Gurley Stiffness, Gurley Densometer, Tear, Basis weight, and Caliper were performed using standard Tappi procedures.

EQUIPMENT USED

Bausch and Lamb Spectrophotometer, Spectronic 88

12 T Carver Press model B

Gel (free) water test apparatus (figures 2 & 3)

Noble & Wood Handsheet machine

CHEMICALS USED

Blue Dextran Dye

Sigma Chemical Company
P. O. Box 14508
St. Louis, MO. 63178

$24.00/10 grams

EXPERIMENTAL RESULTS

SAMPLE (wt incre. - nips)	BASIS*WT (lb/ream)	TENSILE (kg/in)	STIFFNESS (Gurley)	TEAR (standard units)	POROSITY (sec/100cc 1¼" plate)	CALIPER (1/1000")	BULK (g/cc)	% SOLIDS (1 pass, 2 pass)
3wt - 1	50.99	7.07	277	85.3	9.44	8.89	.334	33.1
4wt - 1	50.48	7.72	264	102	11.61	8.67	.339	40.3
5wt - 1	47.65	6.87	206	94	9.51	8.23	.338	41.9
w/screen								
3wt - 2felt	52.56	6.93	213	100	6.85	8.34	.368	31.2, 33.4
- 2blot.	"	7.22	222	"	8.3	"	"	" , 39.7
4wt - 2f	51.39	7.14	209	93	7.9	7.76	.386	32.3, 34.5
- 2b	"	7.56	227	"	9.25	"	"	" , 41.1
5wt - 2f	53.06	7.27	206	103	9.25	7.86	.392	33.1, 34.8
- 2b	"	7.44	211	"	11.5	"	"	" , 41.9
w/o screen								
3wt - 2f	50.24	8.26	201	90	6.1	6.8	.431	33.1, 46.9
- 2b	51.24	9.17	347	103	12.3	5.98	.499	32.4, 53.9
4wt - 2f	51.87	9.01	249	106	8.93	6.53	.463	36.1, 52.5
- 2b	50.72	10.1	225	87	15.0	5.63	.525	34.6, 61.2
5wt - 2f	52.81	9.29	258	106	10.6	6.30	.488	36.3, 54.0
- 2b	50.69	9.86	222	106	19.3	5.53	.534	36.7, 65.5

EXPERIMENTAL RESULTS (cont.)

SAMPLE (wt incre. - nips)	BASIS*WT (lb/ream)	TENSILE (kg/in)	STIFFNESS (Gurley)	TEAR (standard units)	POROSITY (sec/100cc 1¼" plate)	CALIPER (1/1000")	BULK (g/cc)	% SOLIDS (1 pass, 2 pass)
Carver press								
500psi	53.56	9.63	282	147	43.7	6.74	.463	54.0
1000psi	59.06	9.67	325	127	93.8	6.90	.499	56.9
1500psi	54.17	10.24	214	114	127	6.04	.523	61.8
2000psi	54.59	10.90	206	113	178	6.11	.521	68.2

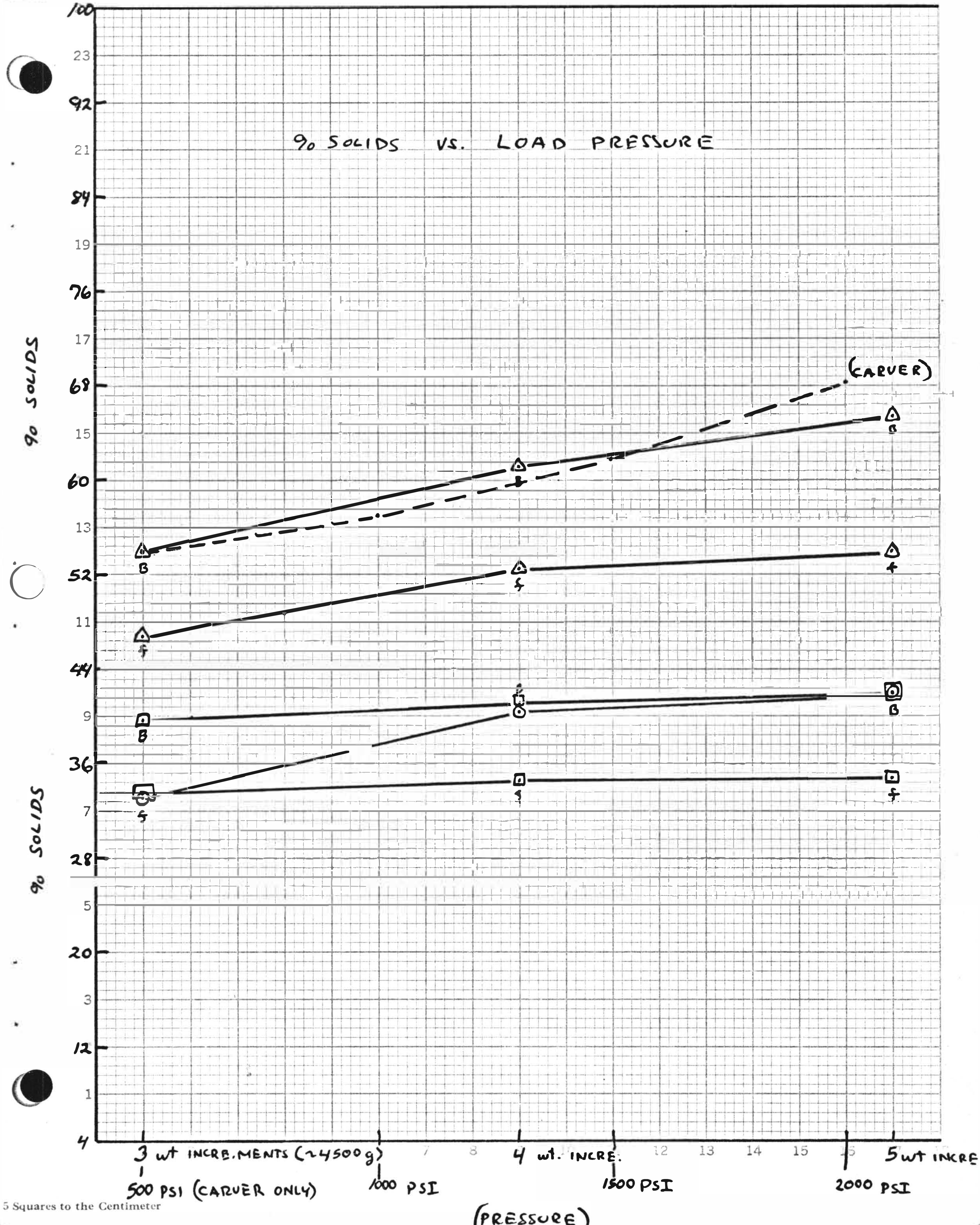
EXPERIMENTAL RESULTS

GEL WATER TEST DATA

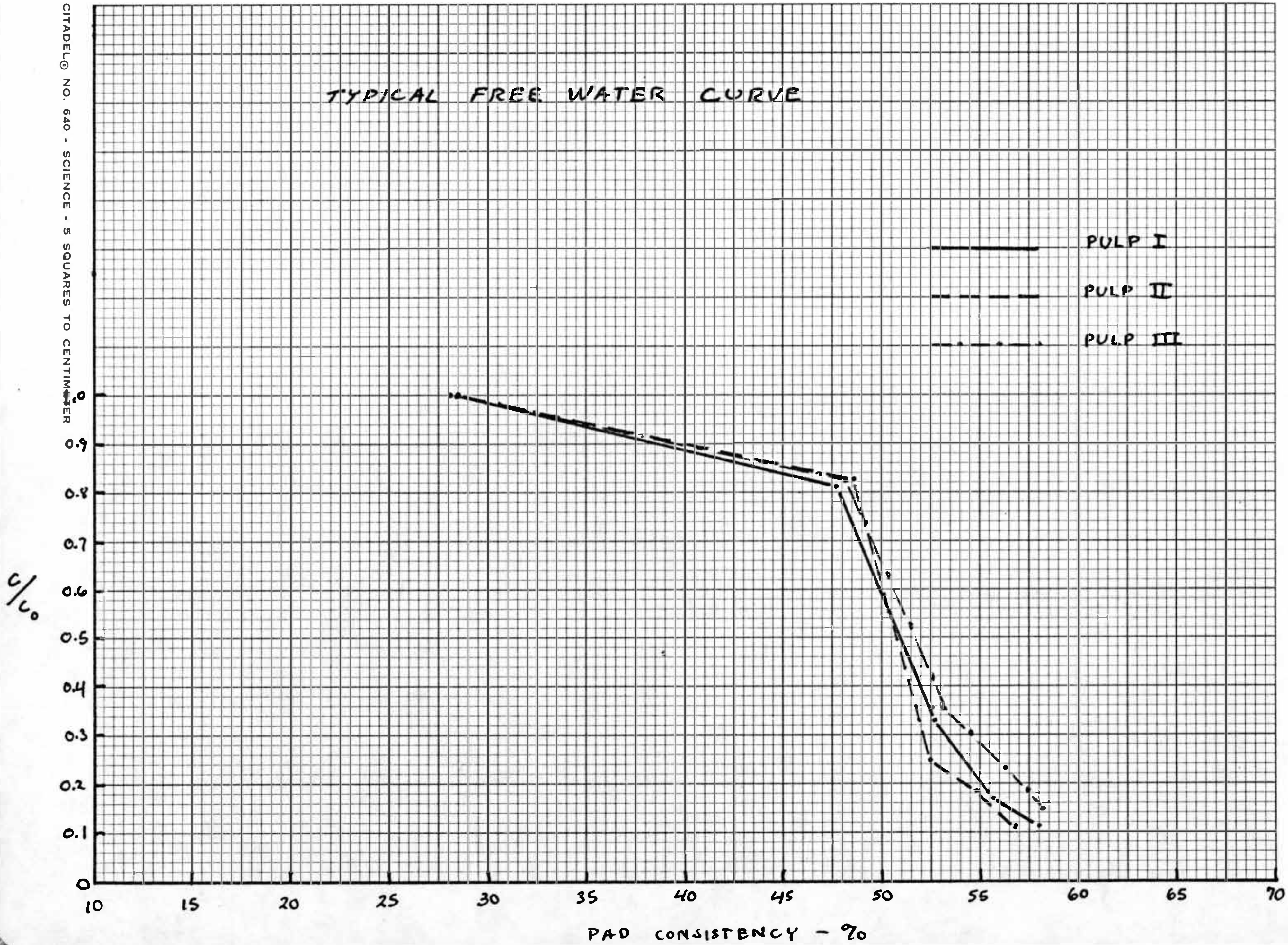
GAUGE PRESSURE (psi)	ML. EXPRESSED (milliliters)	DYE CONC. (percent)	CONSISTENCY (% solids)	DRY ODF (grams)	UNACCOUNTED ML. (milliliters)
0 (pulp I)	177	100	28.5		
5000	27.5	81.3	47.7		
10000	3.9	32.8	52.7	19.50	4.6
15000	2.0	17.1	55.7		
20000	1.4	11.5	58.0		
pulp II					
0	175	100	28.5		
5000	31.0	82.4	48.6		
10000	3.2	24.8	52.5	21.3	0.2
15000	1.7	18.2	54.8		
20000	1.4	11.4	56.8		
pulp III					
0	171	100	28.1		
5000	31.0	82.2	48.7		
10000	3.6	35.6	53.2	20.6	5.7
15000	2.1	23.1	56.3		

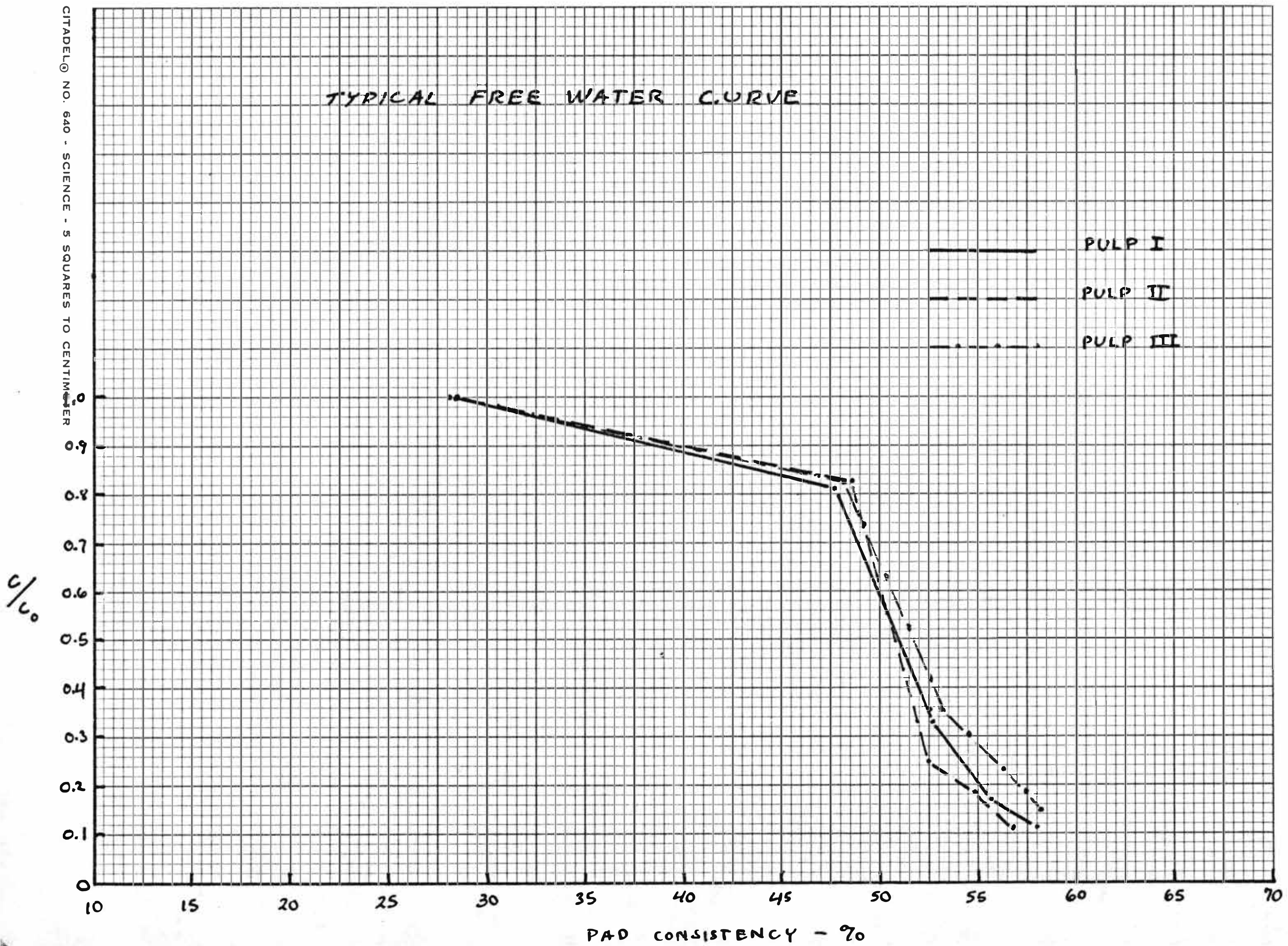
KEY TO GRAPHICAL SYMBOLS

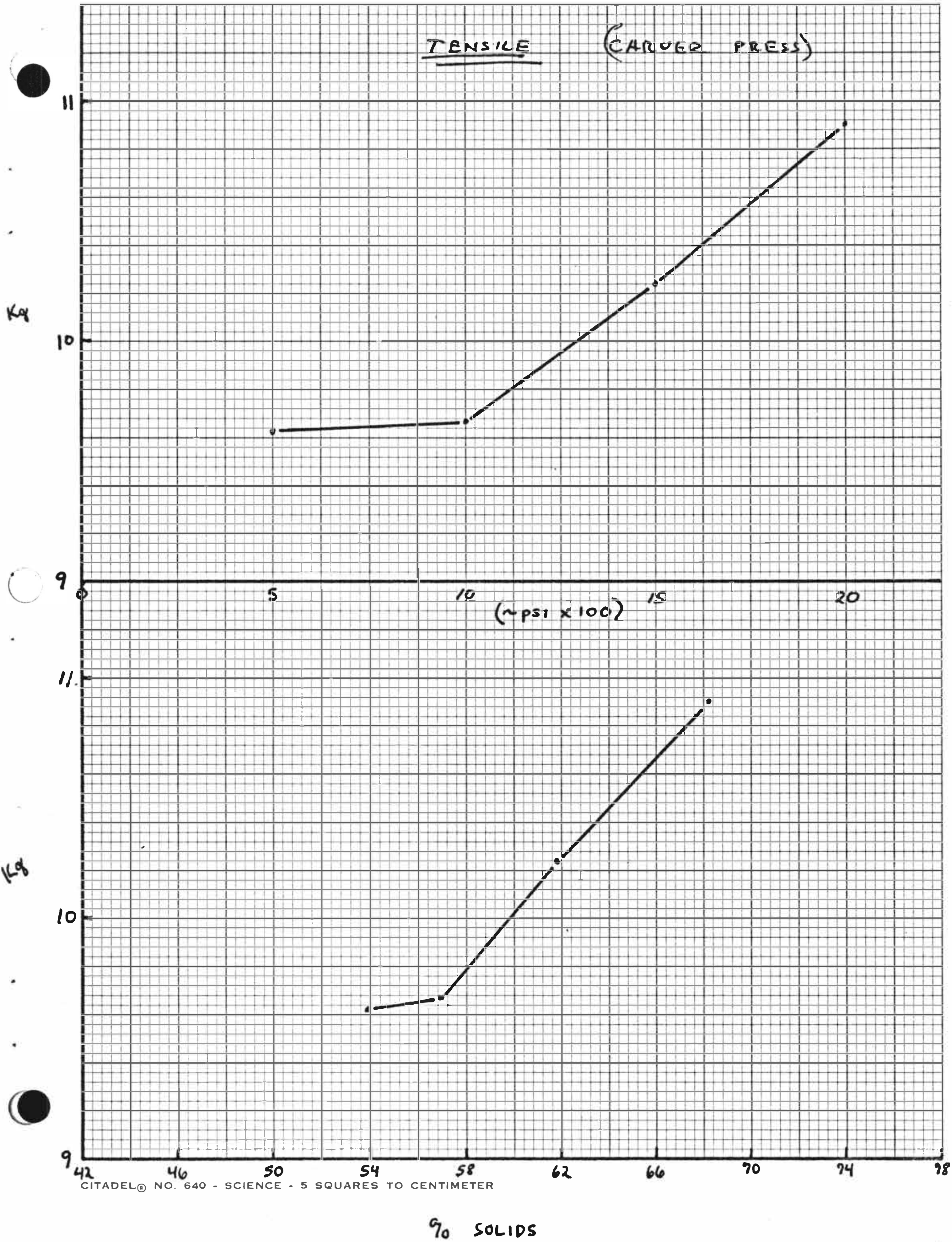
SET	LOAD (increment)	CARVER PSI	2ND PASS (felt/blot.)	SCREEN with/wo	# NIPS	GRAPH SYMBOL
A	3	-	-	w/	1	O----O
B	4	-	-	w/	1	
C	5	-	-	w/	1	
D	3	-	f & b	w/	2	
E	4	-	f & b	w/	2	□----□ f f
F	5	-	f & b	w/	2	□----□ b b
G	-	500	-	-	-	
H	-	1000	-	-	-	
J	-	1500	-	-	-	•----•
K	-	2000	-	-	-	
L	3	-	b	w/o	2	
M	4	-	b	w/o	2	△----△ b b
N	5	-	b	w/o	2	
O	3	-	f	w/o	2	
P	4	-	f	w/o	2	△----△ f f
Q	5	-	f	w/o	2	

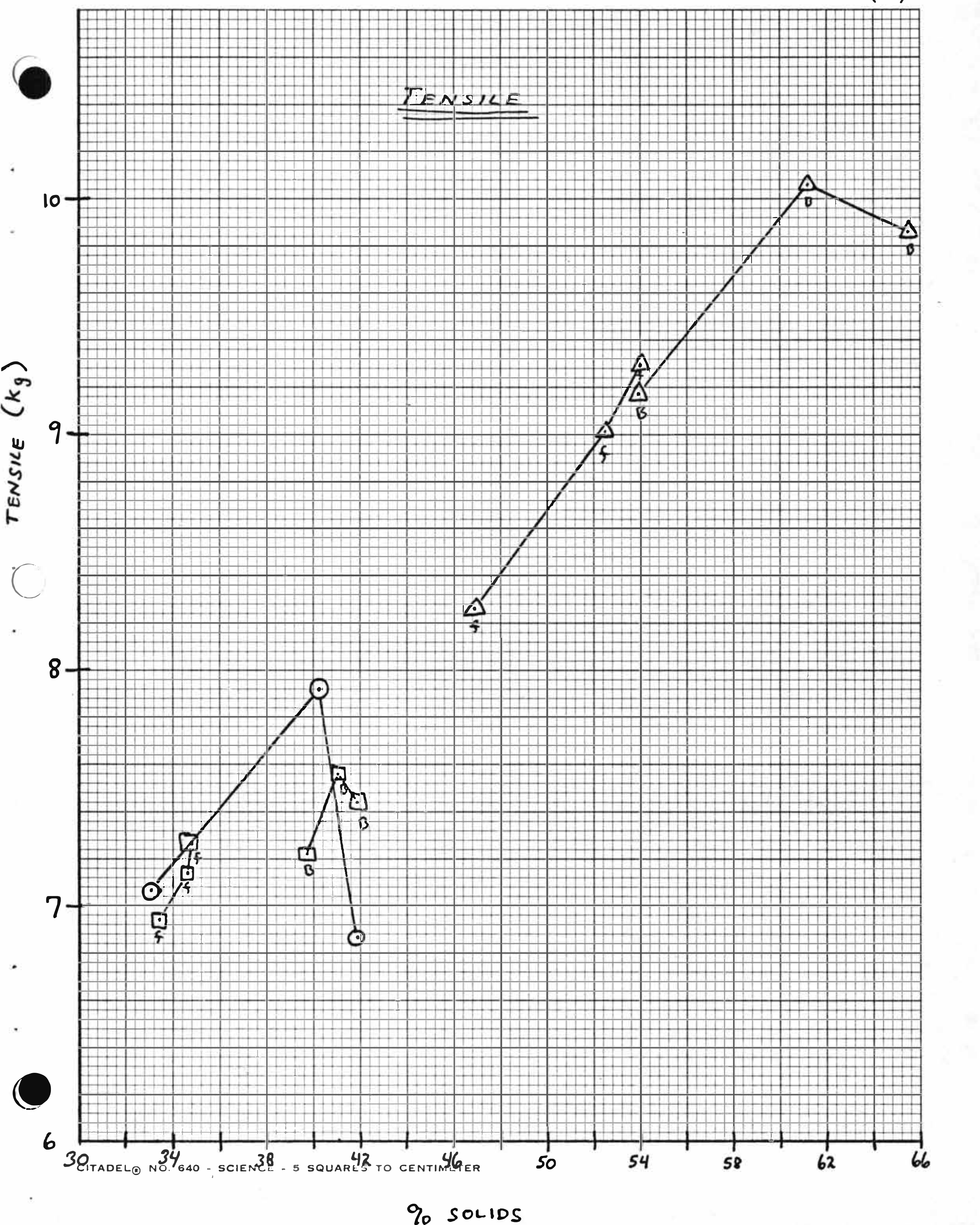


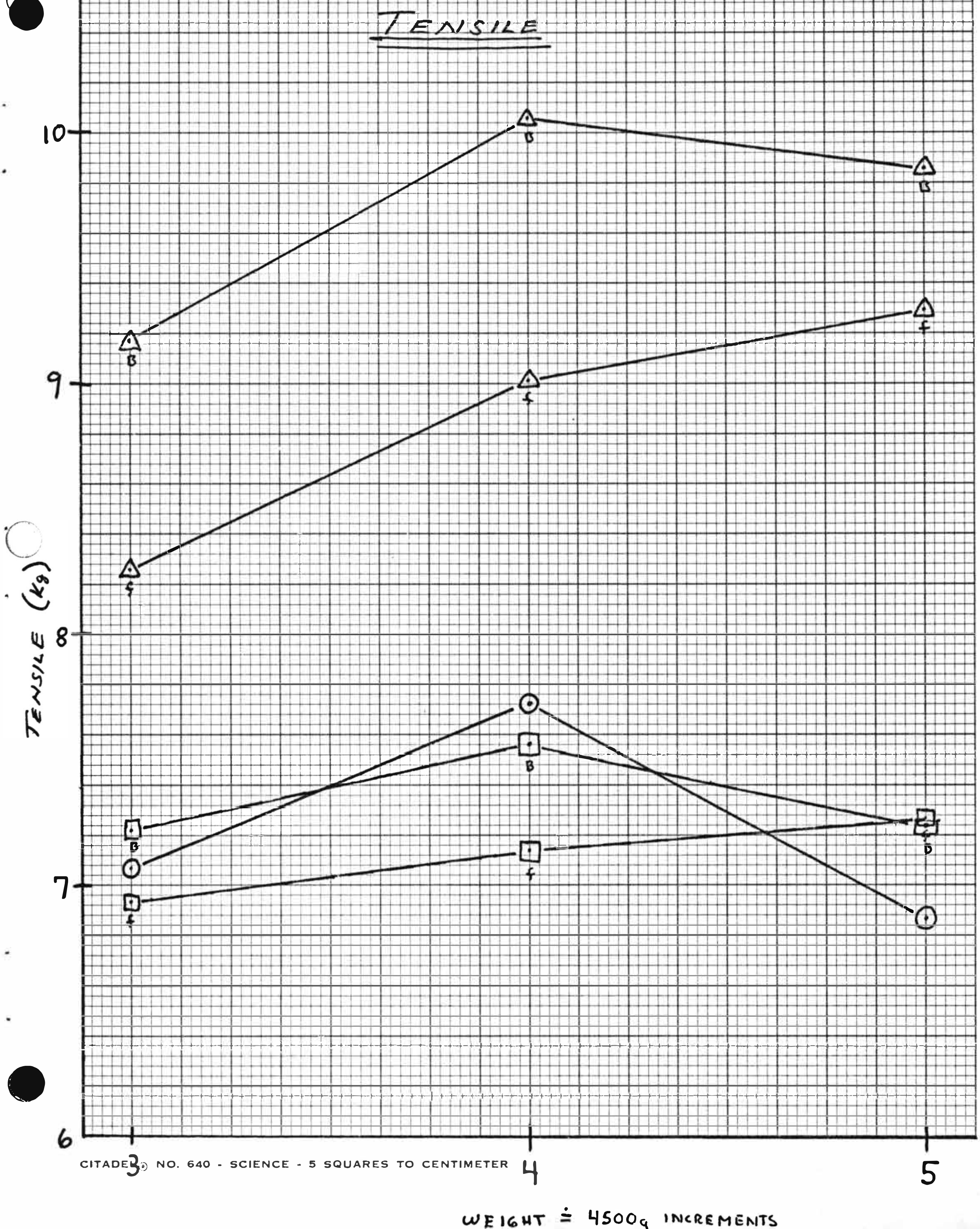
% SOLIDS VS. LOAD PRESSURE
% SOLIDS
100
92
84
76
68
60
52
44
36
28
20
12
4
(CARVER)
B
F
3 wt INCREMENTS (~4500 g)
4 wt. INCRE.
5 wt INCRE
500 PSI (CARVER ONLY)
1000 PSI
1500 PSI
2000 PSI
(PRESSURE)

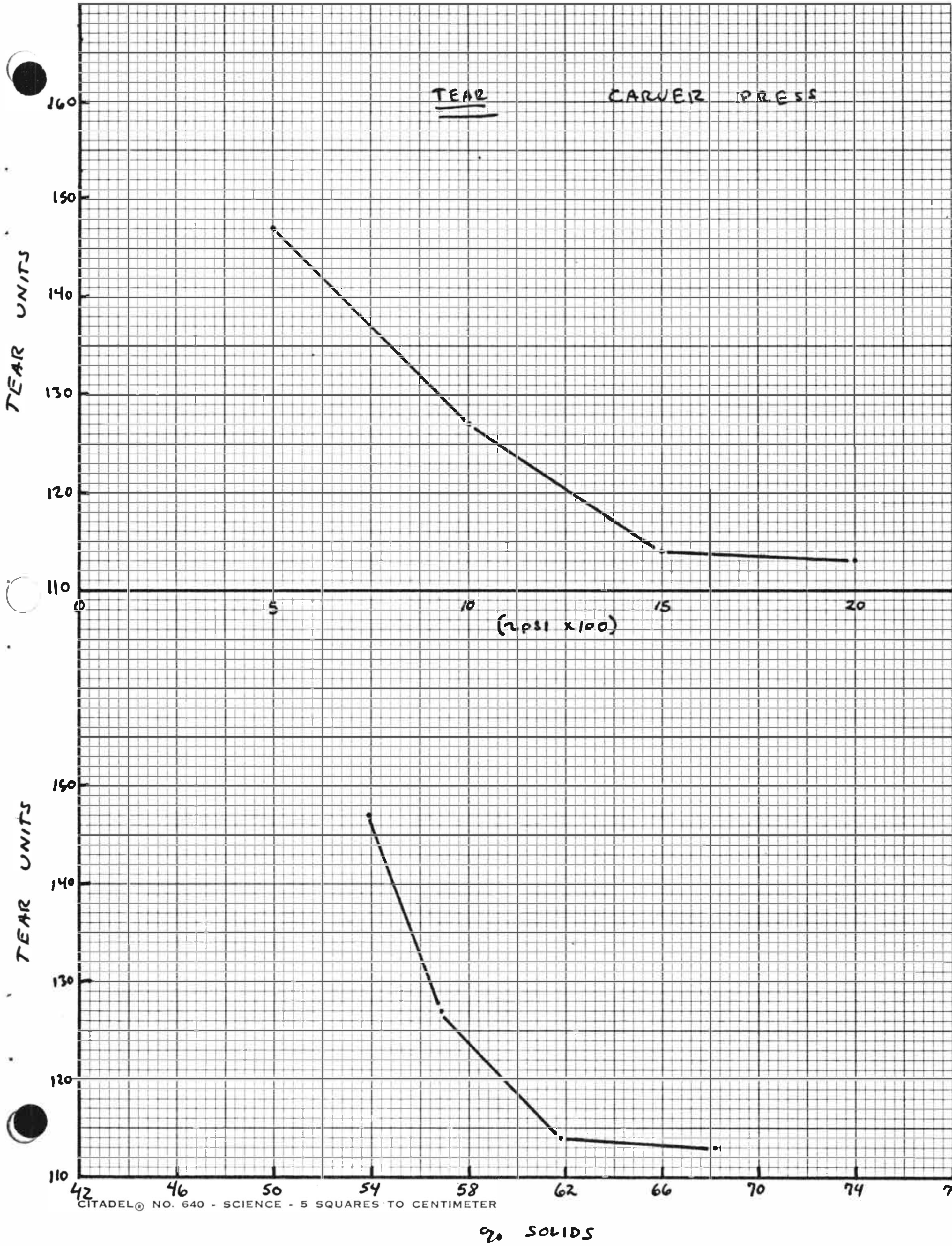

TYPICAL FREE WATER CURVE
PULP I
PULP II
PULP III
C/C₀
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
15
20
25
30
35
40
45
50
55
60
65
70
PAD CONSISTENCY - %


TYPICAL FREE WATER CURVE
PULP I
PULP II
PULP III
C/C₀
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
15
20
25
30
35
40
45
50
55
60
65
70
PAD CONSISTENCY - %
CITADEL® NO. 640 - SCIENCE - 5 SQUARES TO CENTIMETER

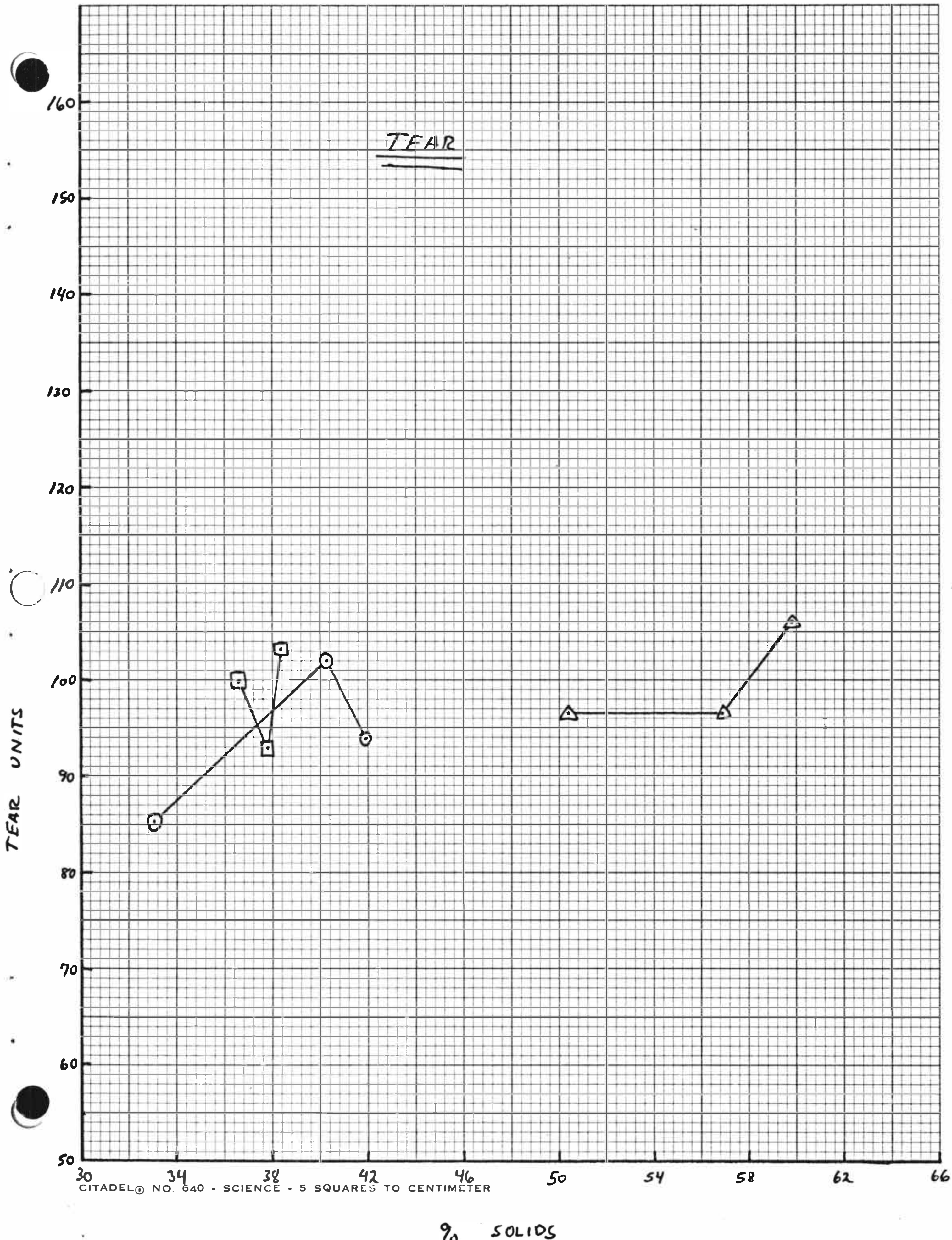

TENSILE (CARVER PRESS)
Kg
11
10
9
0
5
10
15
20
(~psi x 100)
Kg
11
10
9
42
46
50
54
58
62
66
70
74
78
% SOLIDS

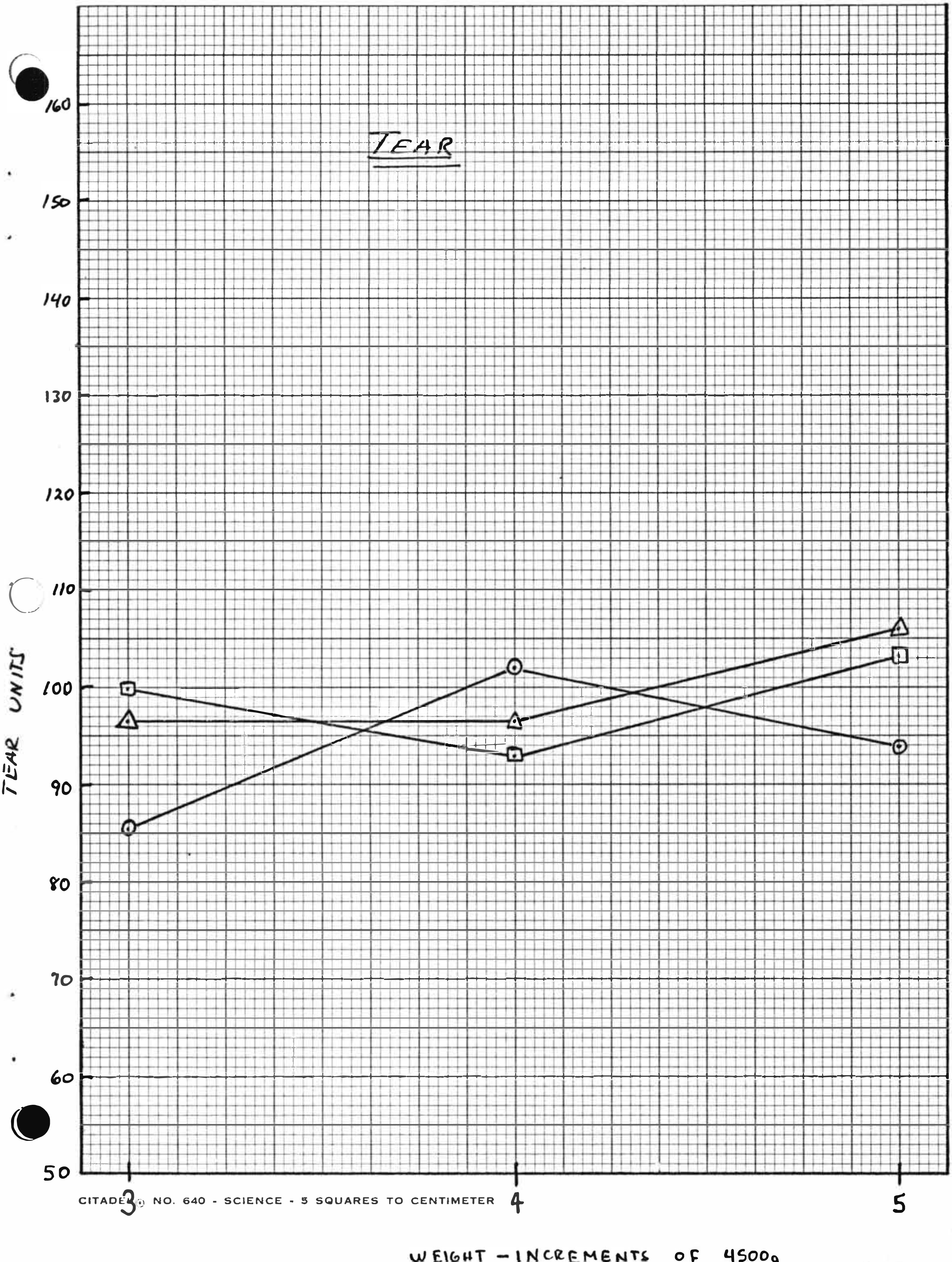

TENSILE
TENSILE (Kg)
10
9
8
7
6
30
34
38
42
46
50
54
58
62
66
% SOLIDS
CITADEL® NO. 640 - SCIENCE - 5 SQUARES TO CENTIMETER

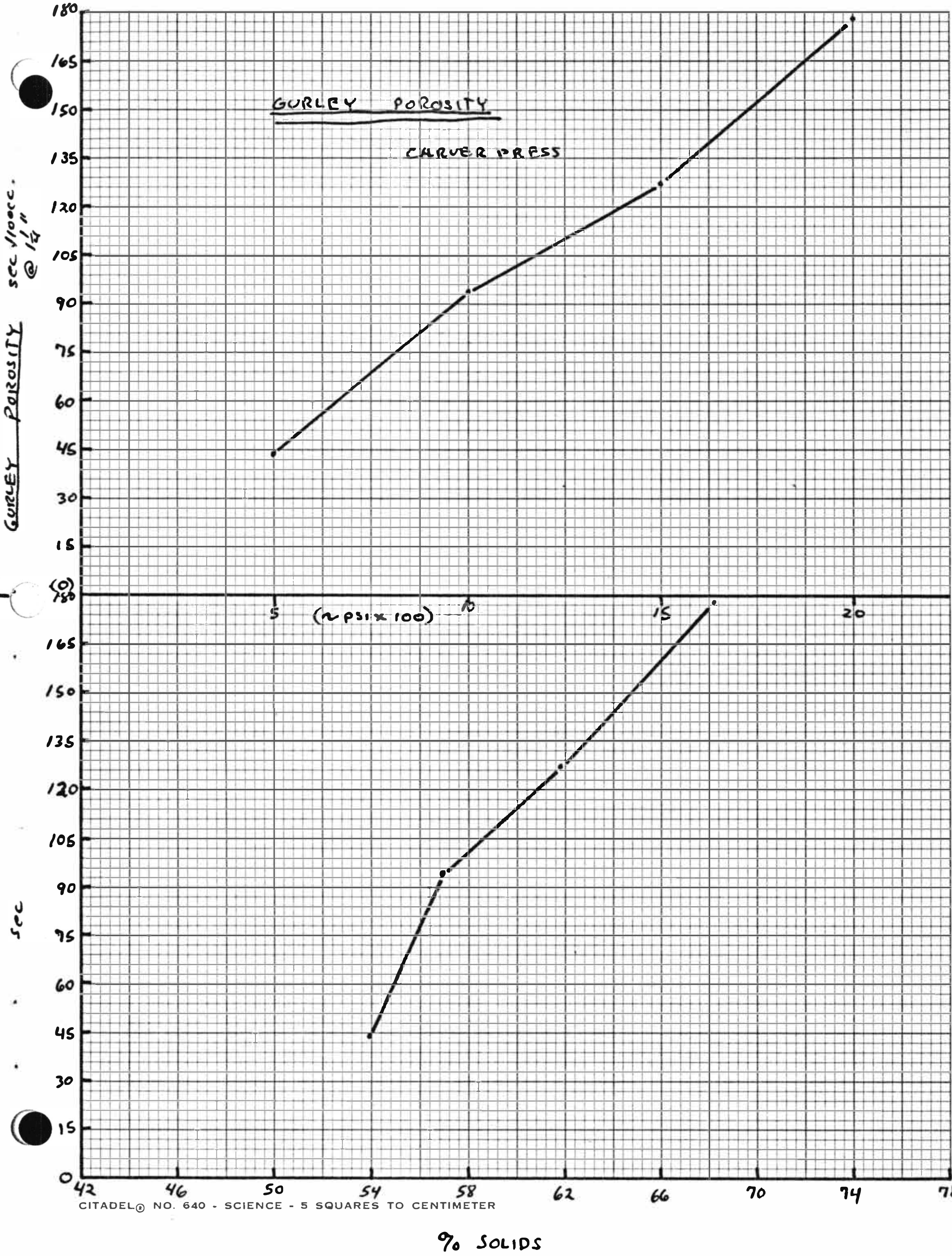

TENSILE
10
9
8
7
6
TENSILE (Kg)
B
f
B
f
B
f
3
4
5
WEIGHT ÷ 4500g INCREMENTS



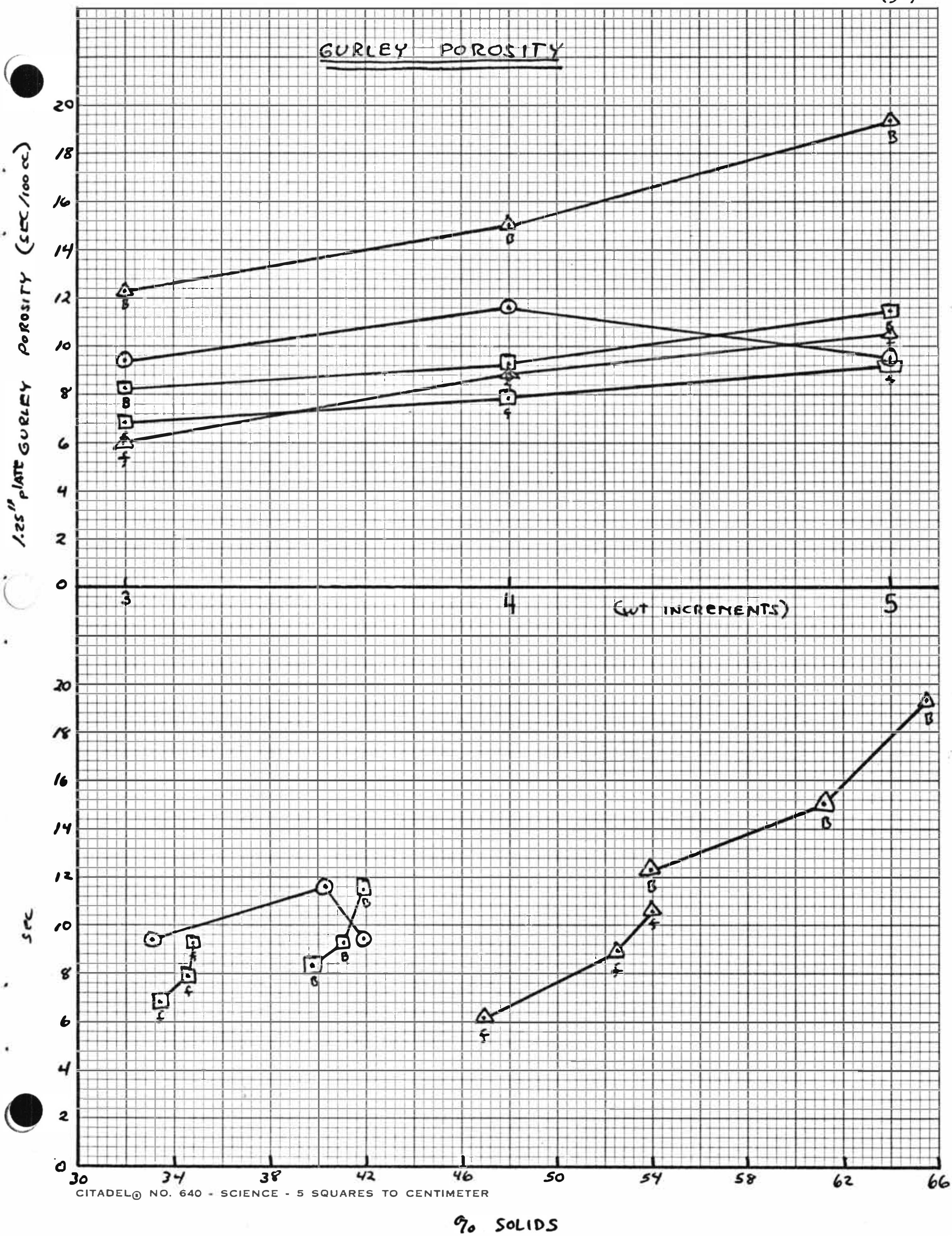
CITADEL® NO. 640 - SCIENCE - 5 SQUARES TO CENTIMETER


TEAR
TEAR UNITS
160
150
140
130
120
110
100
90
80
70
60
50
30
34
38
42
46
50
54
58
62
66
CITADEL NO. 640 - SCIENCE - 5 SQUARES TO CENTIMETER
% SOLIDS

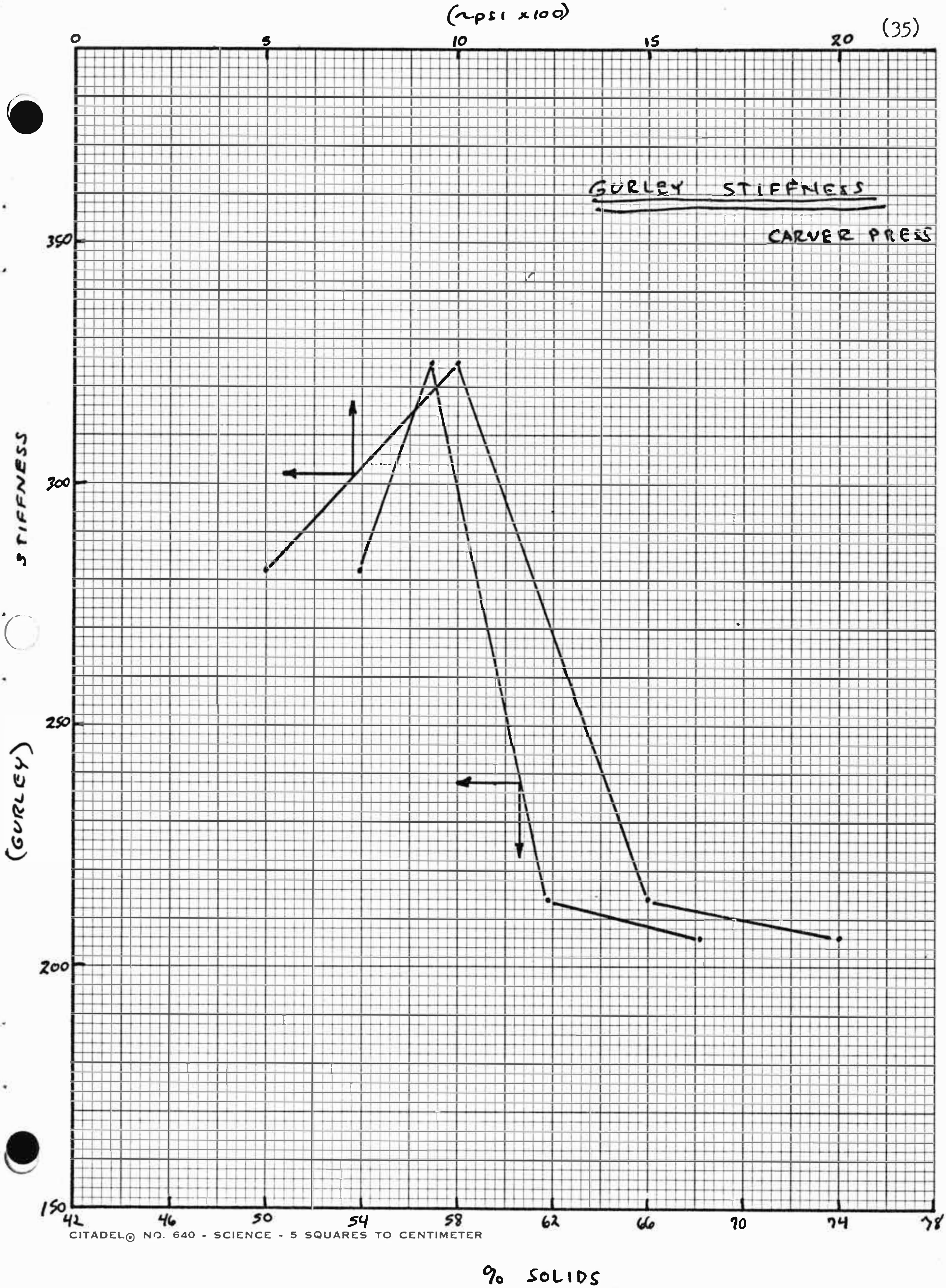

TEAR
160
150
140
130
120
110
100
90
80
70
60
50
TEAR UNITS
3
4
5
WEIGHT – INCREMENTS OF 4500

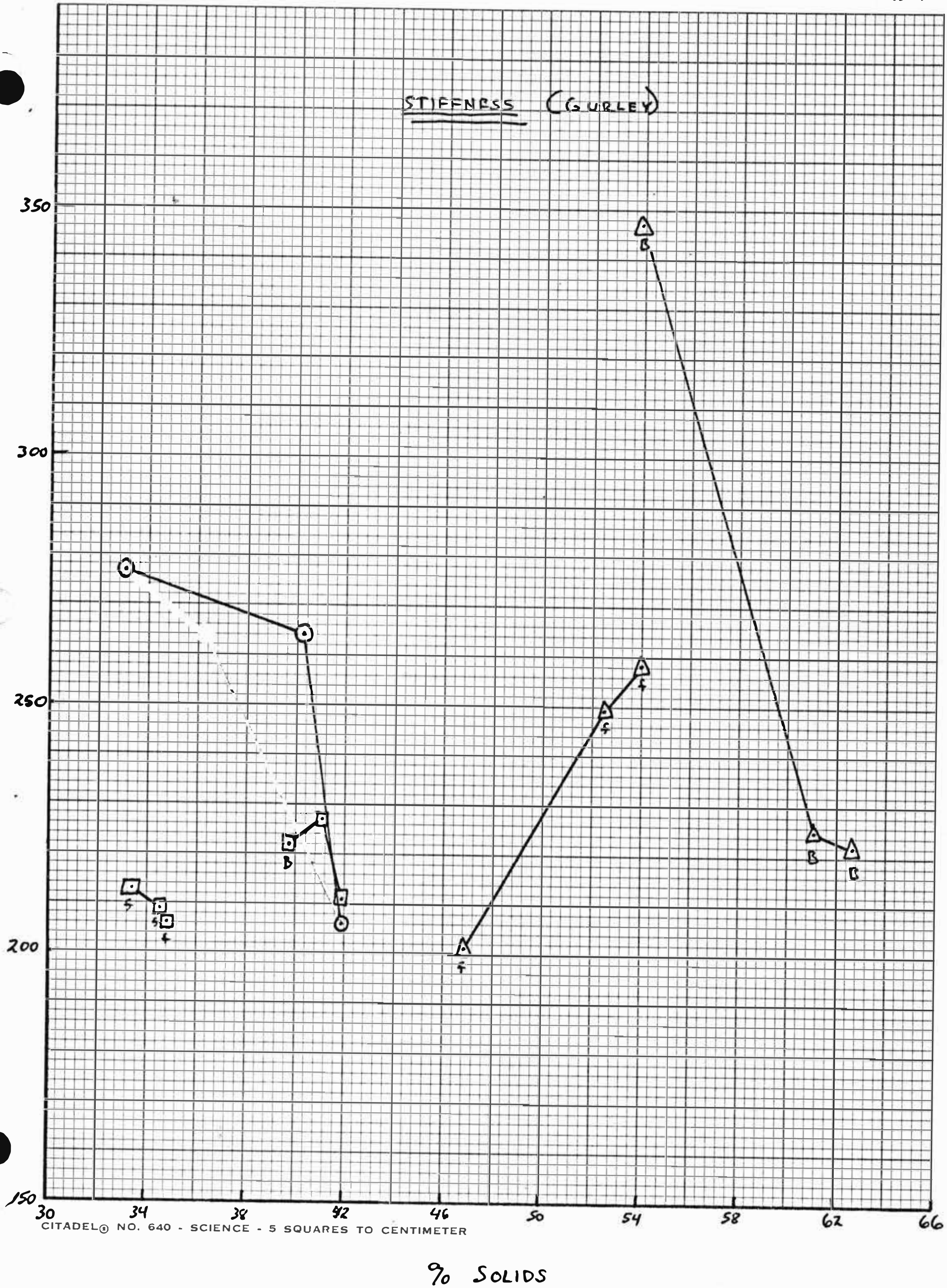


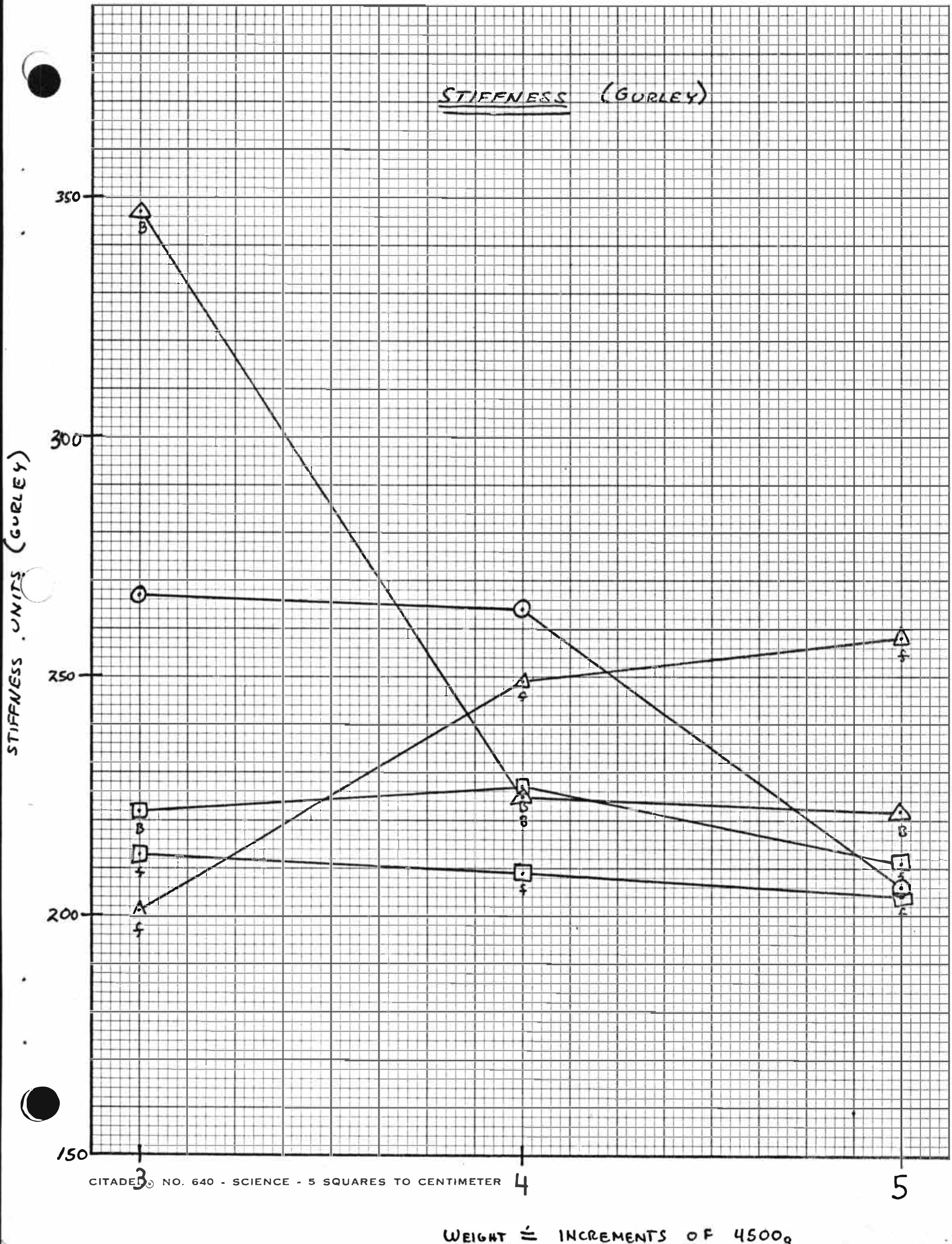
CITADEL® NO. 640 - SCIENCE - 5 SQUARES TO CENTIMETER


GURLEY POROSITY
1.25" PLATE GURLEY POROSITY (SEC/100 CC)
20
18
16
14
12
10
8
6
4
2
0
3
4
5
(WT INCREMENTS)
SEC
30
34
38
42
46
50
54
58
62
66

% SOLIDS


(~psi x100)
0
5
10
15
20
GURLEY STIFFNESS
CARVER PRESS
350
300
250
200
150
STIFFNESS
(GURLEY)
42
46
50
54
58
62
66
70
74
78
CITADEL® NO. 640 - SCIENCE - 5 SQUARES TO CENTIMETER
% SOLIDS


STIFFNESS (GURLEY)
350
300
250
200
150
30
34
38
42
46
50
54
58
62
66
B
F
S
CITADEL® NO. 640 - SCIENCE - 5 SQUARES TO CENTIMETER
% SOLIDS


STIFFNESS (GURLEY)
350
300
250
200
150
STIFFNESS UNITS (GURLEY)
B
f
3
4
5
WEIGHT ÷ INCREMENTS OF 4500g

DISCUSSION/ANALYSIS

Since the function of wet-pressing is to remove water from the formed sheet (or, stated another way, increase the solids content of the paper web) the frame of reference I have taken to be most representative is that of the percent solids content of the sheet, which is a function of the applied load pressure. Henceforward, the mention of "increasing wet-pressure" will be synonymous to "increasing the percent solids of the sheet."

The strength of the resultant paper is noted to increase with increasing wet pressure. However, it is also shown that crushing of the fibers resulted depending upon the method employed of increasing the percent solids. Superimposing the graphical representations of the dynamically-pressed sheets to that of the statically-pressed sheets (the Carver Press samples) a strong correlation is noted between the tensile versus % solids, neglecting the instances of paper sheet crushing (the down-turn portions of the graphical analysis).

The reference, reported earlier, that wet-pressing behaves similarly to the effects of refining is very evident under the research conditions. The Tear resistance decreases with increasing wet-pressure as noted in the graphs of tear under static conditions. Unfortunately, the samples under dynamic conditions were combined among the felt-pressed and the blotter paper-pressed samples due to the lack of material for the test, hence results are not as clear-cut probably sue to compunded compression/drying factors (more on this later).

With increasing density, resulting from increasing press load, porosity, as indicated via the Gurley Densometer, does decrease as noted by the increasing time units.

Concerning the Gurley Stiffness results, they were bizarre. Stiffness was expected to decrease with increasing wet-pressure. However, as is shown in the graphical representations, in the percent solids region of 45% to 55% their is a definite increase in stiffness. This phenomenon would have been dismissed if it wasn't for the fact of an extraordinary high stiffness reported for the start of the next series of wet-pressed sheets at approximately 54% solids. Upon repetition of these two sets of samples, the results, again, indicated an increase in stiffness in the 45% - 55% solids region and a relatively high stiffness introducing the next set.

I have attempted to explain this apparent anomaly by recalling the fact that this is the region where the onset of H^+-bonding strength characteristics purportedly commences. There may be also a better pressure profile across the sheet due to the probability that the fibers are yet able to redistribute themselves under compressive loading, since the amount of water present is too low to permit lateral flow through the sheet (i.e. hydraulic pressure is at a minimum), yet the amount of water is sufficient to permit a visco-elastic flow of the fiber network. This hypothesis is supported by the fact that high-density (high-pressure) spots, or localized areas, were noticed in the hand-sheets where crushing of the fibers were evident as shown in the strength tests (esp. tensile).

The gel water test revealed how similar these pulp batches were, and were intended for further research using drainage aids (if time permitted). By combining the various parameters of a pulp (fines content, degree of refining, etc.) into an indicative test procedure, one can gain some knowledge and understanding as to how similar these pulps are.

Compressibility factors have appeared to play an important role in this investigation. Not only has the compression of the felt and/or blotter paper, used as the drying material, performed an obvious function, but also the amount of water present (% solids) under a corresponding loading, determines the overall effectiveness of wet-pressing.

ERROR ANALYSIS/OBSERVATIONS

- As recorded in the data, the gel water test apparatus had leaks where "unaccounted milliliters" of expressed liquid had escaped the compressive loading.
- Handsheet formation upon the forming screen, at times, appeared to be very uneven in caliper and density.
- The handsheets pressed and dried without the forming screen, upon drying, revealed evidence of shrinkage in the form of "puckering" which may have influenced some tests.
- The tensile, stiffness, and tear test values are reported as being corrected according to a target basis weight of 50 lb/ream.
- Special note is given to the one set of Carver Press pressed sheets in that the basis weight was extraordinarily high. Thus the deviation of this particular data point, as shown in the graphical analyses, is ap-

parently accounted for.

- Irregularity involving the refining of the three pulps may be an influential factor. The "first batch" was used in the production of sets A, B, and C. The "second batch" was used in the production of sets D, E, F, G, H, J, and K. The "third batch" was used in the production of sets L, M, N, O, P, and Q.
- Where the handsheet demonstrated evidence of crushing, it is noted that these particular sheets revealed random "spots" or areas of high density as it passed from the wet press nip, indicative of concentrated load and localized rapid water absorption.

CONCLUSIONS

1) The tensile strength of the resultant paper does increase with increasing wet-pressure (percent solids content) to a strong correlation. Porosity, stiffness, and bulk strengths are inversely related to increased bonding.

2) The rate of water removal from the sheet into the felt will determine the compressibility of the sheet. That is, localized drying of discrete areas of the sheet impeded compression due to the increase of the flow resistance of the paper sheet.

3) The compressibility of the absorption medium (felt, blotter paper, etc.) will determine the extent of the crushing of the fibers that results in loss of strength.

4) The amount of moisture, as represented as percent solids, allied with the particular load pressure, may greatly influence the extent to which water can be removed without crushing. Hence, theoretically, crushing is able to occur at any particular percent solids region.

5) In the percent solids region representative of the onset of H^+-bonding (approx. 50%), shrinkage forces appear to influence certain strength characteristics by an as yet unknown mechanism.

RECOMMENDATIONS

- Further research concerning the interrelationships of water content at different press loads may give further insight into this mechanism of crushing.
- Drainage aids and their effects upon the gel water content of pulps with respect to the resultant paper strength is also a viable area of research.
- Multiple wet-pressings incorporating the use of one and two-felt presses to attain higher solids content without crushing is another area of investigation that has a tremendous financial potential.

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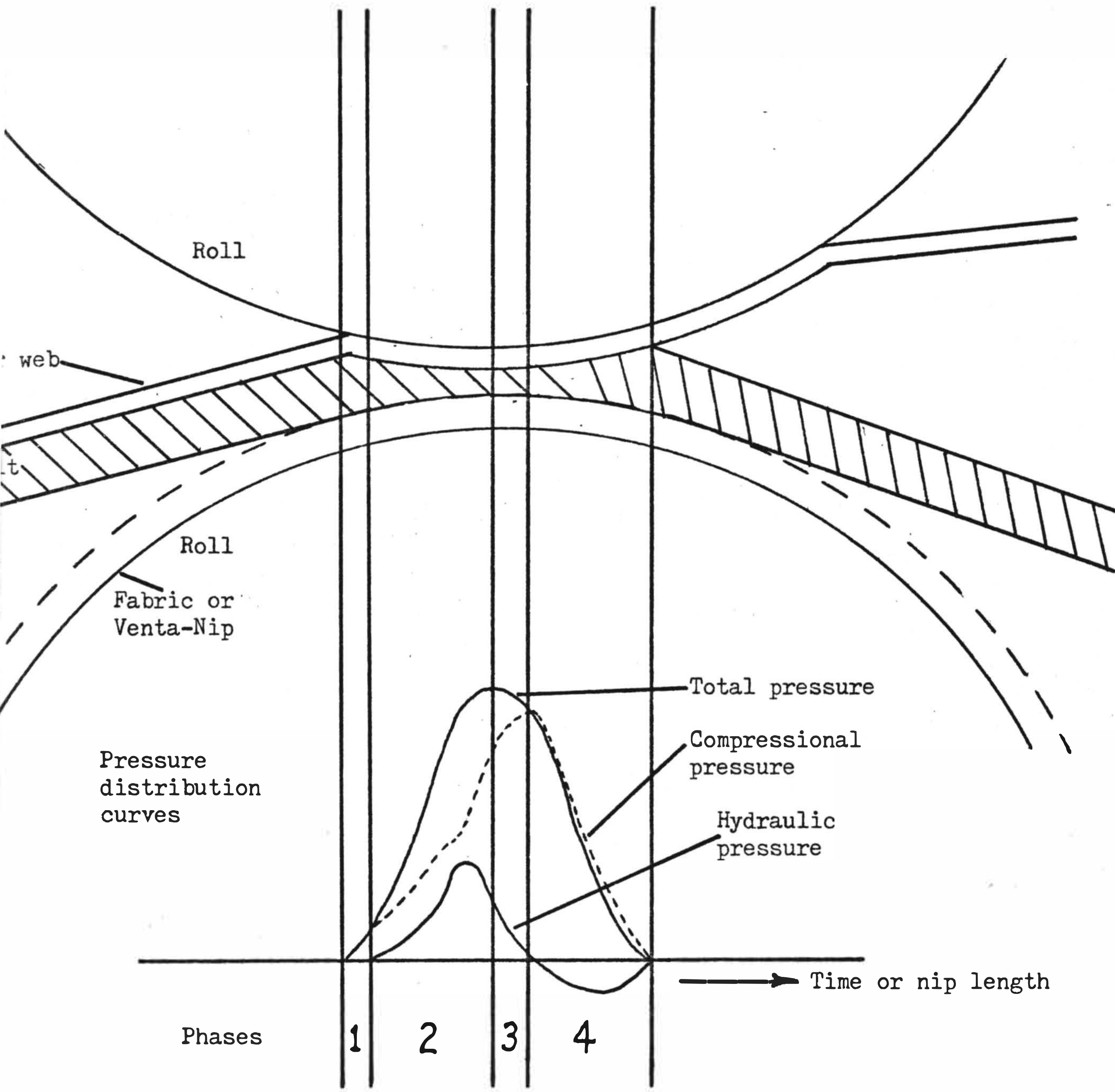
APPENDIX I

Gel (Free) Water Test

1) Wipe oil off of piston and cylinder.
2) Place seal and wires in place and secure cylinder.
3) Soak 100 grams of wet stock (20 grams OD fiber) with 150 milliliters of 5 gram/liter Blue Dextran Dye solution for 1 hour.
4) Pour pulp into the cylinder and place 50 ml beaker under drain hole.
5) Position piston and turn jack screw to drive piston downward.
6) Increase pressure until the desired pressure level has been attained. Hold this pressure for 5 minutes.
7) Measure the expressed liquid.
8) Save a sample of expressed liquid for spectrophotometric analysis.
9) Repeat steps 6-8 at different pressure levels.
10) Set spectrophotometer at 620 nm to determine the dye concentration.
11) Plot concentration of dye vs. pad consistency. Extrapolate the curve to 0 dye concentration to get the amount of free water.
12) Re-oil the apparatus when one is done for the day.

FIGURE 1



PRESSURE PROFILES

(Wahlstrom's theory)

COMPRESSION CYLINDER

(TOP)

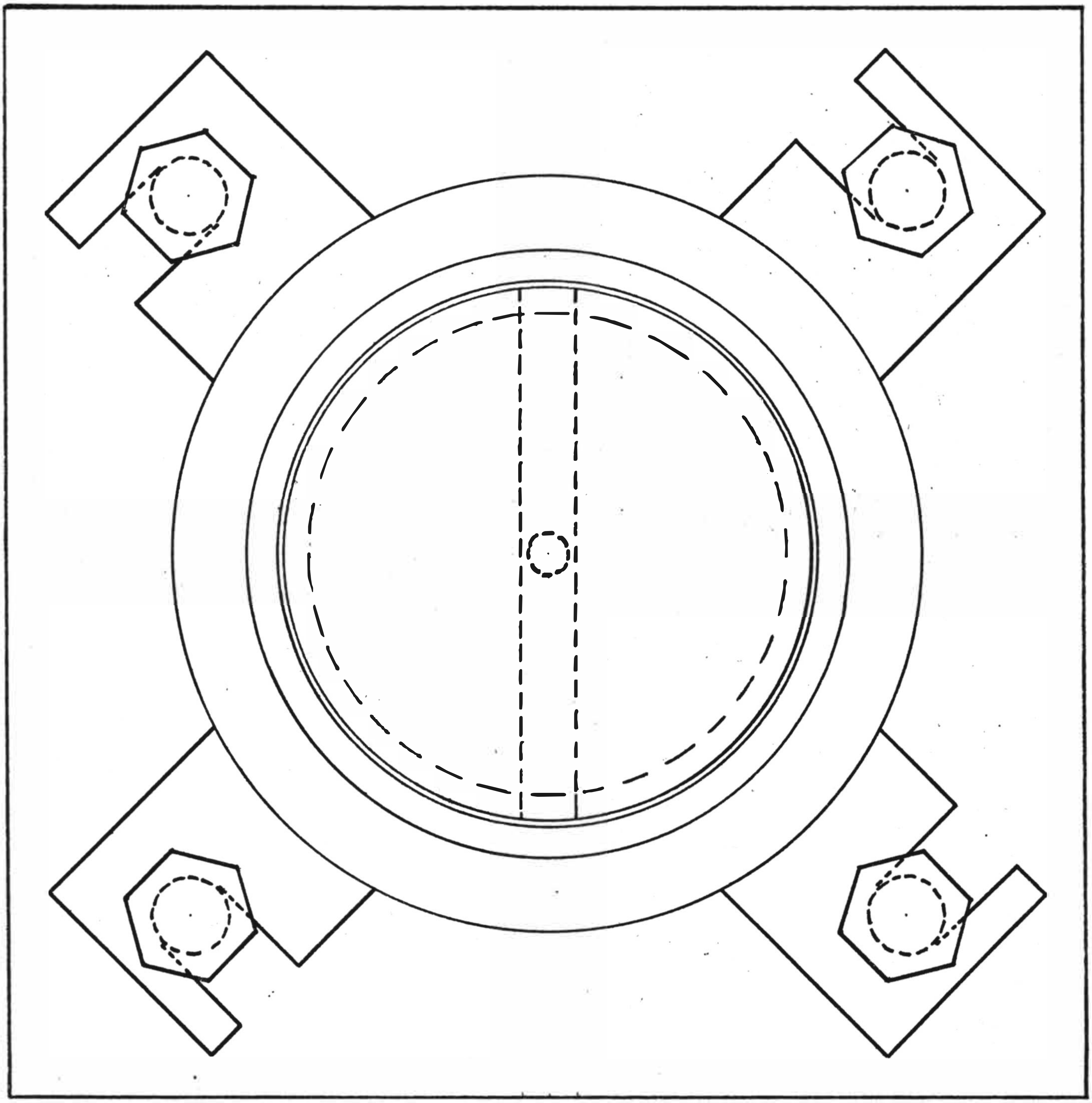


FIGURE 2

SCALE : FULL SIZE

COMPRESSION CYLINDER

FOR FREE WATER TEST

[SECTIONAL VIEW (SIDE)]

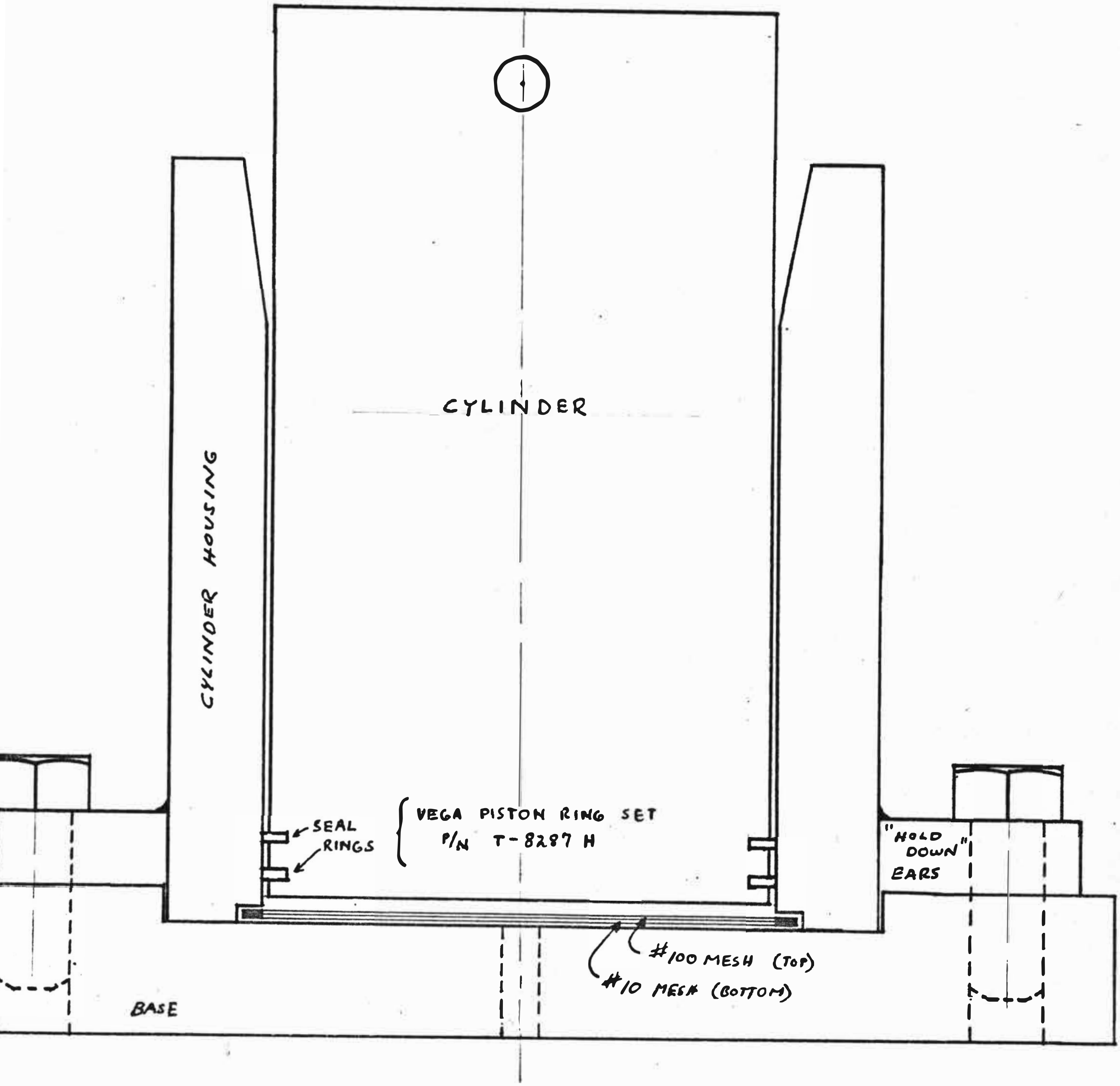


FIGURE 3