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EXPANSIBLE-SHRINKABLE SOCKETS

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ABSTRACT

This report discusses the design criteria necessary for the fabrication of forms suitable to make and expand laminates of sufficient shape and size so that upon post heating the expanded laminate would shrink to the exact contour of the stump shape being fitted. Fifteen to twenty basic preforms would be necessary to fit the majority of B.E. amputees.

The porous laminate system was evaluated and found to be unsatisfactory in that effective expansions of only 35% were obtainable whereas a minimum of 70% would be required to make the system at all feasible; in addition the physical properties of the laminates were very poor.

Finally, the overall practicality of introducing the expansible-shrinkable system into the limb industry is discussed.

1. INTRODUCTION

A program was initiated to eliminate the use of wet layups in limb shops. This program consisted in the development of a series of plastic preforms that could be expanded and then shrunk back to conform with an amputee's stump.

A series of preform shapes was designed based on data correlated from the circumferential measurements of a series of fifteen below-elbow stump models. The shapes designed from these data were conical in form.

Using these circumferential measurements it was calculated that 10 of the 15 stumps used for the design could be fitted with four preform shapes.* An expansion of 15% was estimated to be sufficient to fit these 10 models. Later work required the design of an additional shape.

Several resins were evaluated in efforts to obtain a satisfactory expansion system.** The best system gave 30-35% expansion. Such a system had a room temperature recovery of 7-8% and a 100 deg. centigrade recovery of 80%. This means that a laminate with an original diameter of 2.00" could be expanded to 2.70" and upon standing would recover to 2.65" and upon heating would finally recover to 2.14". This would give an effective expansion of 24%.

This expansion should have been sufficient to fit 67% of the amputees if the basic assumptions were correct. Unfortunately, this was not the case.

The basic idea that circumferential measurements would be adequate to design preform shapes failed to take into account the fact that many stump cross sections are not circular, particularly as the distal end is approached.

The maximum and minimum diameters at any cross section are more important considerations than circumferential measurements as they more closely represent the actual cross sectional contour.

To obtain proper fit, the unexpanded preform for any given stump must have all diameters less than the corresponding stump diameters. The expanded preform must have all diameters greater than their corresponding stump diameters. For the reasons cited above, a series of preform shapes had to be designed taking into consideration both the maximum and minimum diameters of the stump models as measured by a series of parallel planes passing through these stump models.

For the design of suitable preform shapes a series of 28 BE stump models were measured and tracings made of the perimeters of these models.

* APRL T.R. 5744
** APRL T.R. 5955

These tracings were divided into several groups according to the general shape of the (stump) models. Each group was further subdivided into different sizes in order to cover the range of models in each group.

This report discusses the design of these preform shapes and the expansion requiring to fit models in the particular groups.

II. PROCEDURE

Tracings were made of the maximum and minimum perimeters of 25 BE stump models.

Diameter measurements were made at one inch intervals from the distal to proximal ends for both maximum and minimum perimeter tracings.

The per cent expansion required to expand from the minimum diameter to the maximum diameter was determined at inch intervals from the distal to the proximal end. This was computed from the following equation:

$$E = \left(\frac{d_2 - d_1}{d_1}\right) X\ 100$$

Where: E = per cent expansion

d_1 = minimum diameter

d_2 = maximum diameter

The models were divided into 5 groups based on shape, size, and maximum to minimum diameter ratio.

Average diameter measurements were calculated for each group. These measurements were used to sketch a general shape for each group. Then using this general shape, a similar shaped contour was drawn that would be as small as the smallest model of the group. In a similar manner a drawing was made so that the contour included the largest model of the group. These shapes are shown in Figures 1-5.

Using the smallest drawing as the preform shape and the largest drawing as the expander shape the per cent expansion required was calculated.

Based on these calculations, 1 to 3 intermediate shapes were designed for each group. The expansions possible for each group were determined. For the 3 shape group, 3 expansions were possible. For the 5 shape group there were 10 possible expansions.

If the forms are designated as A, B, C for the 3 shape groups and A, A^1, B, B^1, C for the 5 shape groups the following combinations are possible:

3 Shape Group	5 Shape Group
A → B	A → A^1
A → C	A → B
B → C	A → B^1
	A → C
	A^1 → B
	A^1 → B^1
	A^1 → C
	B → B^1
	B → C
	B^1 → C

In these examples A is the smallest and C is the largest.

The sketches of the stump models of each group were then matched to find the shapes to be used for preforming and expanding that would give minimum expansion. This was done first for the 3 shape group, then the 5 shape group. After these matchings, the per cent expansion for each matched sample was determined at 2 inch intervals from the distal end. These results are tabulated in the following section. Based on previous work with expansible systems, it was realized that the actual system would require greater expansion to compensate for (1) room temperature recovery of the expanded form and (2) total recovery (recovery after heating) which is always less than 100%. The actual expansions that would be required were based on 7% room temperature recovery and 80% total recovery.

This means that the stump model to be fitted must always be at least 7% smaller than the expander or 20% larger than the preform, (unexpanded laminate). This would require either a greater number of preforms or greater expansions.

After determining the required expansions necessary to fit the stump models of this control group (group used to design the shapes) a second, or test group, of typical ~~BE~~ below elbow stump models were measured and the required expansions were calculated.

A series of epoxy laminate expansions was carried out to determine the maximum expansion obtainable with available systems. These expanded laminates were checked for shelf stability then reheated to determine total recovery.

The basic resin system used for these expansions was:

ERL 2795*	- 65 g.
Versamid 140**	- 35 g.
Trichloroethylene	- 43 g.
Pigment	- 1 g.

* Union Carbide Chemical Co.
** General Mills

III. RESULTS

Part A

TABLE I

Controls: Group I

Stump Model	Fabricator	Expander	Per Cent Expansion Distance from Distal End (Inches) 2	4	6
D	A	C	69	65	64
XI	A	B	34	35	36
H	A	C	69	65	64

In this group it can be seen that the greatest expansion occurs at the distal end, an area where good fit is essential, thus making it extremely important to develop a highly expansible resin system.

With two additional shapes (A' B'), the above models could be expanded as follows:

TABLE II

D	A'	C	45	33	40
XI	A	B	34	35	36
H	A'	B'	28	22	27

TABLE III

Controls: Group II

			Major Axis 2"	4"	6"	Minor Axis 2"	4"	6"
XIII	A	C	62	50	48	79	62	56
IX	A	C	"	"	"	"	"	"
VI	A	C	"	"	"	"	"	"
I	A	B	30	28	27	40	34	30
E	A	B	"	"	"	"	"	"
III	A	B	"	"	"	"	"	"
XVII	A	C	60	50	48	79	62	56
F	A	C	"	"	"	"	"	"
C	A	C		"	"	"	"	"
B	A	C	'	"	"	"	"	"

If two additional Shapes (A' B') are made the following expansions would be required:

Model	Fabricator	Expander	Expansion % Major Axis 2"	4"	6"	Minor Axis 2"	4"	6"
XIII	A	B'	46	43	38	59	51	43
IX	A'	B'	28	27	22	33	23	28
VI	A'	C	41	37	30	41	33	30
I	A	B	30	28	27	40	34	30
E	A	B	"	"	"	"	"	"
III	A	B	"	"	"	"	"	"
XVII	A	B'	46	43	38	59	51	43
F	A'	B'	28	27	22	33	23	22
C	A'	B'	"	"	"	"	"	"
B	A'	B'	"	"	"	"	"	"

TABLE IV

Control: Group IIIA

XVIII	A	C	46	54	60	37	42	43
XIX	A	C	"	"	"	"	"	"
X	A	C	"	"	"	"	"	"
IV	A	C	"	"	"	"	"	"

TABLE V

Control: Group IIIB

XX	A	C	62	100	83	25	28	31
XV	B	C	23	29	24	10	12	14
XIV	A	C	62	100	83	25	28	31

TABLE VI

Control: Group IV

VIII	E	C	84	73	58	90	71	61
XVI	A	B	30	39	32	45	37	32
V	A	B	"	"	"	"	"	"
G	A	B	"	"	"	"	"	"

With an additional Shape (A') the following expansion would be obtained:

VIII	A'	C	52	43	35	50	46	46

Part B - Test Group

To test the adequacy of the Shape designs, tracings of a test group of stump models were obtained. These tracings were then matched to the Shape groups and the per cent expansion was calculated.

TABLE VII

Model	Group	Fabricator	Expander	% Expansion Minor Axis 2"	4"	6"	Major Axis 2"	4"	6"
1	IV	A	C	84	73	58	90	71	61
2	IIIA	A	C	46	54	60	37	42	43
3	II	A	B	40	34	-	30	28	-
4	II	A	C	79	62	56	62	50	48
5	IV	A	C	84	73	58	90	71	61
6	II	B	C	28	21	-	25	19	-
7	No group, smaller than size A, Group II								
8	I	A	C	69	65	64	-	-	-
8	I	A	B'	52	52	52	-	-	-
9	I	A	C	69	65	64	-	-	-
10	II	A	C	62	50	48	79	62	56
10	II	A	B'	46	39	39	59	49	42
11	IV	A	C	90	71	61	84	73	58
12	IV	A	C	"	"	"	"	"	"
13	IV	A	C	"	"	"	"	"	"
5	IIIB	B	C	62	100	83	25	28	31

From the above table it may be seen that 12 out of 13 models could be fitted with these model Shapes designed. This would indicate that the design criteria for these Shapes were adequate. A comparison of the group break down of controls vs. test is recorded in the next table.

TABLE VIII

Group	Number in Group Control	Number in Group Test	Per Cent in Group Control	Per Cent in Group Test
I	3	3	12.5	18.7
II	10	3	41.7	31.2
IIIA	4	1	16.7	6.3
IIIB	3	1	12.5	6.3
IV	4	5	16.7	31.2
NONE	0	1	0	6.3

Considering the small sample size in the test group the correlation between Test and Control is quite good.

If we consider that both Control and Test groups are typical of B.E. models, then for further discussion they will be grouped together, and furthermore, models that fit into two groups will be given appropriate weight.

Next is a tabulation of the per cent expansion required to fit the amputee population represented by this group.

Amputee Population Fitted:

TABLE IX

	3-SHAPE GROUP				5 SHAPE GROUP			
	No. Covered		% Covered		No. Covered		% Covered	
% Expansion	Diff.	Cumul.	Diff.	Cumul	Diff.	Cumul.	Diff.	Cumul
10	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
30	2	2	5	5	3	3	7.5	7.5
40	5	7	12.5	17.5	9	12	22.5	30
50	3	10	7.5	25	6	18	15	45
60	5	15	12.5	37.5	9	27	22.5	67.5
70	5	20	12.5	50	2	29	5	72.5
80	10	30	25	75	2	31	5	77.5
90	6	36	15	90	5	36	12.5	90
100	3	39	7.5	97.5	3	39	7.5	97.5

From this table it can be seen that if 3 Shapes/Group are used a laminate expansion of 70% is necessary if only 50% of the cases are to be covered. If 90% are to be covered, an expansion of 50% would be necessary. If a 5-Shape Group are used, 70% expansion would cover 72.5% of the cases. But even with the 5 Shapes it would take 90% expansion to cover 90% of the cases.

Part C. - Resin Systems

From an analysis of the data discussed in Parts A & B, it is obvious that 75 to 100% expansion is necessary. Previous work indicated that the expansion of the regular epoxy laminates was limited to 30-35% therefore, it was decided to investigate porous epoxy systems in the belief that the nature of such a system would allow greater expansion.

The results of this investigation are recorded in the following table.

TABLE X

Designation	Stockinet Layers	Stockinet Width	Initial Expansion % 2"	3"	4"	6"
164	3	2½"	-	54	-	46
174	3	2½	65	-	56	48
70-2	3	1½	44	-	40	37
69-2	3	2½	40	-	37	32
82-2	3	3	48	-	45	38
84-2	3	3	48	-	41	35
76-2	5	3	45	-	39	34
166	3	2½	-	67	-	49
176	3	2½	76	-	64	43
168	3	2½	-	44	-	37
178	3	2½	53	-	45	37
184	3	2½	52	-	45	39
180	3	2½	39	-	36	32
182	3	2½	40	-	35	31
186	3	2½	41	-	36	34
69-3	3	2½	37	-	38	34
70-3	3	1½	35	-	32	31
82-3	3	3	38	-	35	33
84-3	3	3	41	-	35	35
159-2	3	2½	-	27	-	27
170-2	3	3	-	30	-	26
172-3	3	3	-	25	-	24
76-3	5	3	39	-	37	37
*86-3	3	3	62	-	56	41

* In this formulation 10 parts of ERL 2795 were
d with LP-3 in an effort to make the system more
flexible.

	elf (Room Temp.) ecovery %			Final Recovery After Heating %			
	3"	4"	6"	2"	3"	4"	6"
				-	82	-	80
				73	-	77	72
	-	10	14				
	-	11	24				
	-	15	13				
	-	5	9				
		9	9				
	Tore at End			-	75	-	75
	Tore upon Expansion						
				-	68	-	74
				62	-	71	74
	-	17	17				
				76	-	77	77
	-	27	36				
	-	18	17				
	-	17	17				
	-	20	23				
	-	5	0				
	-	5	13				
				-	100	-	100
				-	93	-	87
				-	80	-	88
	-	8	12				
	-	14	[illegible]				

Comparing laminates 166, 174, 1?4, 176 it may be concluded that the maximum expansion possible with this system is in the neighborhood of 70%. It should be noted that both laminates 166 and 176 were torn upon expansion.

When the expanded laminates were measured after several days, there was a noticeable amount of shrinkage, in one case as high as 35%. Per cent shrinkage or shelf recovery was calculated by dividing the amount of circumferential shrinkage by the circumferential expansion. Comparing various laminates it appears that the shelf recovery is independent of the stockinet size used and must therefore be dependent primarily on the resin system.

As the shelf recovery of the laminates appears independent of the per cent expansion than an averaging of the recovery of all the laminates is justified. The average is 10% at 2", 13% at 4", and 15% at 6". These measurements are from the distal end. The final recovery upon heating was calculated by dividing the amount of circumferential shrinkage after heating by the circumferential expansion. The average final recovery was 75%. This figure is for laminates expanded more than 30%. Those expanded less than 30% have a higher per cent recovery, about 90%.

To determine the effective expansion, the initial expansion, shelf recovery, and final recovery must be considered. Take for example, a typical laminate with a circumferential measurement of 16" at 2" from the distal end. If it is expanded 65% its expanded circumference will be 26.4", then upon standing for a few days it will shrink 10% giving a circumference of 25.4". After final heating it will recover 75% or to a final circumference of 18.6". Therefore, from a practical standpoint the laminate can be expanded from 18.6" to 25.4" which is an effective expansion of 36.6% which is considerably less than the theoretical expansion of 65%.

Taking this figure of 37% and comparing it with Table IX it can be seen that only 17.5% of the amputee would be covered with the 3 shapes/group or 30% if 5 shapes/group were used. As an initial expansion of 65% was the highest obtainable, it is of little value to consider twhat the effective expansions of lesser percentages would be, undoubtedly they would be considerably less than the initial expansions.

Quantitative physical properties of the laminates were not obtained, however qualitative observations were made. The impact strengths of the laminates after recovery were extremely low. The laminates could be completely collapsed by very little pressure. In fact several of the laminates were already misshapened after recovery. Collapsing the laminates towards the longitudinal axis caused delamination in several cases.

IV. GENERAL DISCUSSION

From the above results several things are obvious; 1) the limits of the present resin system have been reached, 2) a large number of laminating and expanding forms are necessary to cover a limited number of amputee cases, 3) effective expansion is much lower than apparent (initial) expansion and 4) fabrication of the expansion forms would be quite complex.

The limits of the resin system of 40% effective expansion present problems of major considerations. To make this project feasible at all it would be desirable to be able to fit at least 75% of the BE amputee population. To fit 75% of the amputees would require an effective expansion of 80%. To obtain this effective expansion would require an initial expansion of at least 110%. This figure is based on 90% recovery after heating and 5% room temperature recovery. These figures are considerably better than those actually found. This means a resin system must be found that has twice the expansion of the present system. It is possible that various extenders, flexibilizers, etc. might be incorporated into the system to improve the expansion slightly. However, such modifiers would lower the physical characteristics of the laminates even below the presently unacceptable level. In addition to developing an entirely new resin system, new stockinets would have to be obtained that would have greater flexibility. This latter problem could undoubtedly be overcome.

Another major consideration is the number of preforms or expanders necessary. A minimum of 15-20 only cover the BE amputee population and it is questionable as to how representative were the samples measured. It must also be remembered that these preforms are only for the inner sockets, and additional series would be necessary for the outer forearms.

If we could assume that one half as many forearm preforms would be required this would mean a total of 25-30 forms. If we next assume that the strength of the expanded laminates is adequate, a fact not in evidence, a limb shop would have to stock great numbers of these laminates to have them available to fit any given amputee. With 3 Caucasian shades and 3 Negro shades a limb shop would have to stock 300-360 laminates to have just a duplicate set. This is obviously extremely impractical.

As the initial purposes of this project was to eliminate wet layups, this is not accomplished as only 75% of BE amputees would be covered. To eliminate 75% of all wet layups would require stocking over a thousand laminates which, even if possible, would be absurd.

Finally, the shapes of the preform-expanders are such that their fabrication would be essentially hand modeled, thus cost, which might involve considerable cost.

V. CONCLUSIONS

Based on the above discussion, we conclude that the development of expansible sockets appears to be impractical with the present resin filler systems tried.

FIGURE I

GROUP I

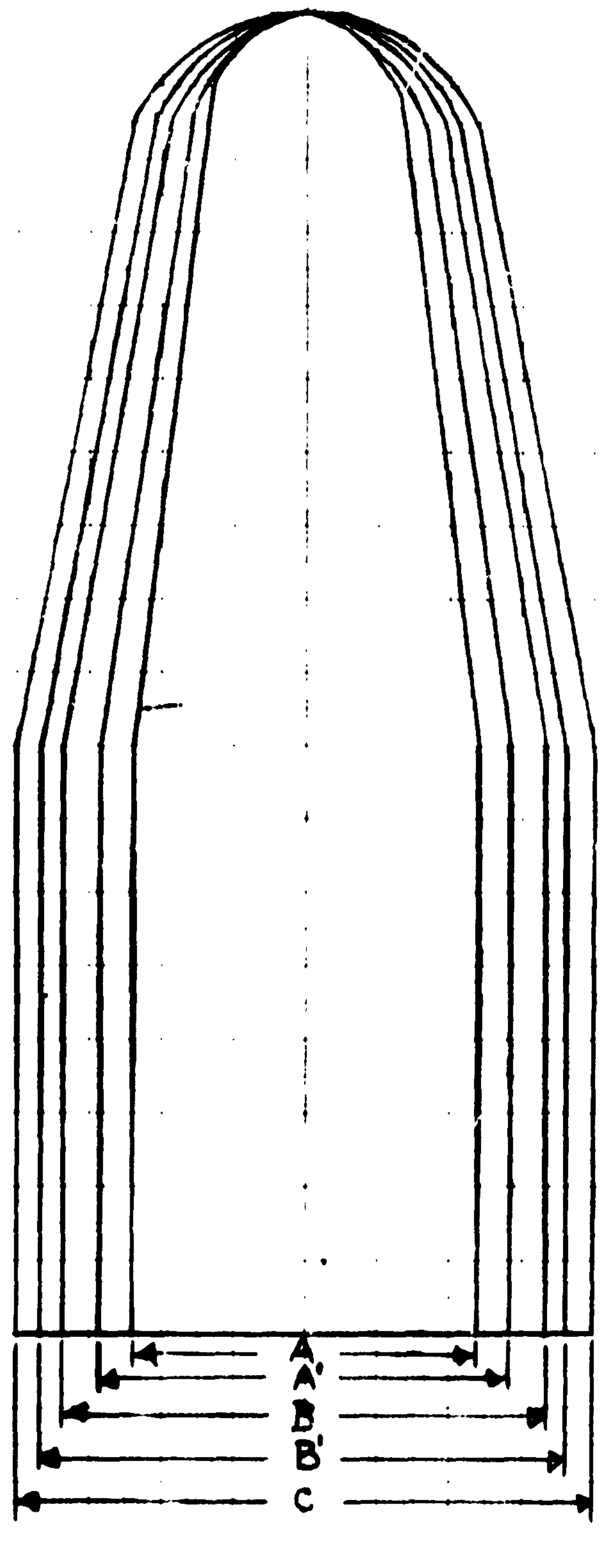

FIGURE 2

GROUP II

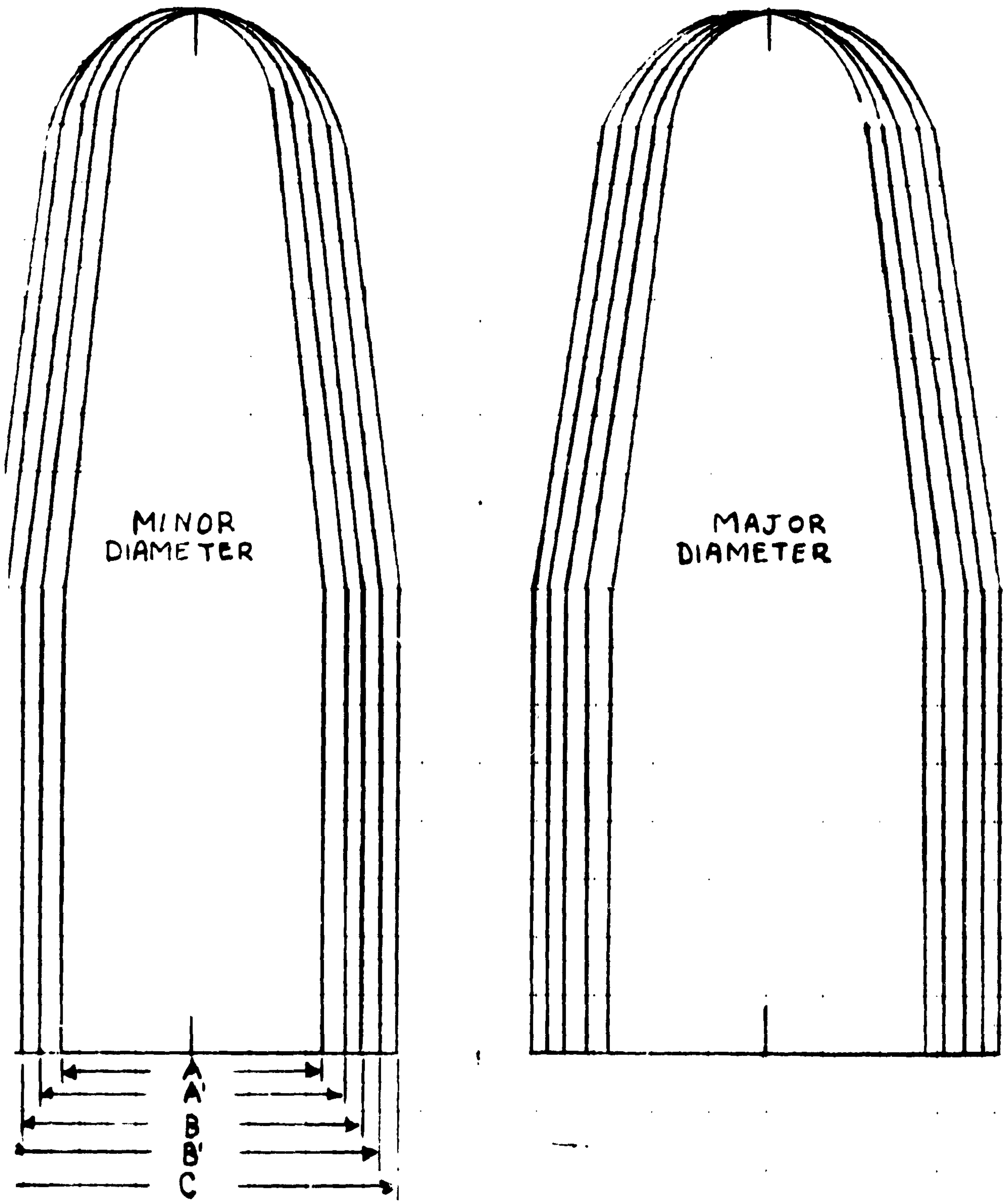

FIGURE 3

GROUP III A

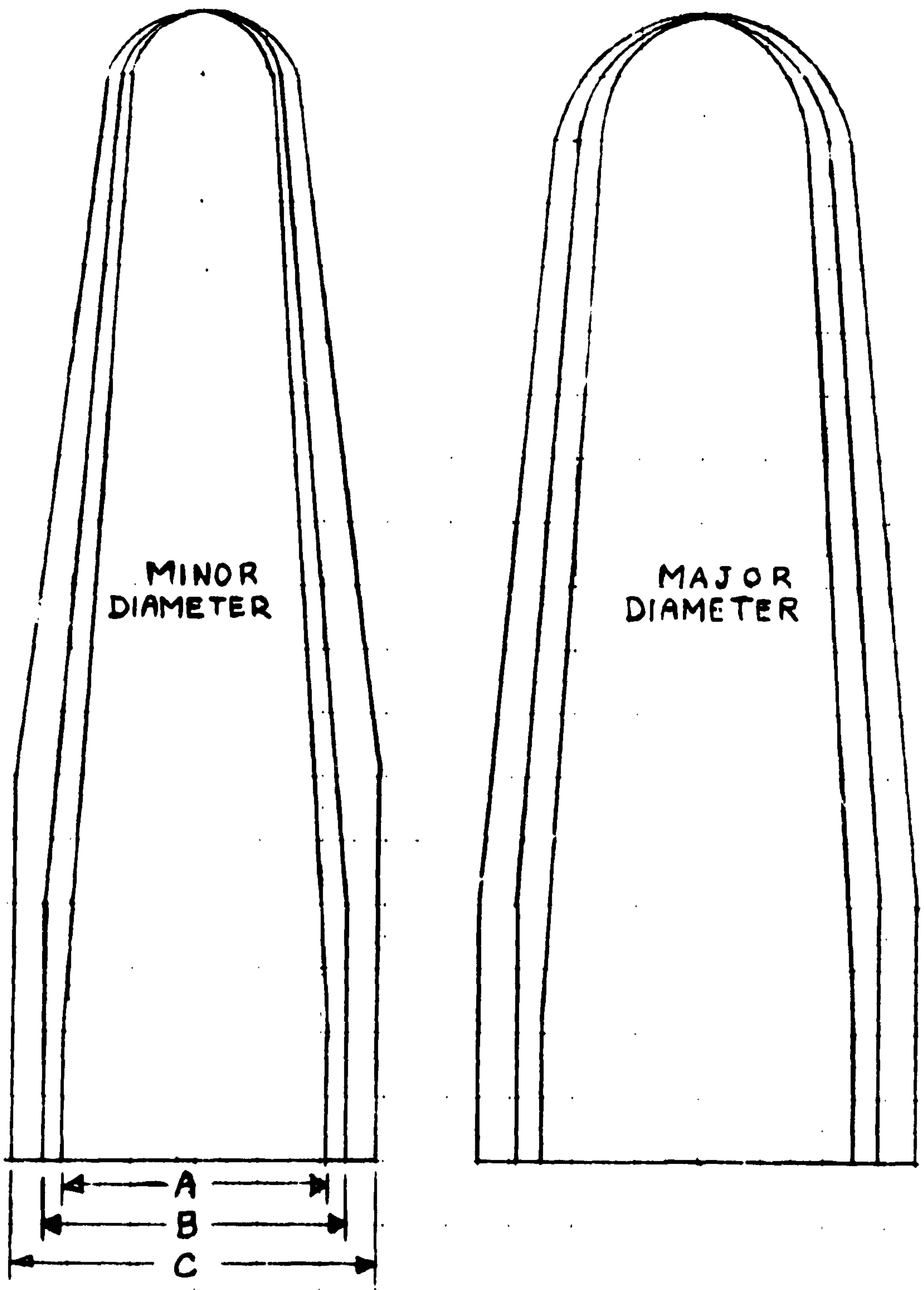

FIGURE 4

GROUP III B

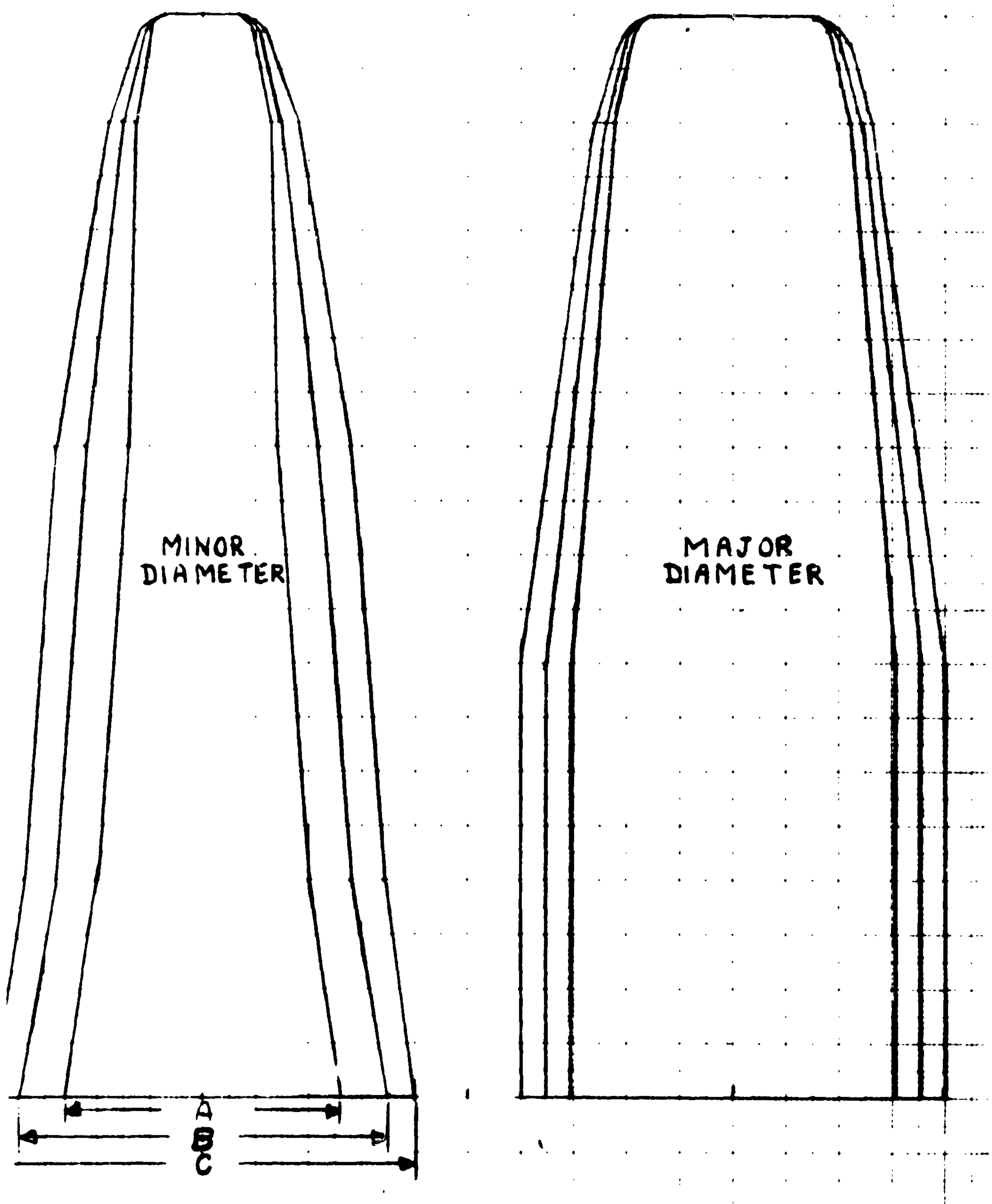

FIGURE 5

GROUP IV