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Direct Stress Fatigue Tests on Redux-Bonded and Riveted Double Strap Joints in 10 S.W.G. Aluminium Alloy Sheet

By

S. Kelsey and J. B. Spooner

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Direct Stress Fatigue Tests on Redux-bonded and Riveted Double Strap Joints in 10 S.W.G. Aluminium Alloy Sheet

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S. Kelsey and J. B. Spooner,
Imperial College
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SUMMARY

Tensile fatigue tests were carried out on sheet specimens in D.T.D. 610B, 546B and 687A with double strap Redux and riveted joints. Bonded joints tended to fail by shear of the bond at the higher stress ranges and by tension of the sheet at the lower stress ranges. Riveted joints failed by tension across the first row of rivets in all cases, though tests on three-row riveted joints showed considerable improvement in endurance over those with two rows of rivets. Endurances were greater for bonded joints but with rather more scatter than for riveted joints, particularly where bond shear was the cause of failure.

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1. Introduction

1.1 This report describes and presents the results of a programme of fatigue tests on some Redux bonded joints in aluminium alloy sheet carried out in the Aircraft Structures laboratory at Imperial College of Science and Technology.
Most fatigue data available to date on such joints are obtained from tests of small single lap joints in thin sheet material (18 S.W.G. and less). As a more fundamental study, in that peeling stresses are largely eliminated, the series of tests reported here were carried out on double lap joints. Moreover, the specimens tested were of considerably larger size than usual, being made in 10 S.W.G. sheet with a width of 4.5 inches and having static strengths in the range 10 - 20 tons. The materials used for specimens were aluminium alloy clad sheet to specifications D.T.D. 610, 546 and 687.

1.2 For comparison with the Redux bonded joints tests were also made on riveted joints of similar simple design. All riveted joints were made with 3/16" dia. snap head rivets to specification L57 (DTD 327). Preliminary tests had shown disappointingly low results for two-row riveting and some three-row riveted joints were also tested to investigate the effect, if any, of the number of rows of rivets on fatigue strength.

1.3/

1.3 The stress condition in the sheet at the joint line was uniform tensile stress normal to the joint line, the uniformity of stress across the sheet being checked by strain gauge measurements on a typical specimen. Since, in many cases, up to three specimens of possibly different design were tested simultaneously in series it was necessary to standardise to some extent the stress cycles used. Tests were accordingly run for various values of maximum load (P_{max}) and three values of minimum load (P_{min}) viz. 0, 2 tons, 4 tons.

1.4 As far as possible, each type of joint was tested up to an endurance of 10^7 cycles. However, this proved impracticable in some cases on the standard size of joint due to the difficulty of accurately obtaining the correspondingly low fluctuating loads required and in order to overcome this a limited number of specimens of double width (9") were manufactured and tested. At the other end of the scale endurances of 10^4 cycles represented the practical limit due to the finite time required to build up the load cycle.

1.5 In a previous note[1], results were given of some preliminary tests of the same joint design. For completeness, these results are incorporated in the present report.

2. Specimens and Tests

2.1 Fig. 1 gives details of the particular Redux joint tested which was designed to develop as high a static strength as could reasonably be expected and Fig. 4 shows a complete specimen. Preliminary tests had demonstrated that it was unsatisfactory merely to clamp the plain unreinforced ends of the sheet specimens directly in the jaws of the testing machine. Not only did this lead to failures at the edge of the jaws under low fluctuating loads but proved troublesome in practice due to the difficulty of aligning correctly the specimen to obtain uniform stress distribution and smooth operation of the testing machine. Since the usual waisted form of specimen was out of the question due to the width required at the joint line and would, in any case, have proved unnecessarily wasteful of material the design shown in Fig. 4 was adopted. In this the load is applied via fitted 1" dia. bolts in the reinforced ends of the specimens. The bolts themselves passed through special fittings permanently clamped in the jaws of the machine. With the adopted scheme, the accurate assembly of specimens into the machine was enormously facilitated. In addition, it proved possible to test simultaneously up to three specimens at the same load by mounting them in series. On failure of one specimen, a new one was inserted in the chain in place of the fractured specimen and the test restarted. The interruption entailed for the specimens still intact was so small as to involve negligible influence on the results due to possible recovery. For tests over long lifetimes this "chain" mounting of specimens more than doubled the testing rate in specimen cycles.

The end reinforcement of the specimens to take the loading bolts consisted of 10 S.W.G. and 14 S.W.G. doubling plates Redux bonded to the specimen plate at the same time as the joints were made. (In tests made with only the 10 S.W.G. plates tensile fatigue failures occurred across the 1" dia. holes). Occasional failures of the plate at the entry to the reinforcement still occurred in the earlier tests due to the stress concentration at the change of section and it proved necessary to radius the ends of the doubling and reduce the step to the minimum possible on the milling machine. (Fig. 5C).

2.2 The design of the double width specimens was identical with the standard ones except for the increased width and the two holes which were used at each end (at the quarter width points) to pick up the loading bolts. These latter located in further special fittings themselves attached by single bolts to the end plates clamped in the testing machine jaws.

2.3/

2.3 Details of the riveted joints tested are given in Figs. 2 and 3. The specimens themselves were otherwise identical with the Redux ones.

2.4 All specimens were manufactured as continuous joints across the full width (4 ft.) of the sheet, the direction of rolling thus being in all cases along the specimen axis. All joints and doubling plates were assembled dry and pilot holes drilled for the tack rivets to hold all parts in exact position during curing of the Redux. Individual specimens were then successively parted off on a milling machine, the tack rivets used during curing being so positioned as to be removed during the parting off. Machining marks on the edges of the specimen were removed by light draw-filing. Riveted joints were manufactured in essentially the same way, the doubling plates being bonded in place prior to riveting up the joints. Specimens were machined to exact width after rough parting off in order to ensure symmetric location of the rivet group.

2.5 All tests were run in the Losenhausen U.H.S. Universal fatigue testing machine at frequencies between 500 and 1,000 cycles per minute. The method of mounting specimens has already been described in connection with their design (2.1). Static ultimate tests on complete specimens of all types of joint and control tests on material samples cut from the sheet material were also carried out on the same machine.

3. Static Tests

3.1 Table I gives results of tensile control tests on the sheet materials used in the fatigue tests. All properties were well above specification minima. Table II presents results of static tensile tests on complete specimens of joints. These results illustrate clearly the dependence of the static strength of glued joints on the mechanical properties of the adherents when these are stressed into the plastic range. Failure was in all cases by rupture of the bonding medium yet failing stresses are related more to the 0.2% proof stress of the sheet than to a permissible shear stress in the bond. The dependence of bond strength on the geometry of joint is well known and arises due to the brittleness and high stiffness of the adhesive film. The high stiffness causes rapid diffusion of stress between the adherents with its high attendant shear stresses at the ends of the joint overlap. Plastic strains in the sheet intensify the effect, being roughly equivalent to a local reduction of the sheet stiffness, and since the brittleness of the glue prevents its accommodating the peak shear strains by itself yielding, failure takes place at a lower average stress than would be developed with perfectly elastic adherents. It should be noticed also that a higher fraction of the ultimate stress is developed in D.T.D. 687, and 546 sheet (97% and 96% respectively) than in D.T.D. 610 sheet (82%) due to the much earlier onset of plastic strain in this last case. It would appear therefore that materials with a high ratio (0.1% proof stress/ultimate stress) are inherently more efficient as far as static strength is concerned.

3.2 Failure in the riveted joints was by shear of the rivets except for 3-row joints in D.T.D. 610 which failed in tension across the first row. Static strength results for two-row riveted joints show therefore negligible differences between different materials. In the three-row joints both D.T.D. 610 and D.T.D. 687 were able to develop approximately 95% of their ultimate stress on the nett area across a rivet row.

3.3 To check the uniformity of stress distribution across the specimen width, strain gauge measurements were made on a double width specimen under a load of 16 metric tons. The strain distributions measured at the base of the joint strap plate and also next to the tapered reinforcement on the ends of the specimen are illustrated in Fig. 6. At the joint itself the measured stresses fall within

$\pm 2\frac{1}{2}\%$ of the average stress. At the doubling plate the variation is within $\pm 5\%$. Bearing in mind the accuracy of strain gauge measurements the stress distribution at the joint is as uniform as is likely to be achieved. At the doubling plate the peak stresses which correspond roughly to the positions of the 1" dia. holes for the loading pins may be critical in causing failure there. Increased distance of the holes from the tapered edge of the doubling should help in reducing these stress irregularities in the sheet for future specimens.

4. Fatigue test results - Redux Joints

4.1 Detailed results of all tests are given in Table III which shows specimen number, values of maximum and minimum fluctuating load (P_{max} and P_{min}) and the number of cycles of load to failure. The mode of failure is also shown. Stress/endurance curves are plotted in Figs. 8 to 16. The basic ordinate in these is P_{max}/P_{ult} i.e., the ratio of the maximum fluctuating load (stress) to ultimate static load (stress), the latter being that determined in static ultimate tests. Subsidiary vertical scales give also σ_{max} - the direct stress in the sheet associated with P_{max} - both in lb/in² and kg./cm². A different curve is plotted for each value of the minimum load to avoid overlapping due to scatter of results. The mode of failure is also indicated by the use of different symbols for the points plotted (See Key on Fig. 7).

4.2 Failures in the Redux bonded specimens are of three kinds:

(a) rupture of bonding medium

(b) tension failure in the sheet at the entry to the joint i.e., at the base of the strap plates

(c) tension failure in the sheet at the entry to the end reinforcement of the specimen.

The first class may be further subdivided into cohesive and interfacial failure. Cohesive failure consists of a rupture of the adhesive film itself and is detected by the presence of a residual layer of adhesive on the parted faces of the adherents. In interfacial failure the adhesive detaches cleanly from the surface of the adherent exposing the metallic face and leaving a shiny surface on the adhesive film. In practice most failures involved a mixture of the two and where this was recorded the approximate percentages of joint area over which the two types occurred are given in Table III. Thus, the figures 80C, 100C indicate that on one face of the plate, failure was cohesive over 80% and interfacial over the remaining 20% of the area of one face of the sheet while on the other face it was 100% cohesive failure.

As a general rule, failure of specimens was by rupture of the bond at the higher values of fluctuating stress and by tension of the sheet either at the joint or the doubling at the lower stress ranges. In the case of D.T.D. 687 specimens this dividing line seems to be quite rigidly drawn at a value of $\sigma_{max} - \sigma_{min} = 25{,}000$ lb/in² approx. One case of bond rupture did in fact occur (2B1-7w) with a value of $\sigma_{max} - \sigma_{min} = 15{,}400$ but at an endurance only a third of the lowest for tension failure at that stress. Although no such sharp dividing line could be drawn for specimens in D.T.D. 610 and 546, where failures by bond rupture occurred down to the lowest stress ranges tested, such cases were usually associated with endurances slightly on the low side. In no cases were tension failures observed at the higher stress ranges ($\sigma_{max} - \sigma_{min} > 20{,}000$ lb/in²).

The most noticeable feature associated with failure by bond rupture was the large scatter in the results, particularly in several D.T.D. 610 specimens of the first series which failed at such

low/

low endurances as to be considered premature failures. Most of these were characterised by a predominance of interfacial failure (unfortunately exact figures were not recorded) and were discovered to have been parted off from the same parent joint of 4 ft. width (See 2.4). The suspect specimens were returned to Aero Research Ltd., for inspection where the low results were attributed to inadequate pickling of the sheets before bonding. Such a conclusion is, of course, supported by a prevalence of interfacial failure, as indicative of inadequate preparatory treatment of the metal surface to be bonded, rather than a weakness of the bond material itself. As a result of this all subsequent cases of bond failure were examined with a view to attempting correlation of the fatigue results with the extent of interfacial failure. However, the figures recorded have proved quite inconclusive although it should be remarked that the second test series was free from abnormally low results and most bond failures were predominantly cohesive.

A comparison of all test results where failure occurred by shear of the bond indicates no detectable difference between specimens of different materials. Since in all these cases the stresses in the adherents were within the elastic range of the materials such a result is to be expected, there being no essential physical differences in the conditions at the joints. One might, of course, expect differences to arise when the stresses are sufficiently high to produce plastic strains but the present results suggest that the increased scatter associated with high stress and bond rupture would tend to mask them.

In cases where failure occurred in the sheet, either at the strap plates of the joint or at the end doubling plates, failure was presumably precipitated by the stress concentrations associated with the sudden change in cross-section and consequently one would expect the results to be dominated by material properties of the sheet - particularly with respect to the notch sensitivity. Significant differences of endurance at a given stress range were, however, only apparent at the lowest stress ranges tested. Here the D.T.D. 687 specimens gave consistently lower endurances than the other two materials for a given cyclic stress range. Differences between materials are greatly increased if we compare endurances for a given ratio P_{max}/P_{ult}, due to the increases in static strength of D.T.D. 546 and 687 specimens over D.T.D. 610 specimens without corresponding increase in fatigue strength. The practical significance of these differences may be even more spectacular. Thus, if we consider civil aircraft, the most significant stress range is generally of the order $P_{max} - P_{min} = 0.2\ P_{ult}$. For this range the endurance of the D.T.D. 687 joints is below 10^6 cycles, for D.T.D. 546 we should expect values between 10^6 and 10^7 while for D.T.D. 610 the inference from the trend of results, as far as they go, is an endurance so large as to be virtually infinite.

Results of tests where failure occurred in tension at the doubling plates are, strictly speaking, invalid from the point of view of the properties of the joint itself. They are, however, of value in connection with the design of the test specimens and also themselves reveal an interesting feature. Examination of the results for $P_{max} = 4$ tons reveals a close bunching of endurance values with no apparent correlation between mode of failure and endurance, whereas at the lowest stress level it would appear that failure at the ends is associated with the least endurance.

5. Fatigue test results - Riveted Joints

5.1 Table IV gives detailed results of all fatigue tests as for the Redux joints and in Figs. 17 - 28 stress-endurance results are shown graphically. Values of stress given by the two stress

ordinate/

ordinate scales are based on the nett area of cross-section of the sheet at the first rivet row.

5.2 In all tests carried out, failure of the joint was in tension of the sheet across the outer row of rivets. All values of endurance given are for complete failure of the specimen. In some cases fatigue cracks appeared at one or both edges of the plate prior to failure, the cracks having developed outwards from the outer rivet holes. It was not possible to detect always the first appearance of such a crack but in most instances some warning of its approach was given by the presence of a slight dimple in the edge of the sheet. In those cases where such cracks were observed the subsequent cycles to failure were between zero and about 10,000. In these experiments it was not possible to detect the progress of such cracks until their development to the edge of the specimen. Examination of the fractured specimen indicated similar cracks developing from most or all of the rivet holes, but again no observations were possible in these tests of their initiation and progress.

The endurances obtained for the riveted joints were remarkably consistent, particularly at the high stress ranges where the scatter, in contrast to the Redux joints, was extremely small. Comparison between results for different materials shows for the two-row riveted joints particularly low lives for D.T.D. 687 specimens; the difference between the other two materials was small except at the lower stress ranges where D.T.D. 546 has a slightly greater life. From a practical point of view comparisons on a basis of P_{max}/P_{ult} are of only limited value due to the rather low static strength of the riveted joints. Since all two-row joints failed statically in shear of the rivets P_{ult} is practically the same for all materials. Changes in rivet pitch to develop higher static stresses in the sheet should, however, have only slight influence on the fatigue results. The effect of different rivet patterns may, however, be considerable as is shown by the results of the limited number of tests on three-row riveted joints in D.T.D. 610 and D.T.D. 687. All fatigue failures were again by tension of the sheet across the first rivet row as in the two-row joints and at the higher stress ranges the endurances obtained for both types fall within the same scatter band. However, as the stress range decreases there is a progressive increase in the life of the three-row joints over that for two-row joints until at the lowest ranges tested the ratio of average endurances is approximately 10 for D.T.D. 610 and as much as 25 for D.T.D. 687. Conditions at the first rivet row, where failure occurred, are of course different since the rivets in the first row are more lightly loaded in the three-row joints, providing some alleviation in the stress concentrations there. Such an influence would be expected to benefit the more notch sensitive D.T.D. 687 rather more than the D.T.D. 610, as indeed happened. The limited nature of the data precludes anything more than tentative conclusions but, bearing in mind the generally low scatter of results for riveted joints, it appears that differences in endurance are likely to be at least of the order quoted.

6. General Conclusions

6.1 Comparison of all the results obtained in the present test series indicate a superiority in fatigue properties of the Redux bonded joints over comparable riveted ones in the same material, but differences in the endurances of the two types of joint may be more than compensated for by the effect of material properties. Thus the three-row riveted joints in D.T.D. 610 have greater lives than the Redux joints in D.T.D. 687 at the same ratio P_{max}/P_{ult}. Compared on the basis of stress, however, the two sets of results practically coincide. Moreover, since stresses in the riveted joints are based on nett area across a rivet line they appear to some advantage in such a comparison, and in a practical joint designed to a given static strength the Redux joints

would/

would still be superior in fatigue. Nevertheless the tests on three-row joints show that the effect of rivet pattern on fatigue strength may be considerable; a more comprehensive test series with wider variation of pitch and number of rivet rows is necessary to establish the fundamental influences. At the same time, recent work[2] has shown that length of overlap may be a significant parameter in the fatigue strength of Redux joints even when it has ceased to be of importance in the static case. Thus, slight over-design for static strength may yield considerable benefit under fatigue. The testing of such specimens is an obvious extension to the present work as also is the development of joints with tapered strap plates to improve the stress distribution in the sheet and the glue at the actual joint. A serious difficulty in the testing of such improved joints will be the design of suitable end attachments to ensure failure at the joint and not at the attachments, possibly necessitating a change in the basic design of specimens.

Quite apart from these developments the problem of scatter in endurances for Redux joints requires more consideration - particularly under those stress ranges where failure of the bond itself occurs. The number of specimens tested in the present series was too limited to provide a reliable assessment of the probable scatter. In this connection the occasional premature failures are of great practical importance and any further work should include the correlation of endurance with the relative extent of cohesive and interfacial failure as well as with such process quality measures as the standard peeling test.

References

No.	Author(s)	Title, etc.
1	S. Kelsey and J. H. Argyris	Comparative fatigue tests on some Redux bonded and riveted double strap joints in aluminium alloy sheet. A.R.C. 17,114. June 1954.
2	F. A. Jacobs and A. Hartman	The effect of sheet thickness and overlap on the fatigue strength at repeated tension of Redux bonded 75S-T clad simple lap joints. N.L.L. Report M. 1969, October 1954.

TABLE I

Average Static Tensile Properties of Sheet Materials Used in Fatigue Tests

Material	0.1% Proof Stress		Ultimate Stress	
	lb/in.^{2}	kg/cm.^{2}	lb/in.^{2}	kg/cm.^{2}
DTD 610B	40,100 (33,600)	2,800 (2,360)	63,600 (56,000)	4,480 (3,900)
DTD 546B	51,200 (47,000)	3,600 (3,300)	65,800 (60,500)	4,630 (4,250)
DTD 687A	71,200 (60,500)	5,000 (4,250)	77,200 (71,600)	5,440 (5,050)

Note: Figures in parenthesis give specification minima properties.

TABLE II/

TABLE II

Average Static Tensile Strengths of Joint Specimens

Material	Type of Joint	Ult. load Metric tons	Ultimate Stress lb/in.²	Ultimate Stress kg/cm.²	Mode of Failure
DTD 610B	Redux	12.6	48,200	3,400	1
DTD 546B	"	16.6	63,500	4,470	1
DTD 687A	"	19.5	74,500	5,250	1
DTD 610B	Riveted (2 row)	10.0	51,000	3,590	2
DTD 546B	" "	9.6	49,000	3,450	2
DTD 687A	" "	10.0	51,000	3,590	2
DTD 610B	" (3 row)	11.9	60,700	4,280	3
DTD 687A	" "	14.2	72,500	5,100	2

Modes of failure:

1. Shear of Redux bond

2. Shear of rivets

3. Tension in sheet at outer rivet row

Note: Stresses in riveted joints are based on nett area of sheet at rivet line.

TABLE III/

TABLE III

(i) D.T.D. 610B

Fatigue Test Results for Redux-Bonded Specimens (see Fig. 1)

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life Cycles $\times 10^3$	Mode of Failure
0	8.0	0.635	1A1- 7	25.6	1
			-16	13.1	1
			-20	Zero	1,2
			-24	2.6	1,2
			-39	51.4	1
0	6.0	0.476	1A1- 8	151	1
			-11	109	1
			-25	93	1
0	5.0	0.397	1A1- 2	250	3
			- 5	273	3
			-17	52	1,2
			-19	0	1,2
			-21	62.7	1,2
0	4.0	0.318	1A1-32	472	4
			-35	498	3
			-38	792	4
			2A1- 1w	504	1 (80C,100C)
			- 7w	655	1 (100C,100C)
0	3.5	0.278	2A1- 4w	2841	1 (100C,100C)
			-11w	11720	5
0	3.0	0.238	1A1-33	2021	4
			-36	4075	4
			-40	3400	4
			2A1-10w	5170	5x
2.0	8.0	0.635	1A1- 6	58	1
			-14	32.2	1
			-22	4.8	1
2.0	7.0	0.556	2A1- 4	47.2	1 (100C,100C)
			-11	95.4	1 (100C,100C)
			-10	31.6	1 (100C,100C)
2.0	6.0	0.476	1A1- 9	330	3
			-12	394	3
			-27	294	3

(Continued)/

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life Cycles $\times 10^3$	Mode of Failure
2.0	5.0	0.397	1A1-31	1,610	3
			-34	1,796	3
			-37	1,972	4
			2A1- 5w	4,000	3
4.0	9.0	0.714	2A1- 1	95	1 (20C,100C)
			- 5	110	1 (50C,80C)
4.0	8.0	0.635	1A1-10	355	1
			-13	237	1
			-26	278	3
4.0	7.0	0.556	1A1- 4	556	3
			-18	1.1	1,2
			-29	1,502	1,3
4.0	6.5	0.516	2A1- 3w	13,230	5
4.0	6.0	0.476	1A1- 3	4,820	5

<u>Modes of Failure</u>

1. Failure of Redux bond
2. Exceptionally low or premature failure
3. Failure in sheet at base of strap plate
4. Failure in sheet at end reinforcement
5. Did not fail.

[x]Machine stopped due to power failure
Damage to specimen prevented continuation of test

(ii) D.T.D. 546B

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles $\times 10^3$)	Mode of Failure
0	8.0	0.487	1C1-21	9.1	1 (100C,80C)
			-14	31.9	1 (80C,100C)
0	7.0	0.426	1C1- 6	4.1	1 (100C,100C)
			-33	22.7	1 (100C,80C)
			-25	119.8	4
			-32	45.9	1 (80C,100C)
0	6.0	0.367	1C1- 3	448.6	1 (100C,100C)
			-22	76.4	1 " "
			-18	28.5	1 " "
0	5.0	0.306	1C1-24	98.6	1 (100C,100C)
			- 2	197.4	1 " "
			-27	154.4	4
			- 1	285.5	3
0	4.0	0.245	1C1- 9w	813	3
			-11w	954	4
			- 5w	698	4
			- 1w	302	1 (100C,100C)
			-16	1,003	4
			-29	542	3
			-15	829	4
0	3.5	0.212	1C1- 2w	1,430	1 (100C,100C)
0	3.0	0.181	1C1-10w	10,636	5
2.0	8.0	0.487	1C1-34	48.6	1 (100C,100C)
			-13	109.2	1 (60C,80C)
2.0	7.0	0.426	1C1-20	123.4	1 (20C,80C)
			-31	232.6	4
2.0	6.0	0.367	1C1-25	384	3
			- 5	443	3
2.0	5.0	0.306	1C1- 4	1,200	3
			-30	1,209	3
2.0	4.5	0.271	1C1- 7w	11,360	5

Continued/

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles $\times 10^3$)	Mode of Failure
4.0	9.0	0.542	101-12 - 9	25.2 95.1	1 (80C,100C) 1 (80C,90C)
4.0	8.0	0.487	101-10 - 8	260 266	3 3
4.0	7.0	0.426	101- 7 -26	1,924 3,361	3 4

Modes of Failure:

1. Failure of Redux bond
2. Exceptionally low or premature failure
3. Failure in sheet at base of strap plate
4. Failure in sheet at end reinforcement
5. Did not fail

(iii)/

(iii) D.T.D. 687A

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles × 10^3)	Mode of Failure
0	10.0	0.512	1B1- 4 -20 -27	13.7 3.0 9.0	1 1 1
0	8.0	0.410	1B1- 1 -10 -17 -24	10.2 14.8 57.0 51.0	1 1 1 1
0	6.0	0.308	1B1- 3 -16 -28	124 151 153	3 3 3
0	5.0	0.256	1B1- 9 -13 -26 -40	157 177 187 183	3 3 3 3
0	4.0	0.205	1B1-33 -36 -39 2B1- 7w - 1w - 3w - 5w	344 483 418 116 809 614 559	3 4 4 1,2 (90C,100C) 3 4 3
0	3.5	0.179	2B1- 4w -11w -12w	570 4,508 1,330	3 4 3
0	3.0	0.154	1B1-32 -35 -38 2B1-10w	1,321 4,556 964 15,808	4 5 4 5
2.0	10.0	0.512	1B1-30 -23 -21 -14	8.9 26.8 11.1 26.9	1 1 1 1
2.0	9.0	0.462	1B1-29 -25 -19	51.6 56.7 58.4	1 1 1
2.0	8.0	0.410	2B1-10 - 4 - 7	140.2 94.7 80.2	3 3 3

Continued/

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles $\times 10^3$)	Mode of Failure
2.0	6.0	0.308	2B1- 6 - 8 - 5	448 409 355	3 3 3
2.0	5.0	0.256	2B1- 1 - 9 -11	1.005 911 911	3 3 3
2.0	4.5	0.231	2B1- 9w	12,542	5
4.0	10.0	0.512	1B1-18	106.5	3
4.0	9.0	0.462	2B1-13 -15	183 176	4 4
4.0	8.0	0.410	2B1- 3 -16	230 281	3 3
4.0	7.0	0.357	2B1- 2 -12	1,693 2,093	3 3

Modes of Failure:

1. Failure of Redux bond
2. Exceptionally low or premature failure
3. Failure in sheet at base of strap plate
4. Failure in sheet at end reinforcement
5. Did not fail

TABLE IV/

TABLE IV

Fatigue Test Results for Riveted Joints
(see Figs. 2 and 3)

(i) D.T.D. 610B - 2 rivet rows

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles × 10^3)	Mode of Failure
0	7.0	0.70	1A2- 8 -12 -15	8.0 8.2 8.5	1 1 1
0	6.0	0.60	1A2-14 -20 -27	18.5 21.7 20.0	1 1 1
0	5.0	0.50	1A2- 2 -10 -26	35.7 30.9 25.3	1 1 1
0	4.0	0.40	1A2- 9 -16 -23	72.3 80.6 69.4	1 1 1
0	3.0	0.30	1A2- 1 -15 -28	187 161 357	1 1 1
0	2.0	0.20	1A2- 7 -13 -24 -30	700 1,264 658 357	1 1 1 1
0	1.5	0.15	2A2- 3w - 6w	13,150 13,150	2 2
2.0	7.0	0.70	1A2- 5 -11	19.0 14.8	1 1
2.0	6.0	0.60	1A2-18 - 3	33.1 28.7	1 1
2.0	5.0	0.50	1A2-19 - 6	68.3 81.2	1 1
2.0	4.0	0.40	1A2-22 -36	250 203	1 1

Continued/

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles × 10^3)	Mode of Failure
4.0	8.0	0.80	1A2-34 -37	11.6 12.7	1 1
4.0	7.0	0.70	1A2-31 -32	30.9 36.9	1 1
4.0	6.0	0.60	1A2-38 -35	93.0 87.8	1 1

Mode of Failure:

1. Tension in sheet at outer rivet row

(ii) D.T.D. 546B - 2 rivet rows

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles × 10^3)	Mode of Failure
0	6.0	0.63	1C2- 2 -13	13.5 14.6	1 1
0	5.0	0.525	1C2- 4 -14	37.0 21.5	1 1
0	4.0	0.42	1C2- 9 -20	115 75.5	1 1
0	3.0	0.315	1C2- 3 -18	161.8 120	1 1
0	2.0	0.21	1C2-10 -16	3,800 1,658	1 1
2.0	7.0	0.735	1C2- 7 -12	14.5 13.0	1 1
2.0	6.0	0.630	1C2- 1 -11	28.1 25.9	1 1
2.0	5.0	0.525	1C2- 5 -19	70.0 40.9	1 1
2.0	4.0	0.42	1C2-15 - 8	261 241	1 1

Mode of Failure:

1. Tension in sheet at outer rivet row.

(iii)/

(iii) D.T.D. 687A - 2 rivet rows

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles $\times 10^3$)	Mode of Failure
0	6.0	0.60	1B2- 3 -16 -20	11.2 13.8 10.8	1 1 1
0	5.0	0.50	1B2- 4 -11 -17	17.2 20.2 25.8	1 1 1
0	4.0	0.40	1B2- 5 - 8 -12	32.4 43.6 37.6	1 1 1
0	3.0	0.30	1B2- 6 - 9 -13	87.6 51.4 58.2	1 1 1
0	2.0	0.20	1B2- 2 -15 -19	130.5 165.6 321.6	1 1 1
2.0	7.0	0.70	1B2-34 - 7 -30	8.3 7.7 8.4	1 1 1
2.0	6.0	0.60	1B2-35 -26 -25 -21	16.4 16.2 14.5 19.5	1 1 1 1
2.0	5.0	0.50	1B2-27 -23	31.1 23.0	1 1
2.0	4.0	0.40	1B2-24 -22 -39	135.9 98.2 94.3	1 1 1
4.0	8.0	0.80	1B2-32 -37	8.5 8.5	1 1
4.0	7.0	0.70	1B2-10 -29 -28	11.9 16.6 17.7	1 1 1

Continued/

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles $\times 10^3$)	Mode of Failure
4.0	6.0	0.60	1B2-31 -36 -40	40.5 62.4 36.7	1 1 1

Mode of Failure:

1. Tension in sheet at outer rivet row.

(iv) D.T.D. 610 - 3 rivet rows

P_{min} (metric ton	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles $\times 10^3$)	Mode of Failure
0	6.0	0.504	3A2- 4 -14	12.7 10.3	1 1
0	5.0	0.420	3A2- 3 -13	29.5 45.2	1 1
0	4.0	0.336	3A2- 5 -15	57.2 212.5	1 1
0	3.0	0.252	3A2- 1 -16	335 1,273	1 1
0	2.0	0.168	3A2- 9 -20	8,949 12,000	1 2
2.0	6.0	0.504	3A2- 6 -11	93.7 47.0	1 1
2.0	5.0	0.420	3A2-10 -17	378.4 378.4	1 1
2.0	4.0	0.336	3A2- 8 -12	1,462 1,165	1 1

(v)/

(v) D.T.D. 687 - 3 rivet rows

P_{min} (metric ton)	P_{max} (metric ton)	$\frac{P_{max}}{P_{ult}}$	Specimen	Life (cycles $\times 10^3$)	Mode of Failure
0	6.0	0.426	3B2- 2	10.4	1
			-11	13.9	1
0	5.0	0.355	3B2- 1	54.2	1
			-17	29.2	1
0	4.0	0.284	3B2- 4	113.7	1
			-19	73.3	1
0	3.0	0.213	3B2- 5	652	1
			-18	222	1
0	2.0	0.142	3B2-10	5,471	1
			-15	3,425	1
2.0	7.0	0.497	3B2- 9	13.6	1
			-14	12.7	1
2.0	6.0	0.426	3B2- 8	26.1	1
			-16	19.2	1
2.0	5.0	0.355	3B2- 6	109.6	1
			-13	57.5	1
2.0	4.0	0.284	3B2- 7	306	1
			-12	306	2

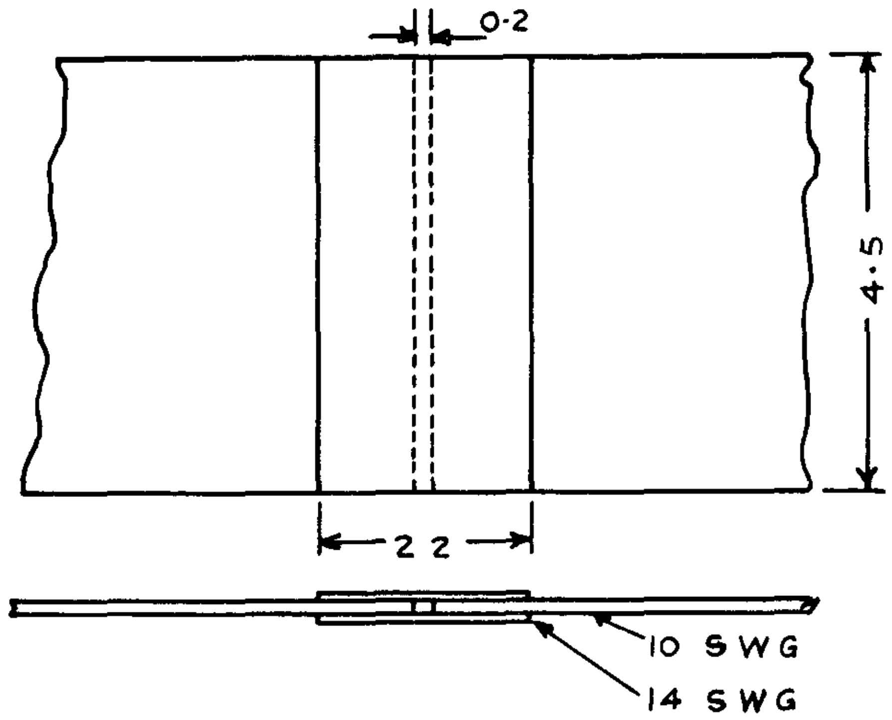
Mode of Failure:

1. Tension of sheet at outer rivet line

2. Did not fail

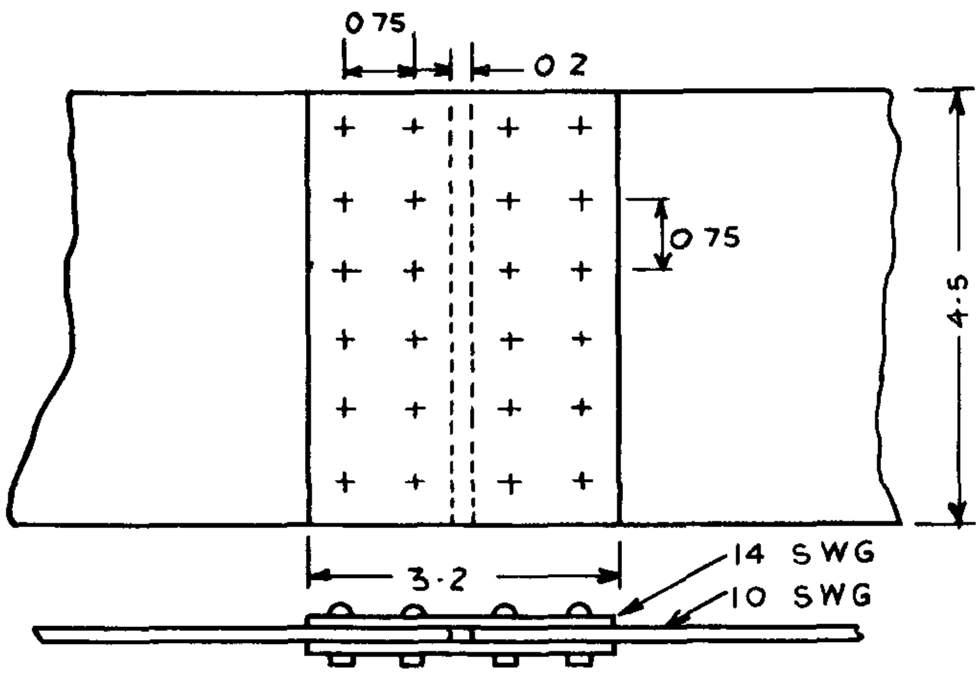
FIGS 1 & 2

FIG 1.



Redux bonded butt joint

FIG 2.

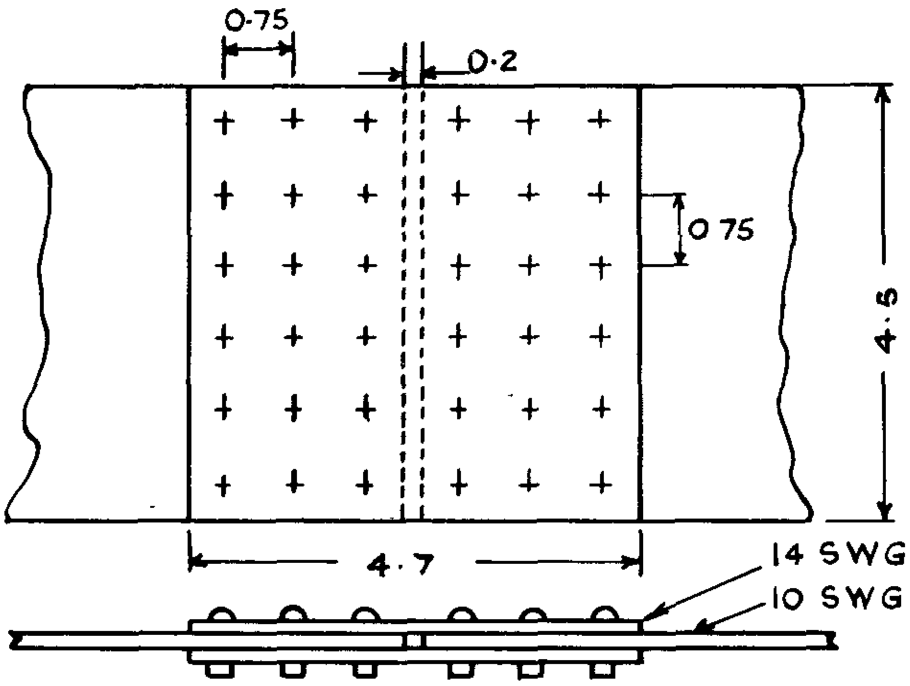


Riveted butt joint (2 rows)

$\frac{3}{16}$" dia DTD 327 (L 57) snap head rivets

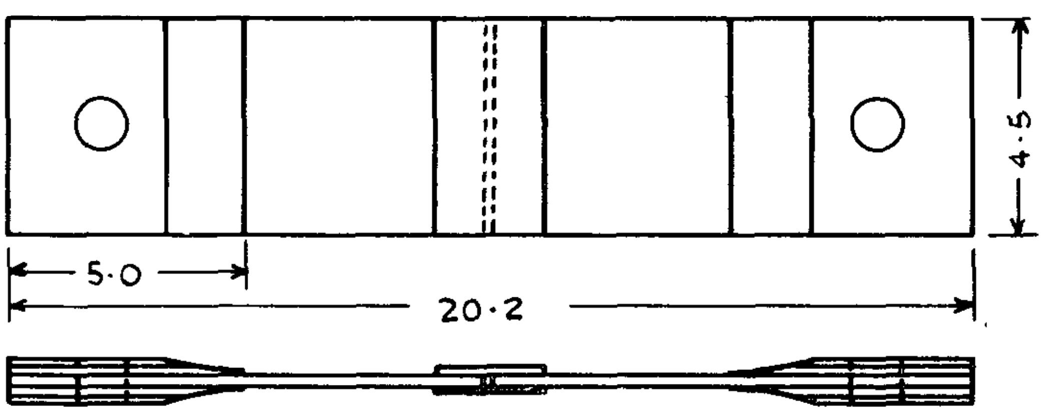
FIGS 3 & 4.

FIG. 3.



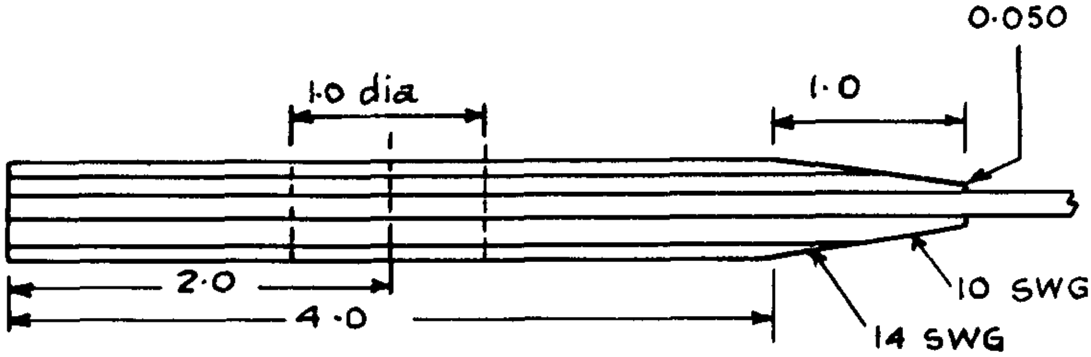
Riveted butt joint (3 row)
$\frac{3}{16}$" dia DTD 327 (L 57) snap head rivets

FIG 4

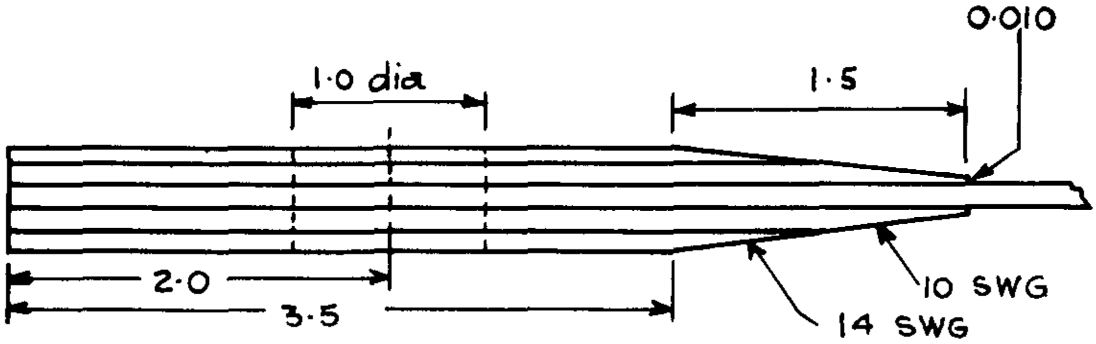


Redux test specimen

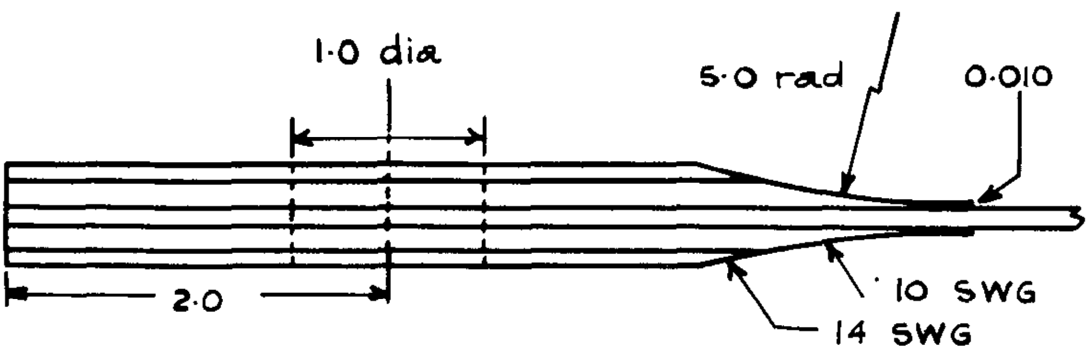
FIG. 5. A, B & C



A 1·0 inch straight taper to 0 050 step



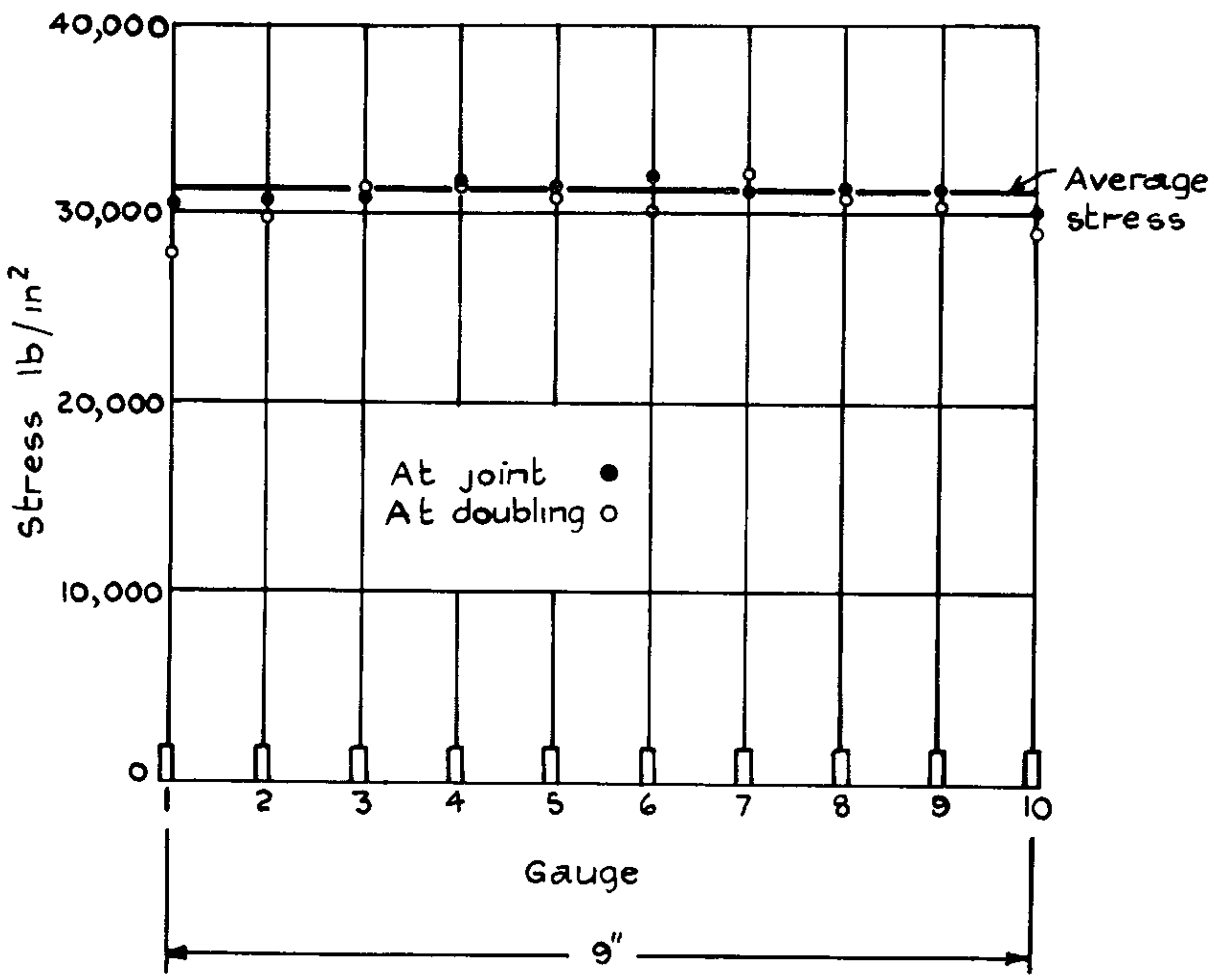
B 1·5 inch straight taper to 0·010 step



C. 5 0 inch radius taper to 0·010 step

Progressive design of specimen end

FIG 6



Distribution of stress over specimen width

FIG 7.

KEY TO GRAPHS

REDUX JOINT

○ DENOTES REDUX FAILURE

□ DENOTES MATERIAL FAILURE AT BASE OF STRAP PLATES

△ DENOTES MATERIAL FAILURE AT BASE OF DOUBLING PLATES

ꝋ ⍊ ⍙ DENOTES WIDE SPECIMEN

RIVETED JOINT

○ DENOTES MATERIAL FAILURE ACROSS OUTER RIVET ROW

ꝋ DENOTES WIDE SPECIMEN

BOTH JOINTS

●→ NO FAILURE OF SPECIMEN

←● PREMATURE FAILURE

VERTICAL AXES

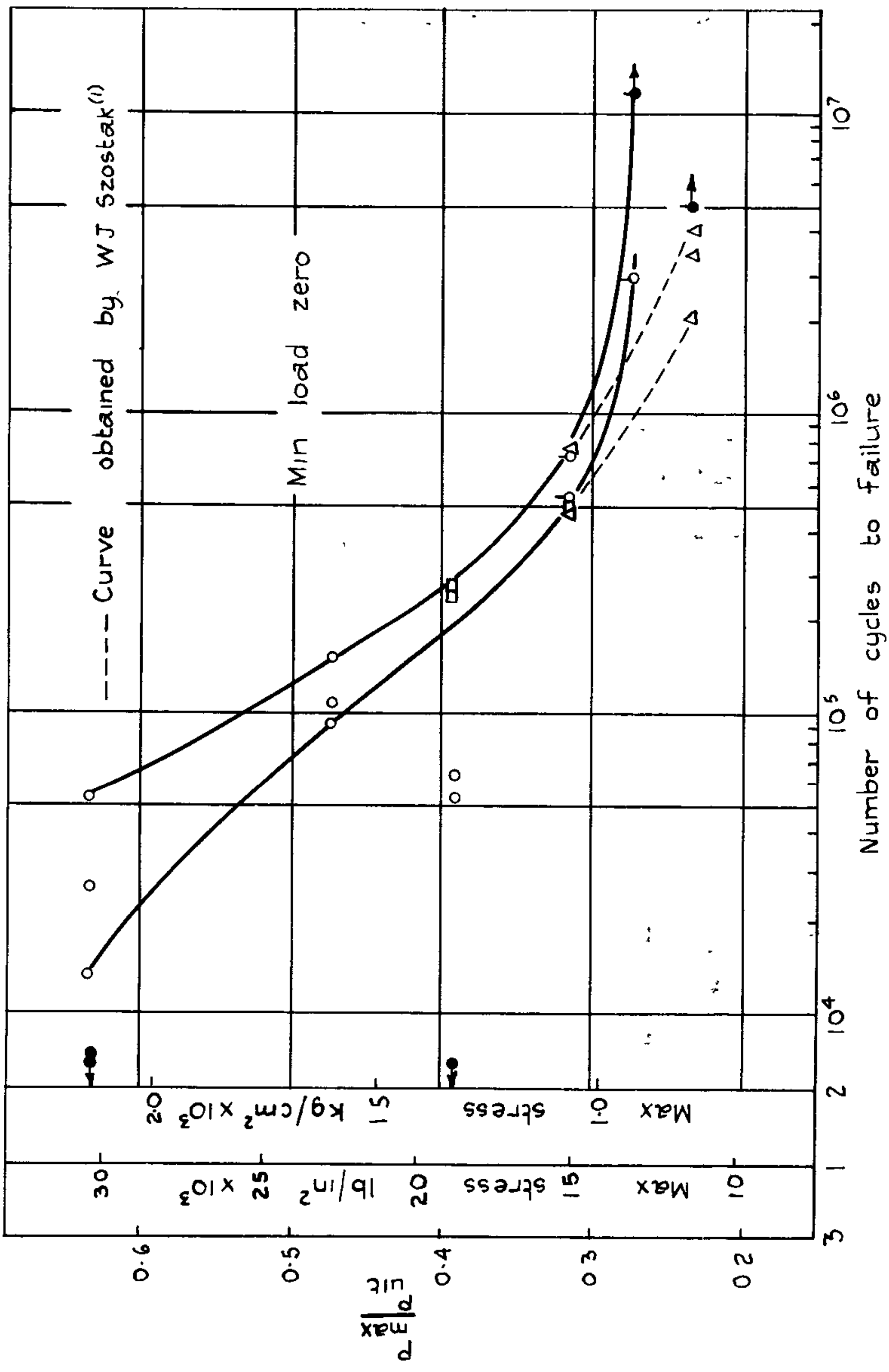
(1) MAX. STRESS $LB/IN.^2 \times 10^3$

(2) MAX. STRESS $KG/CM.^2 \times 10^3$

(3) P_{Max}/P_{Ult}

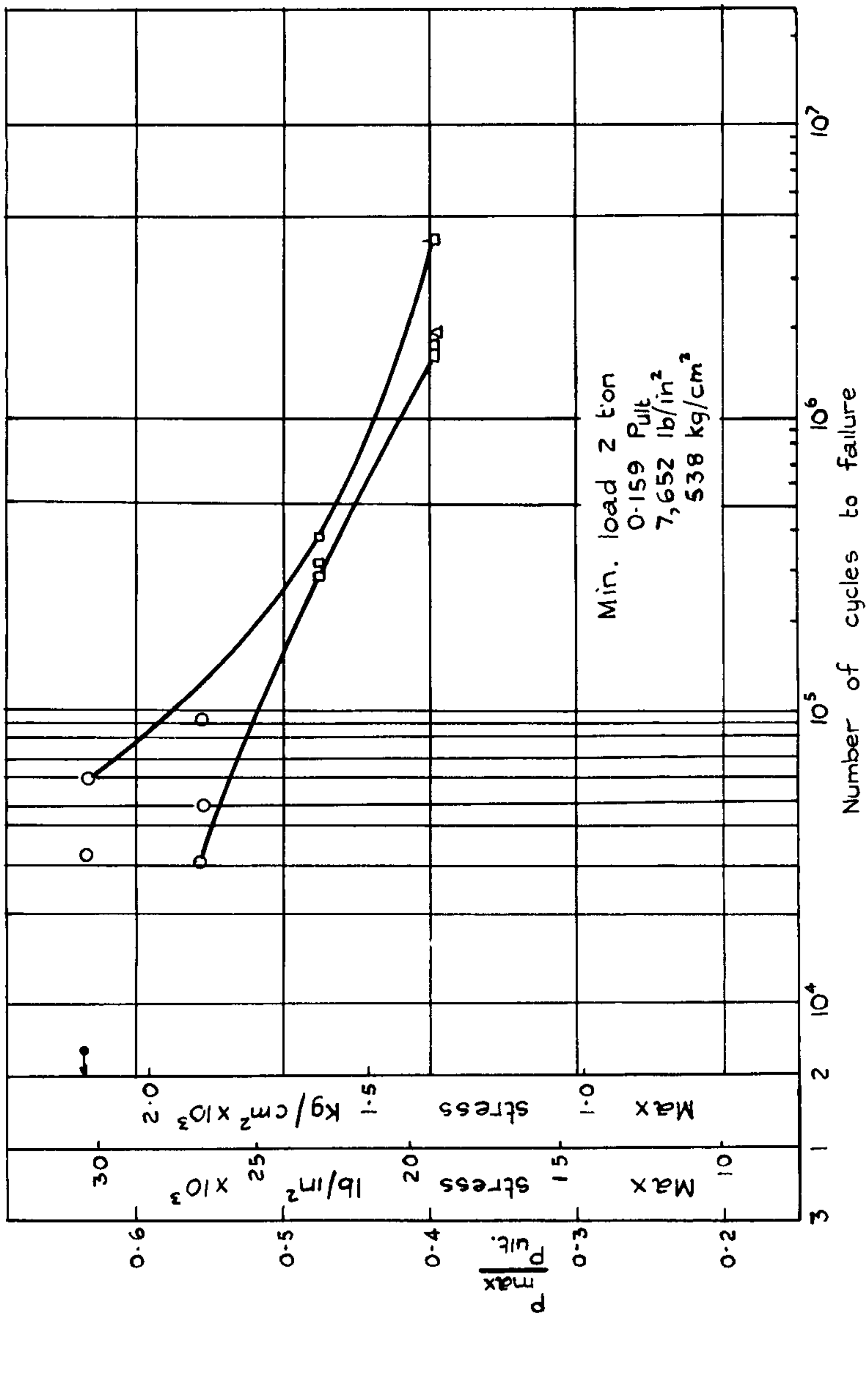
HORIZONTAL AXIS LOG. SCALE

FIG 8



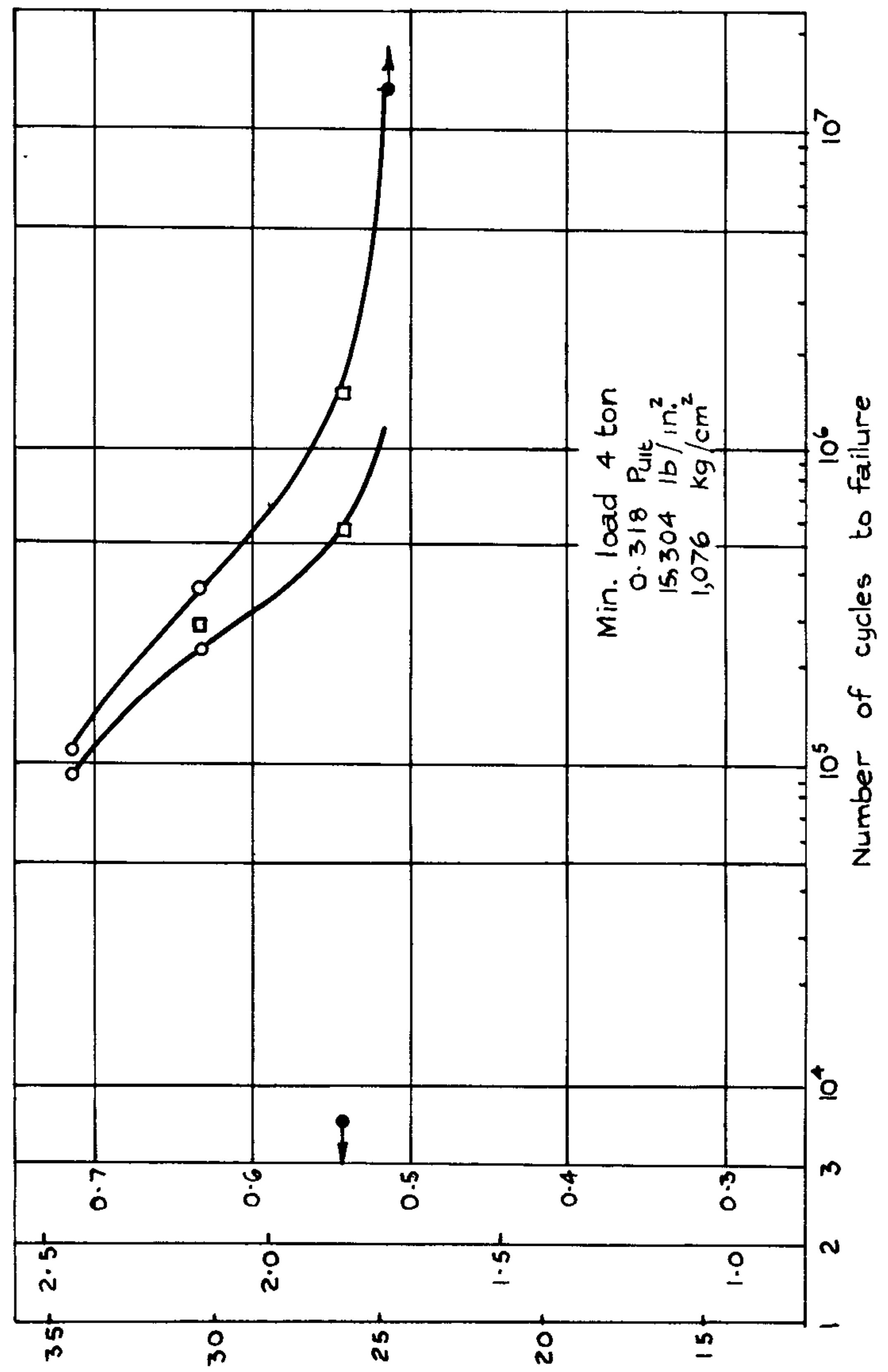
DTD 610 Redux

FIG 9



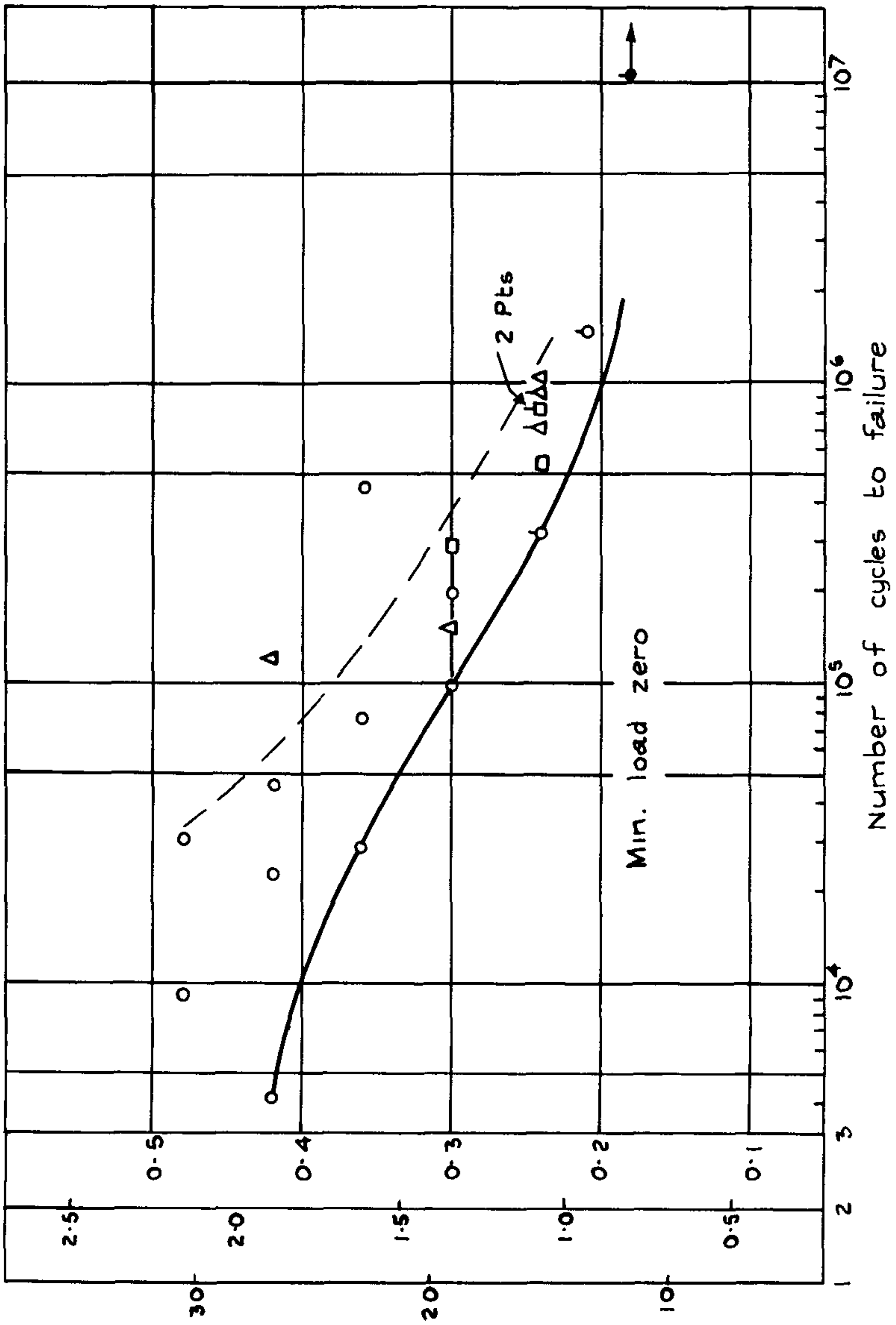
DTD 610 Redux

FIG 10.



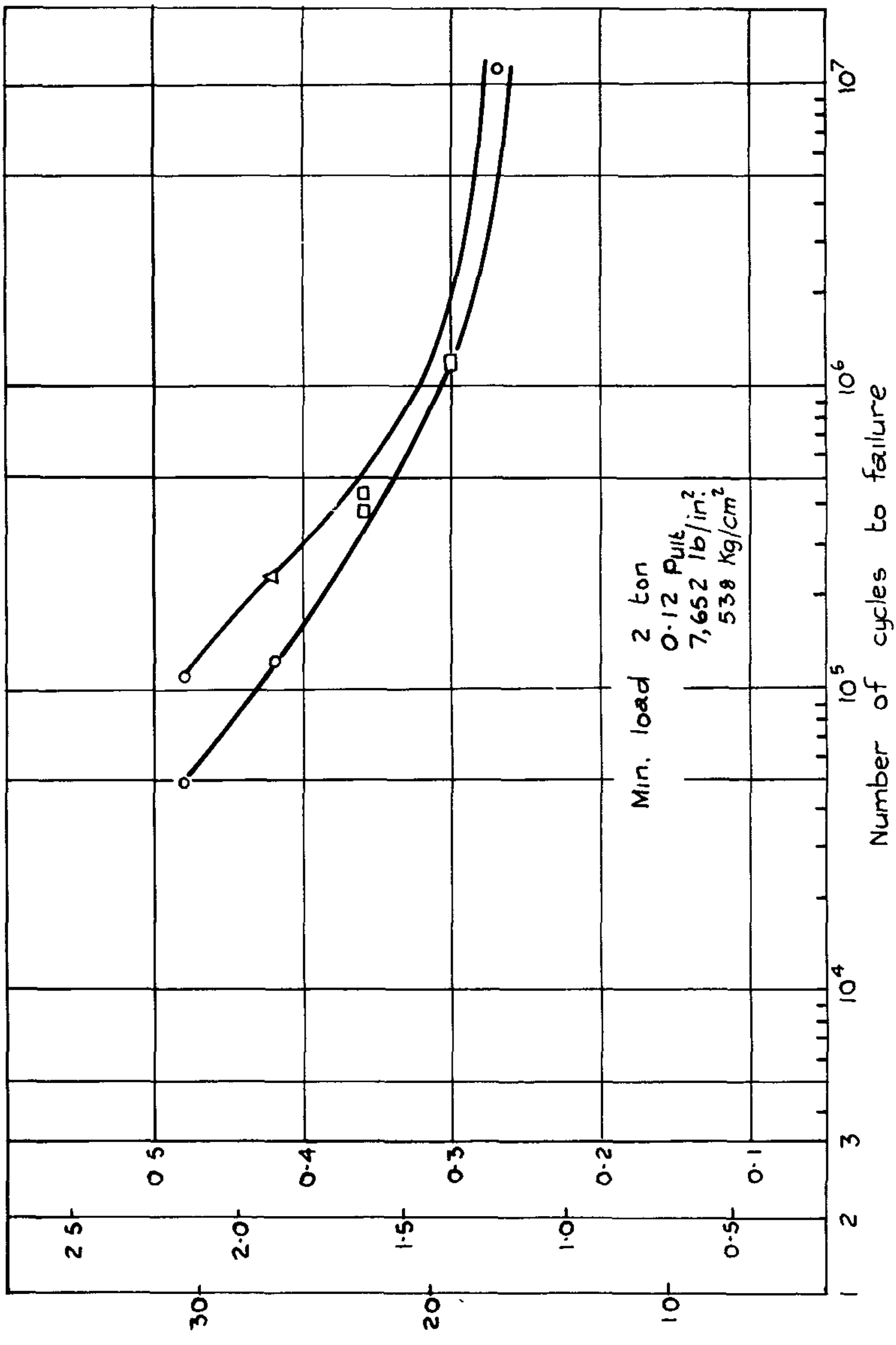
DTD 610 Redux

FIG. 11.

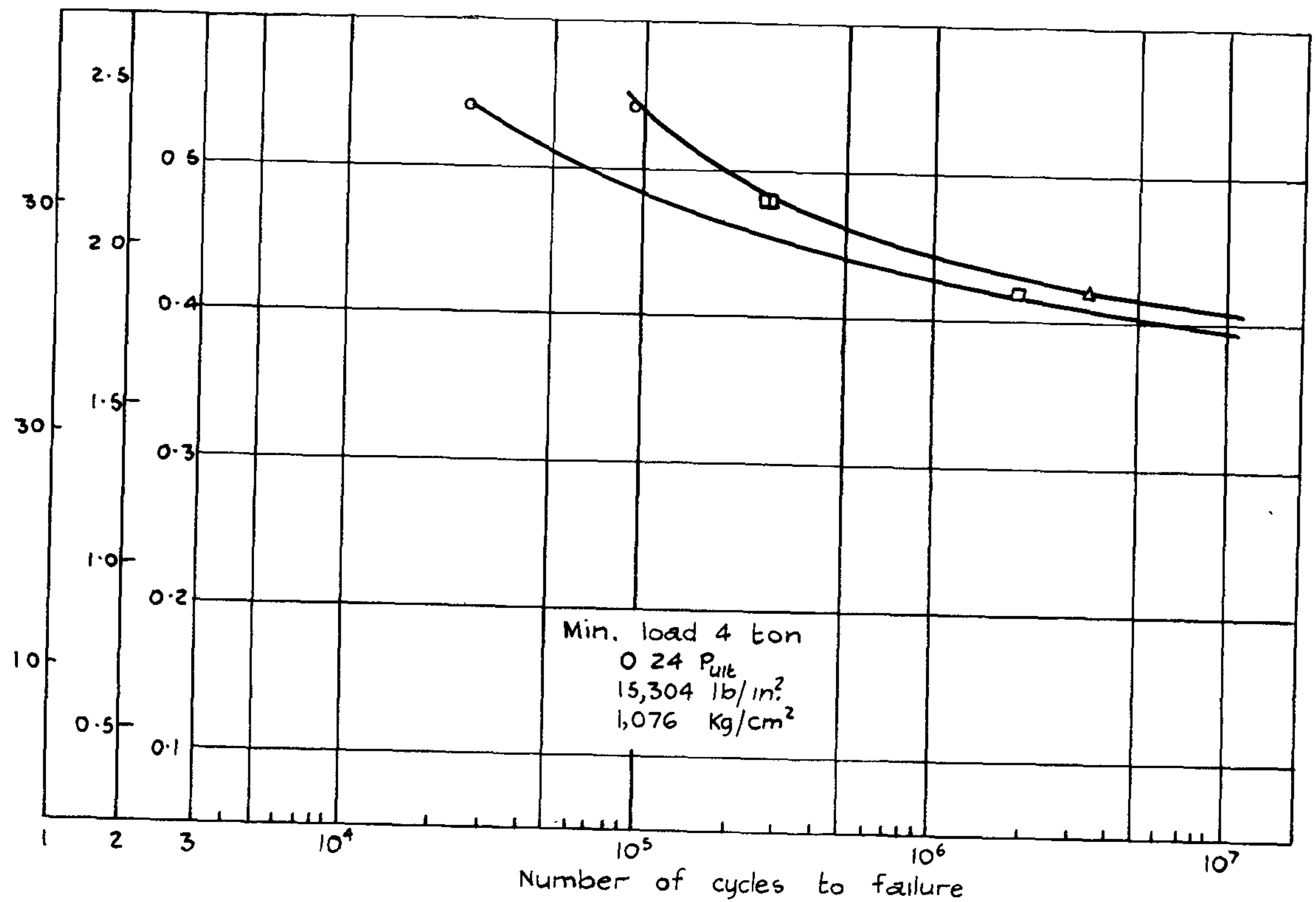


DTD 546 Redux.

FIG. 12



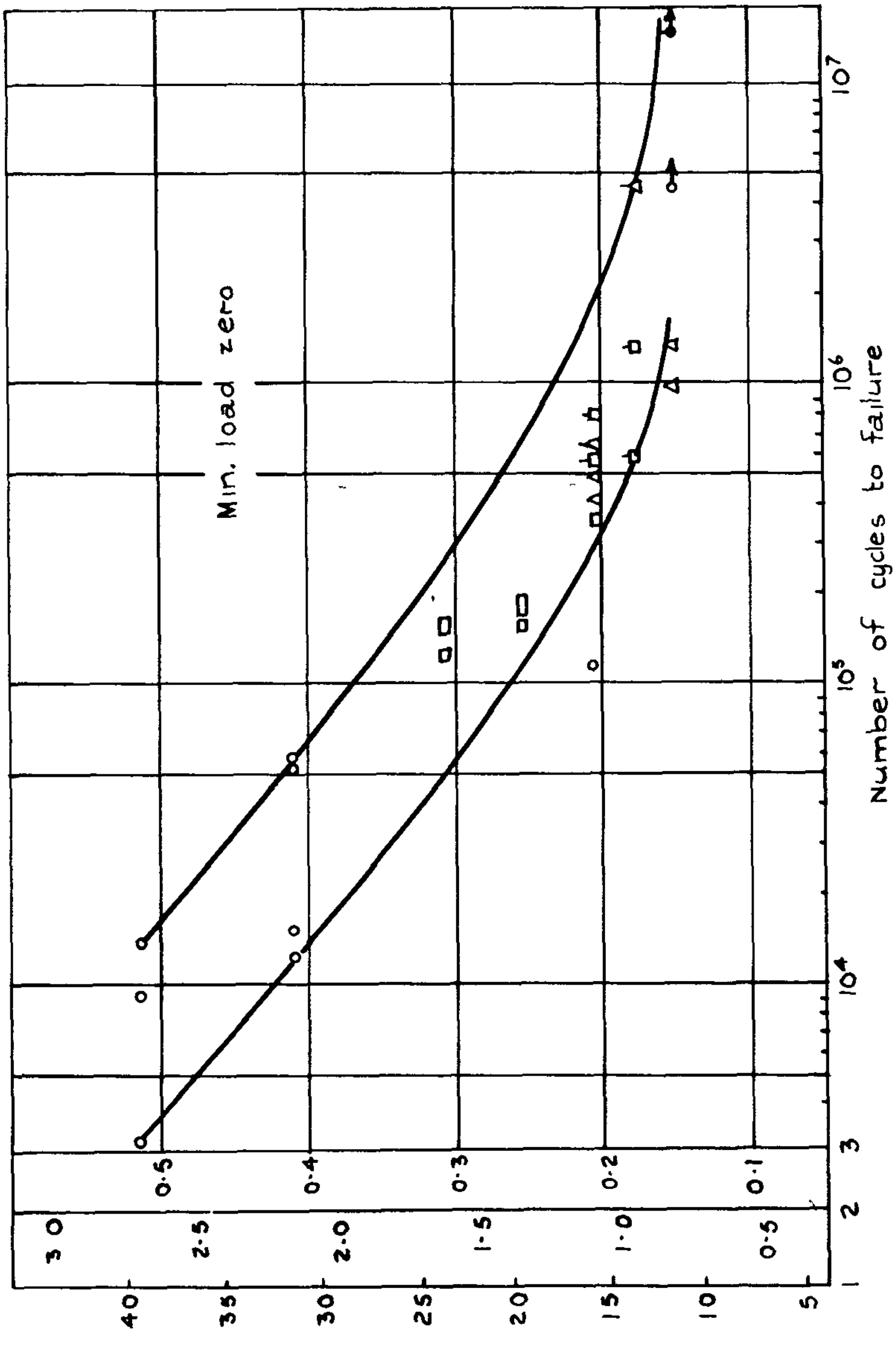
DTD 546 Redux



DTD 546 Redux

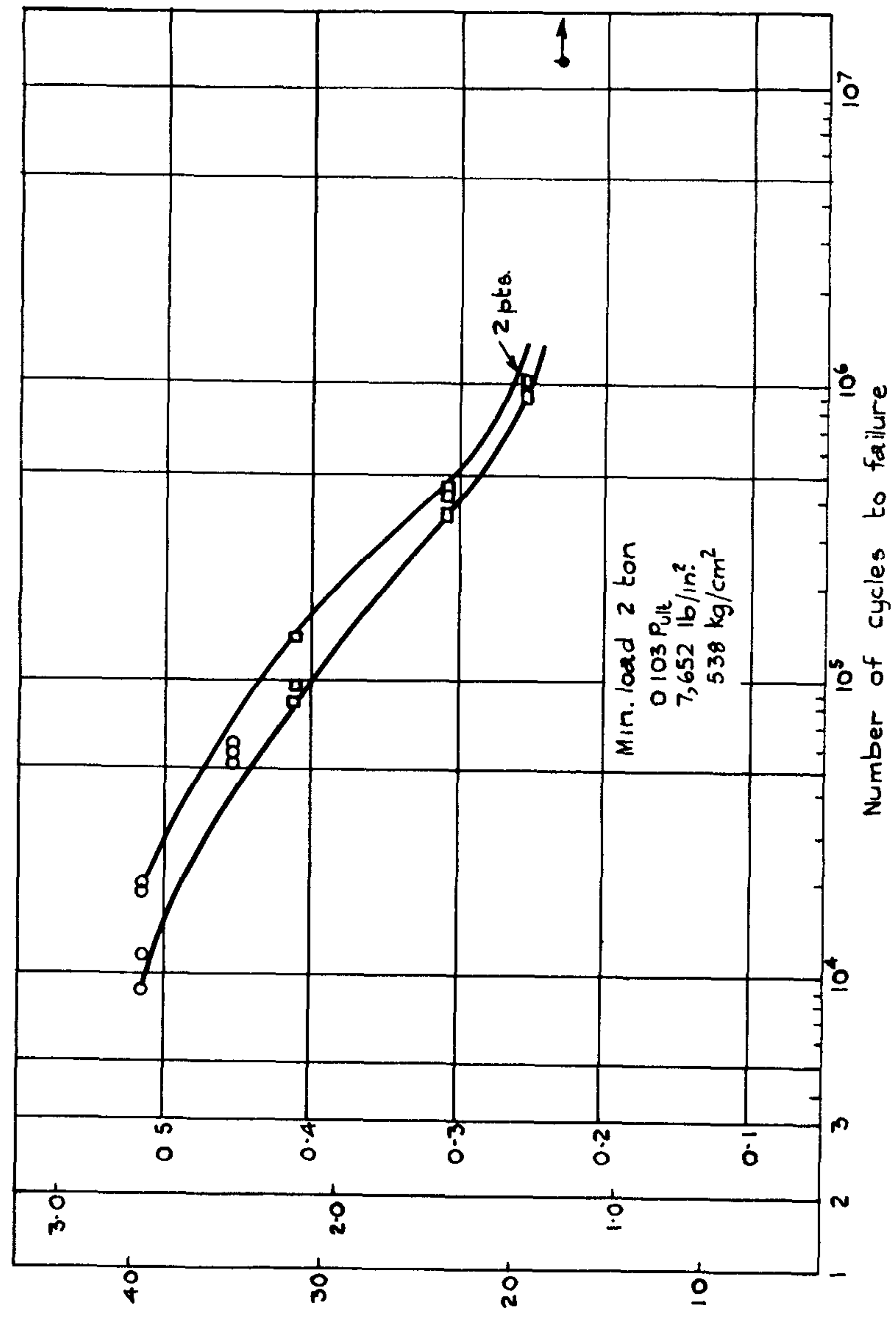
FIG. 13.

FIG. 14.



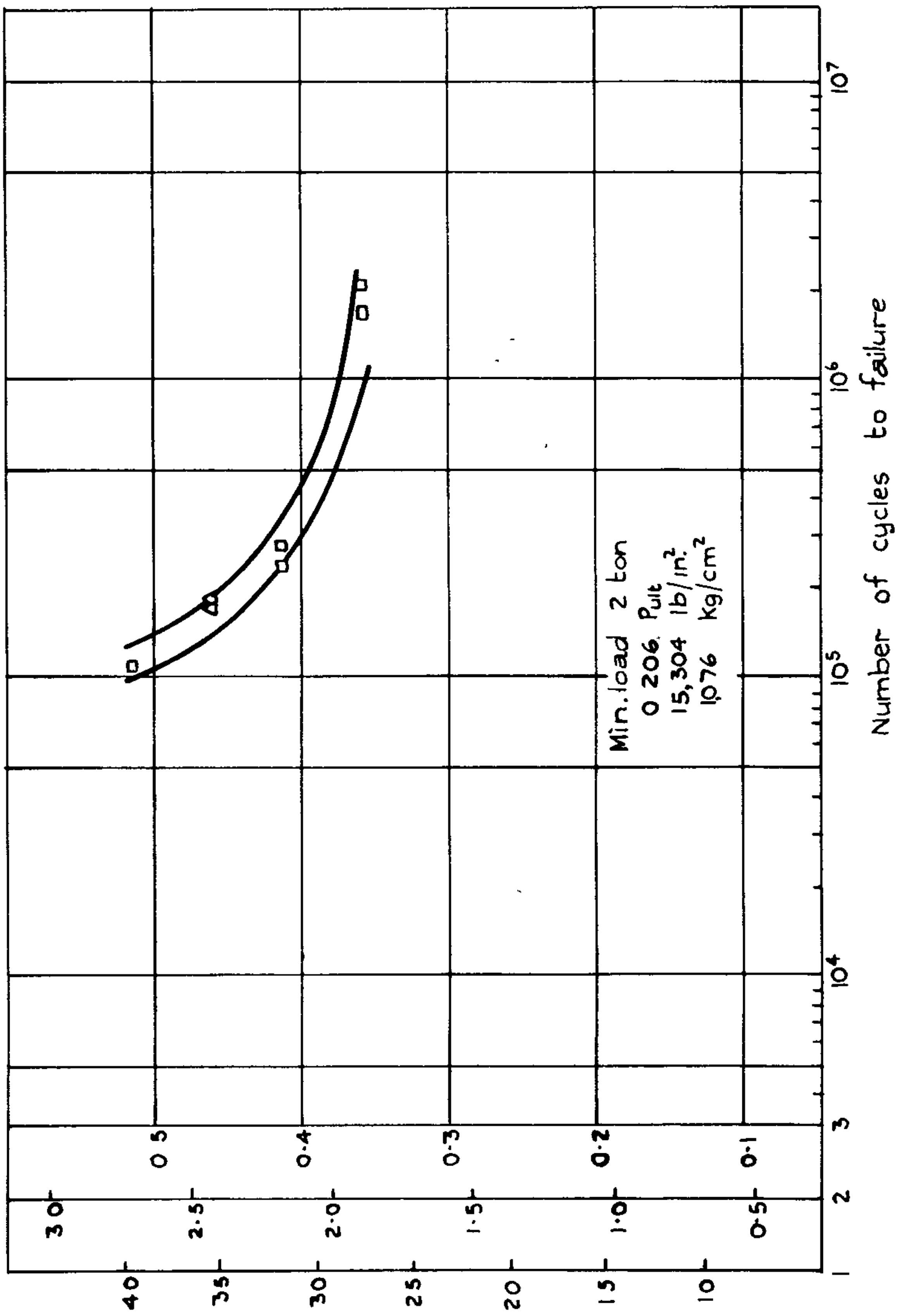
DTD 687 Redux.

FIG 15



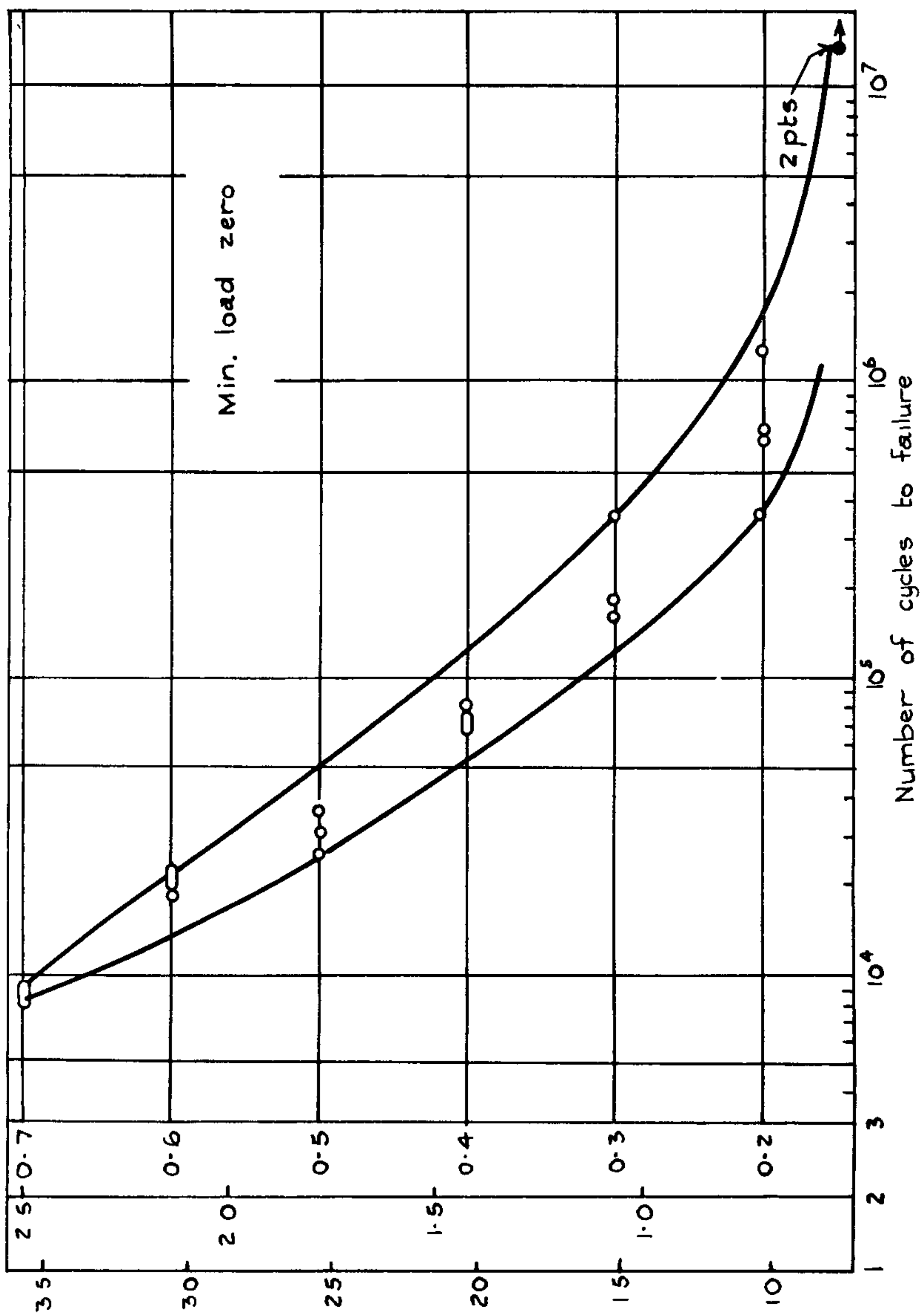
DTD 687 Redux

FIG. 16.



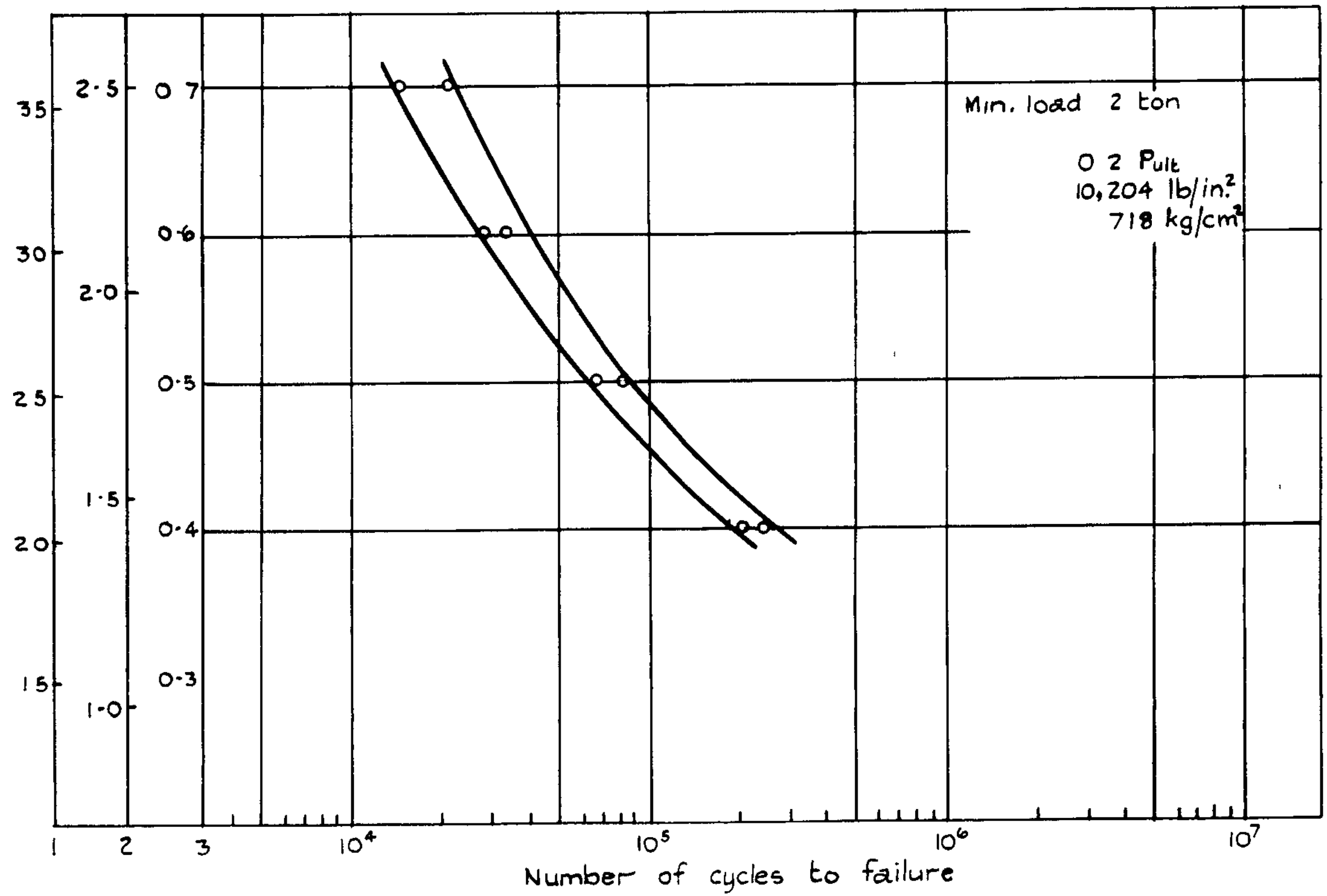
DTD 687 Redux

FIG 17.



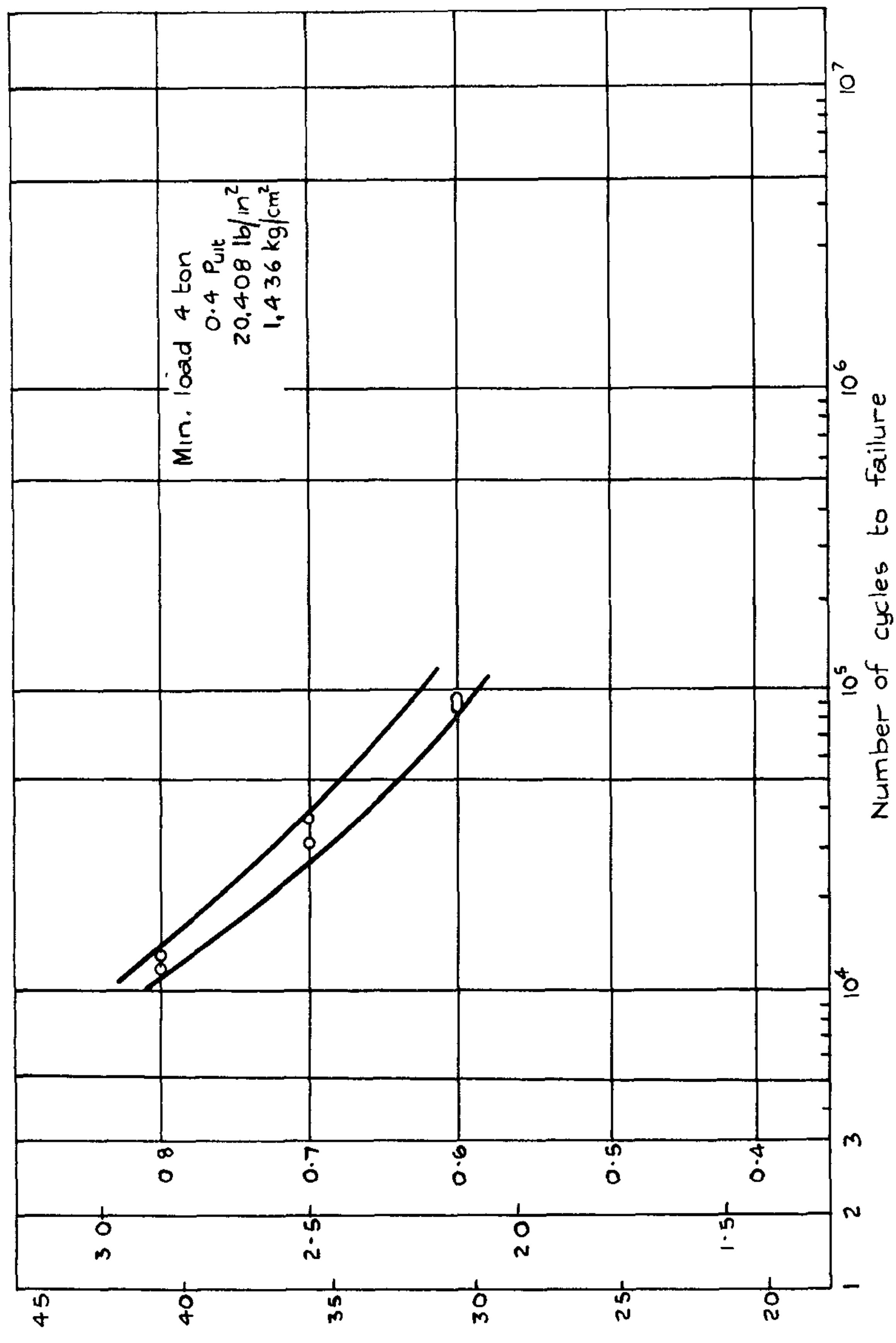
DTD 610 2 row riveted.

FIG. 18.



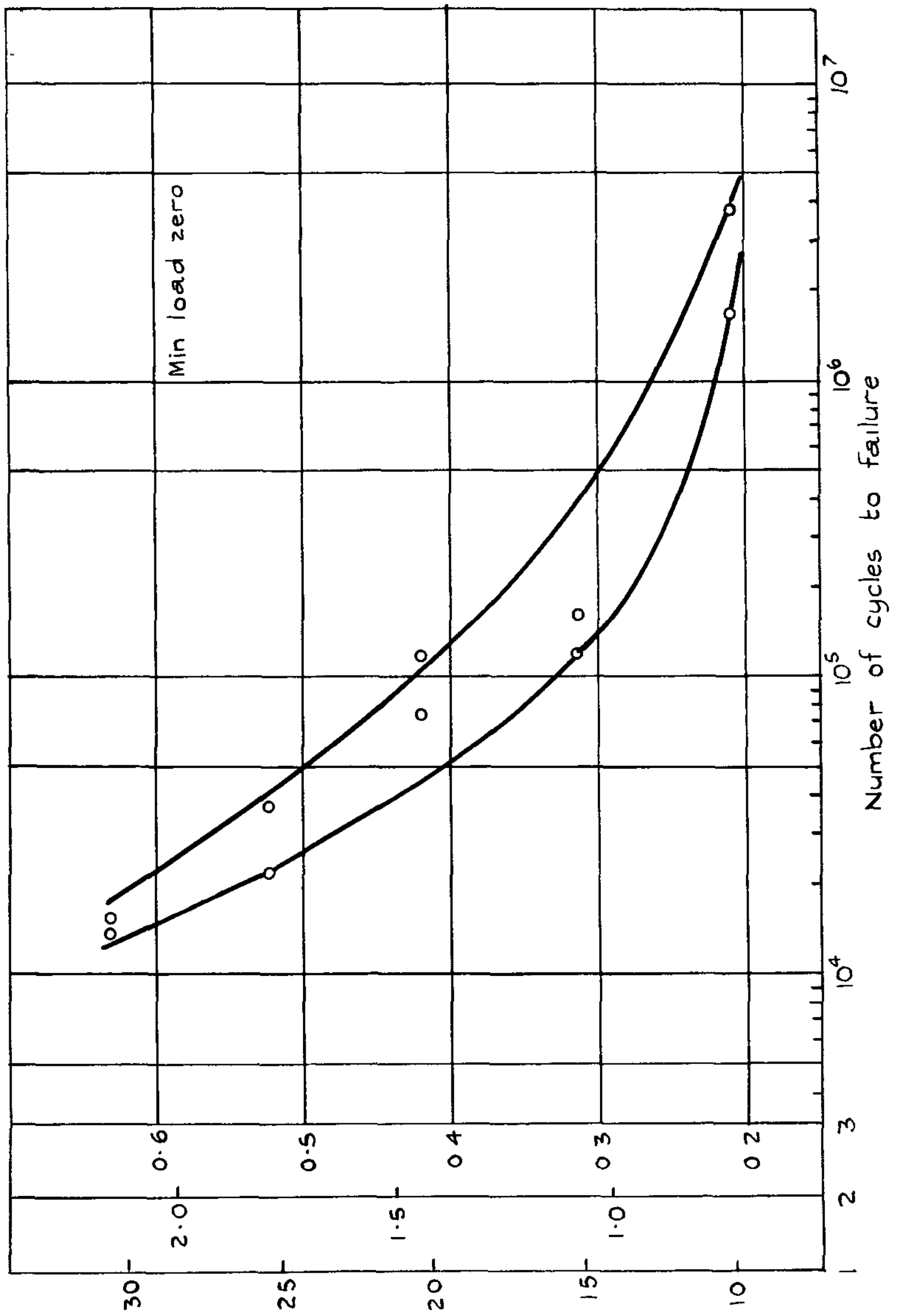
DTD 610 riveted 2 row.

FIG.19



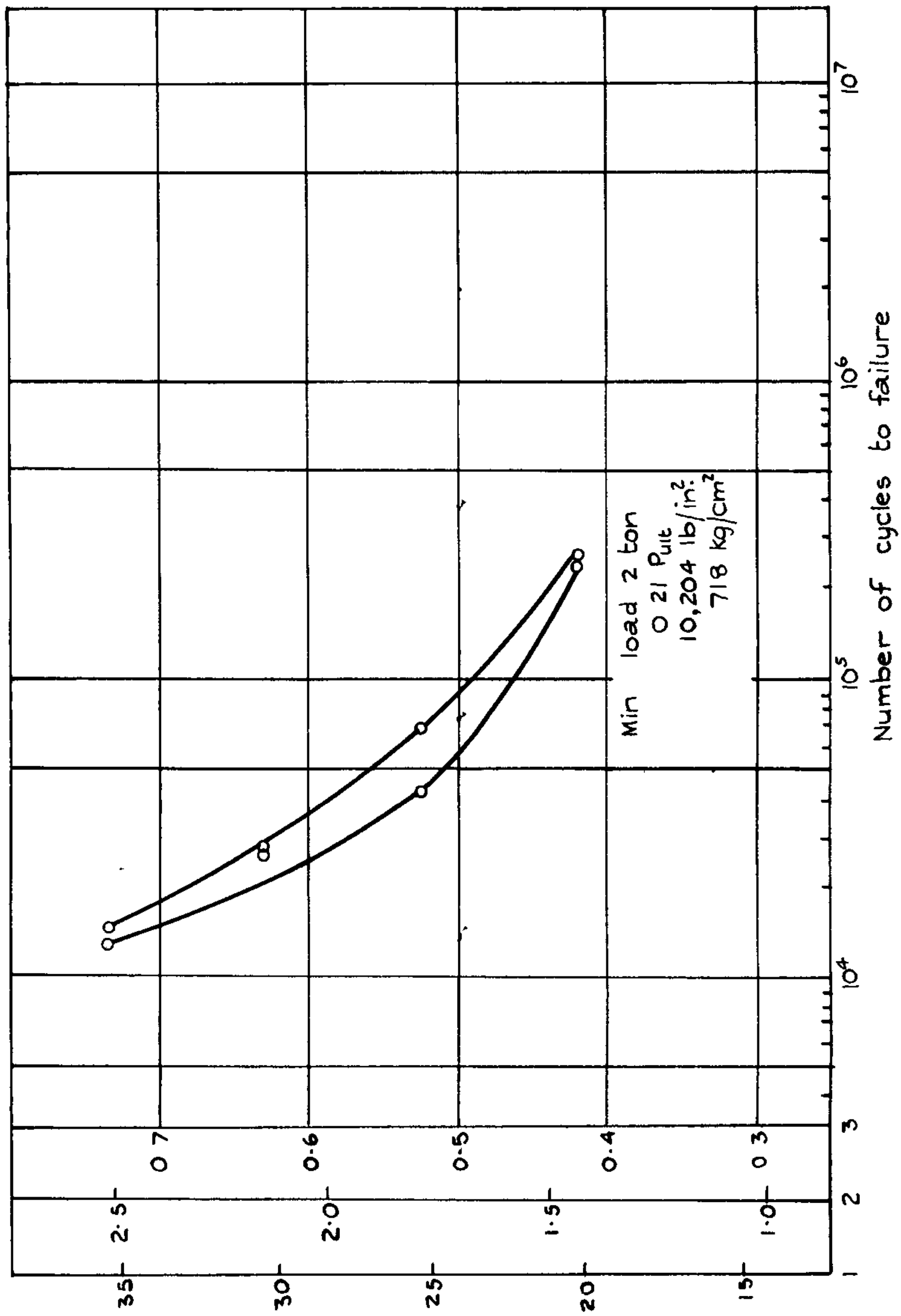
DTD 610 riveted 2 row

FIG 20



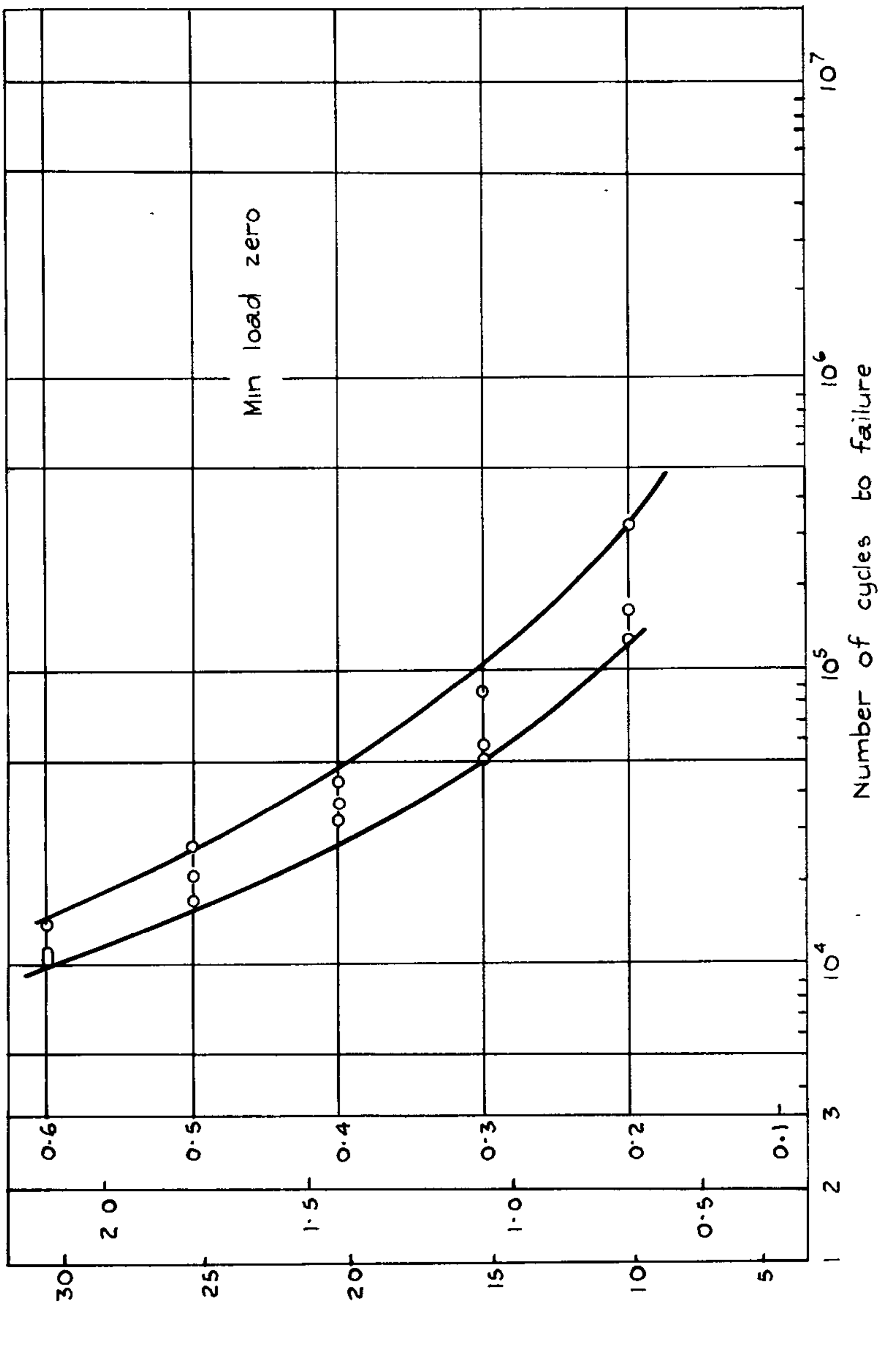
DTD 546 riveted, 2 row

FIG 21

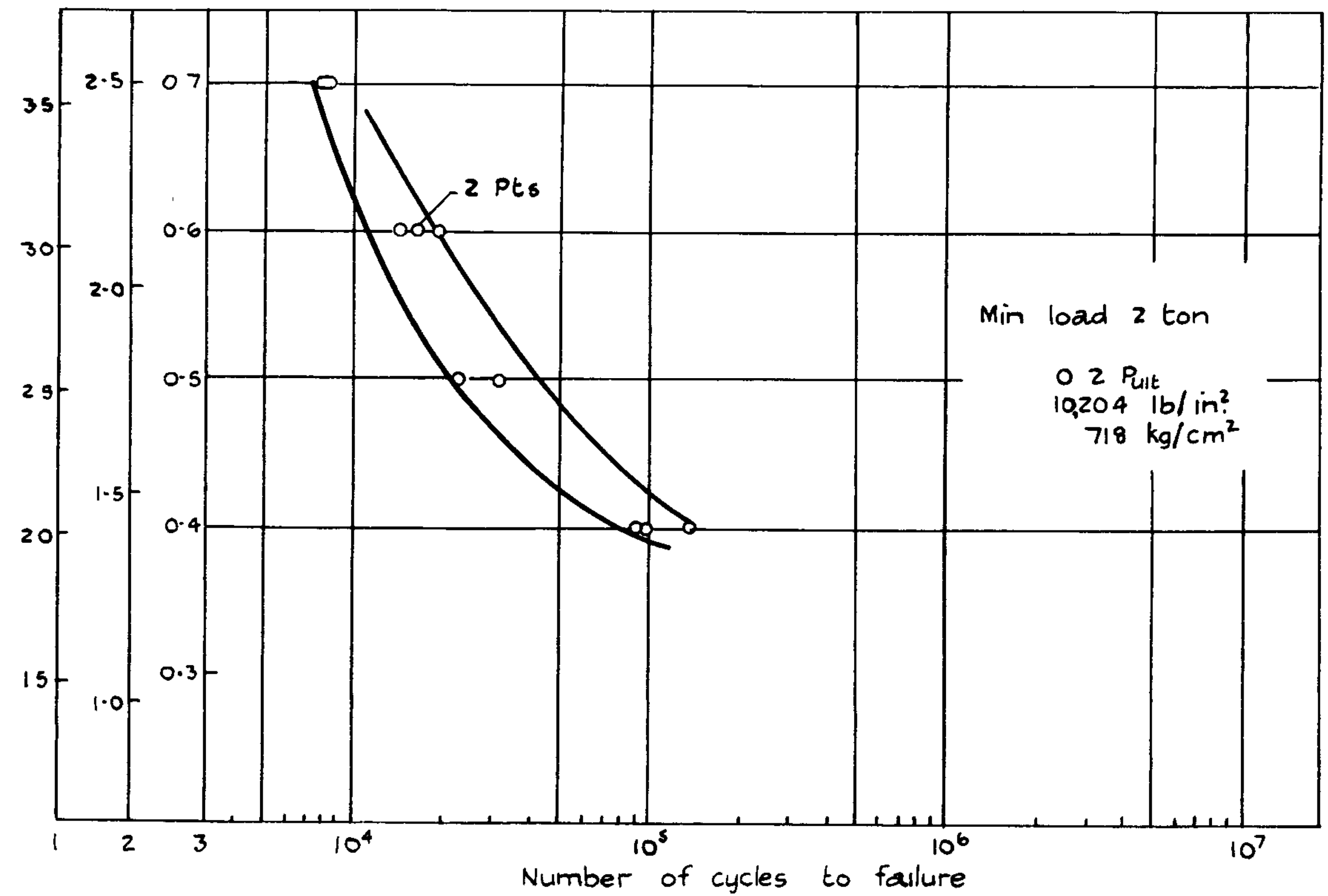


DTD 546 riveted 2 row

FIG 22



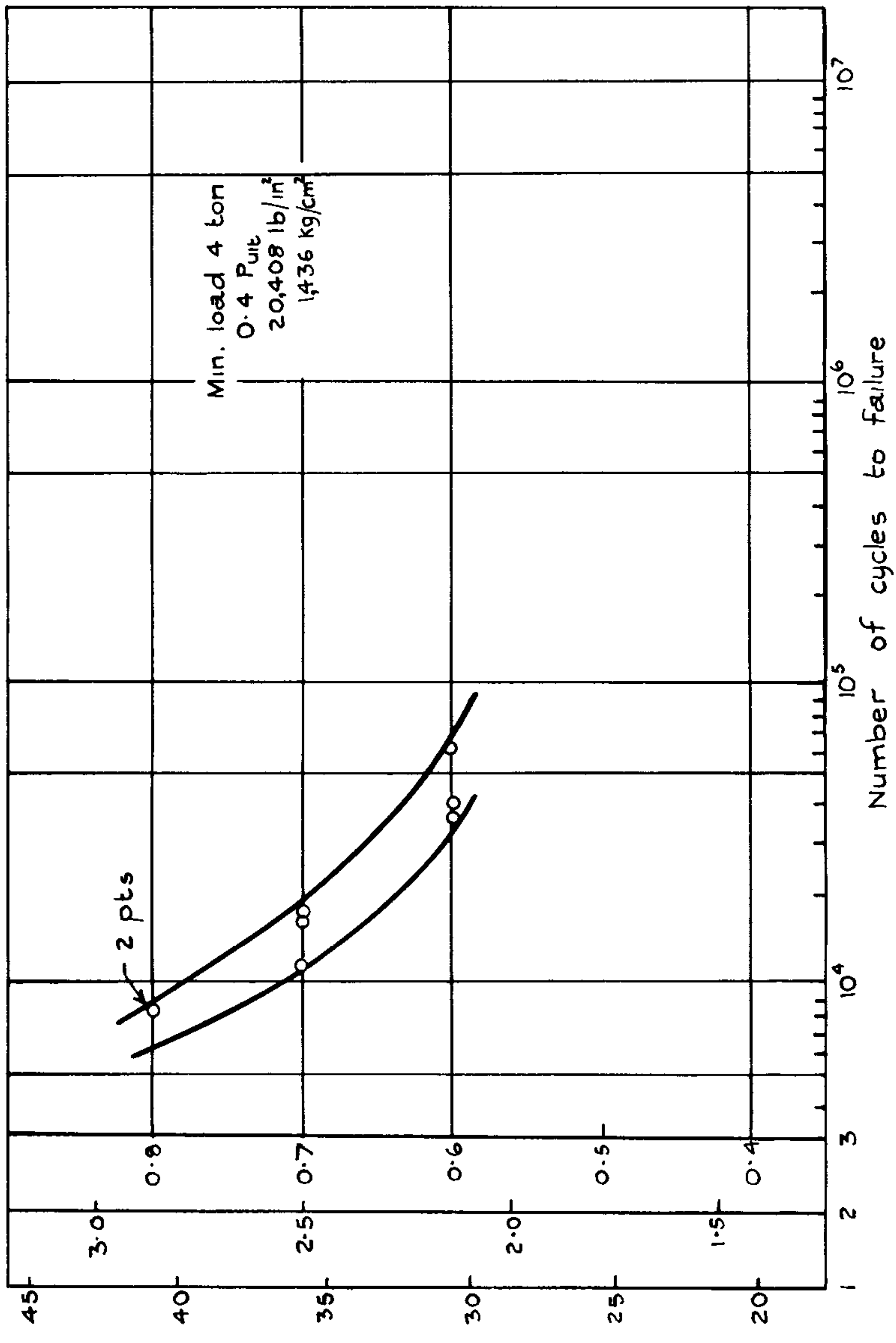
DTD 687 riveted 2 row



DTD 687 riveted 2 row

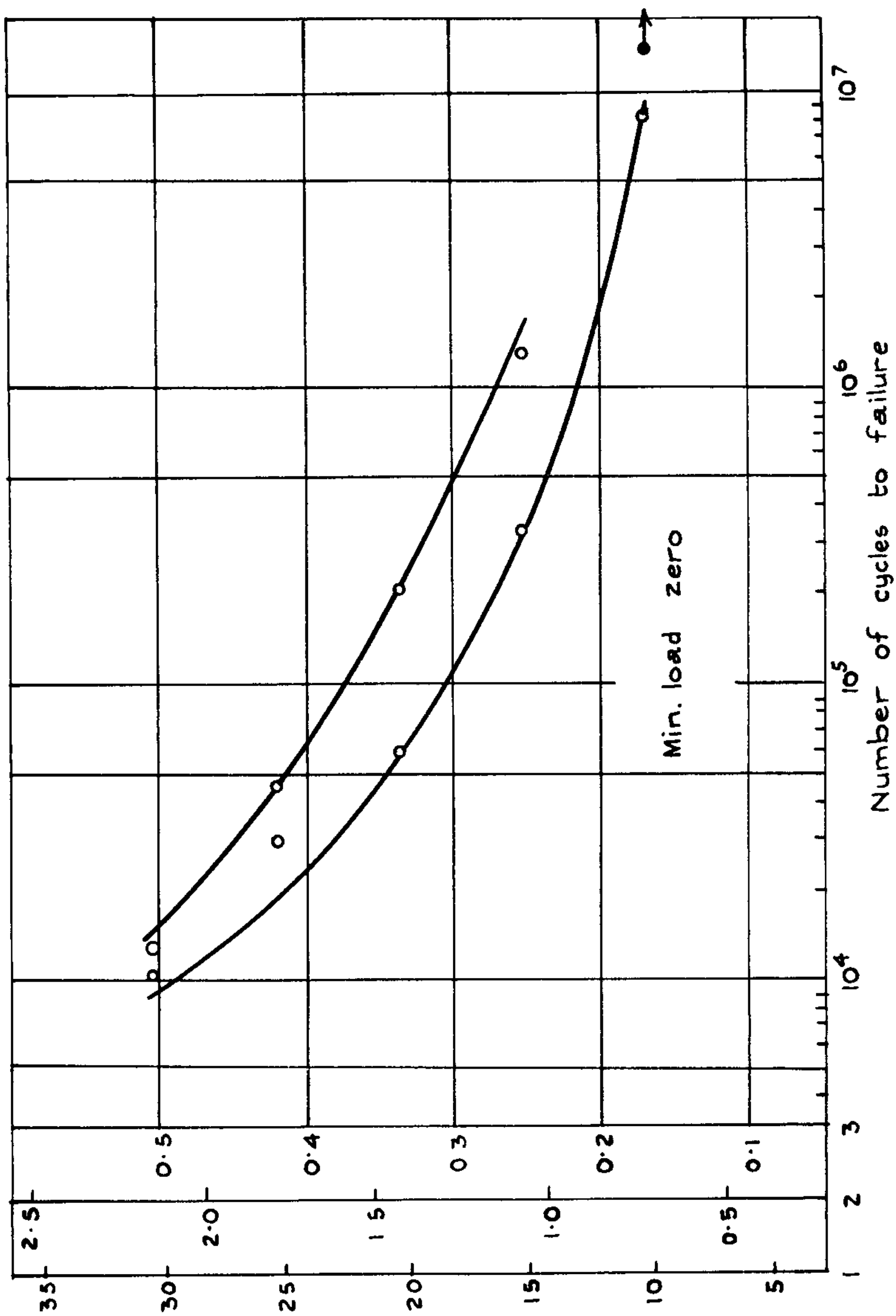
FIG 23

FIG 24

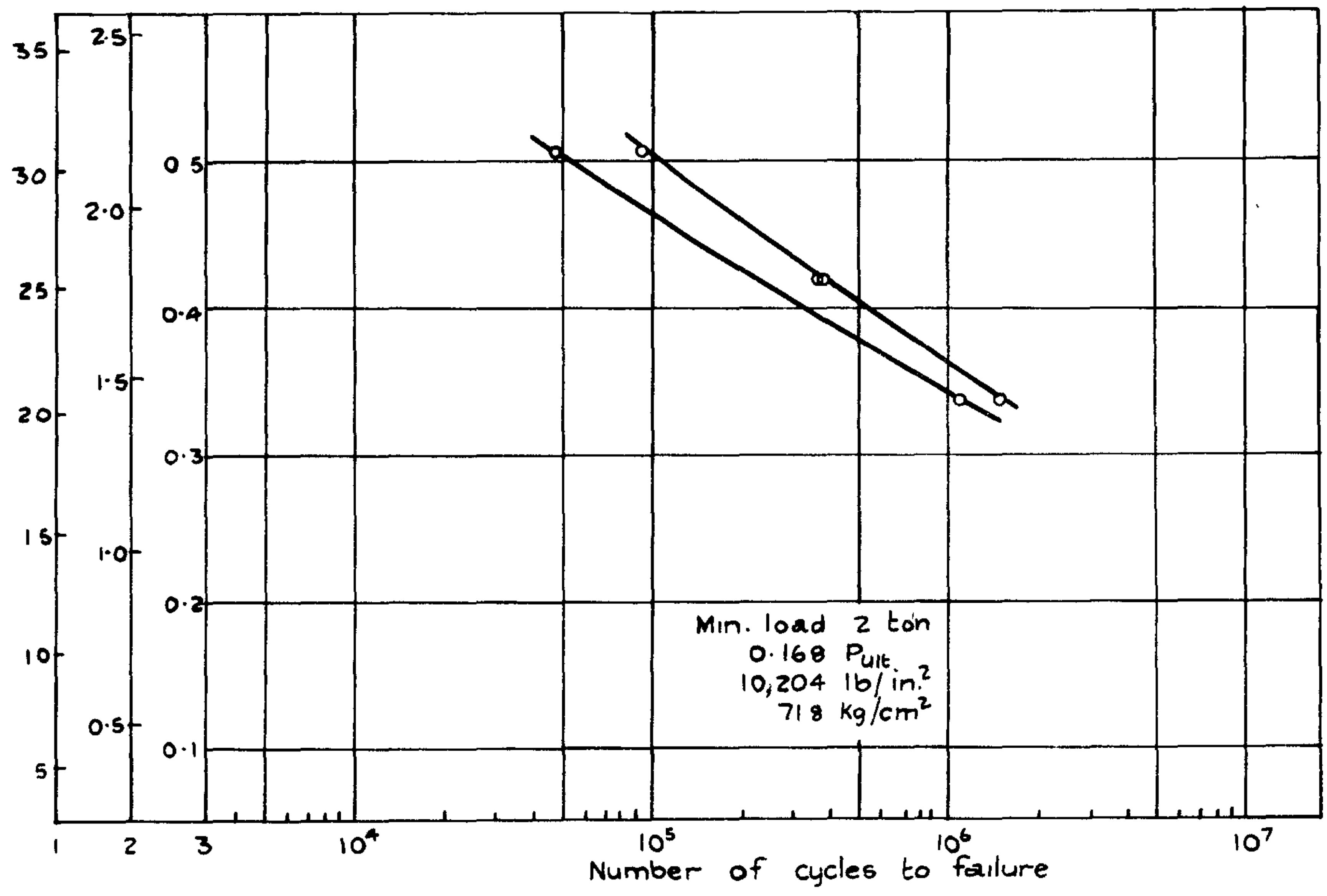


DTD 687 riveted 2 row

FIG 25



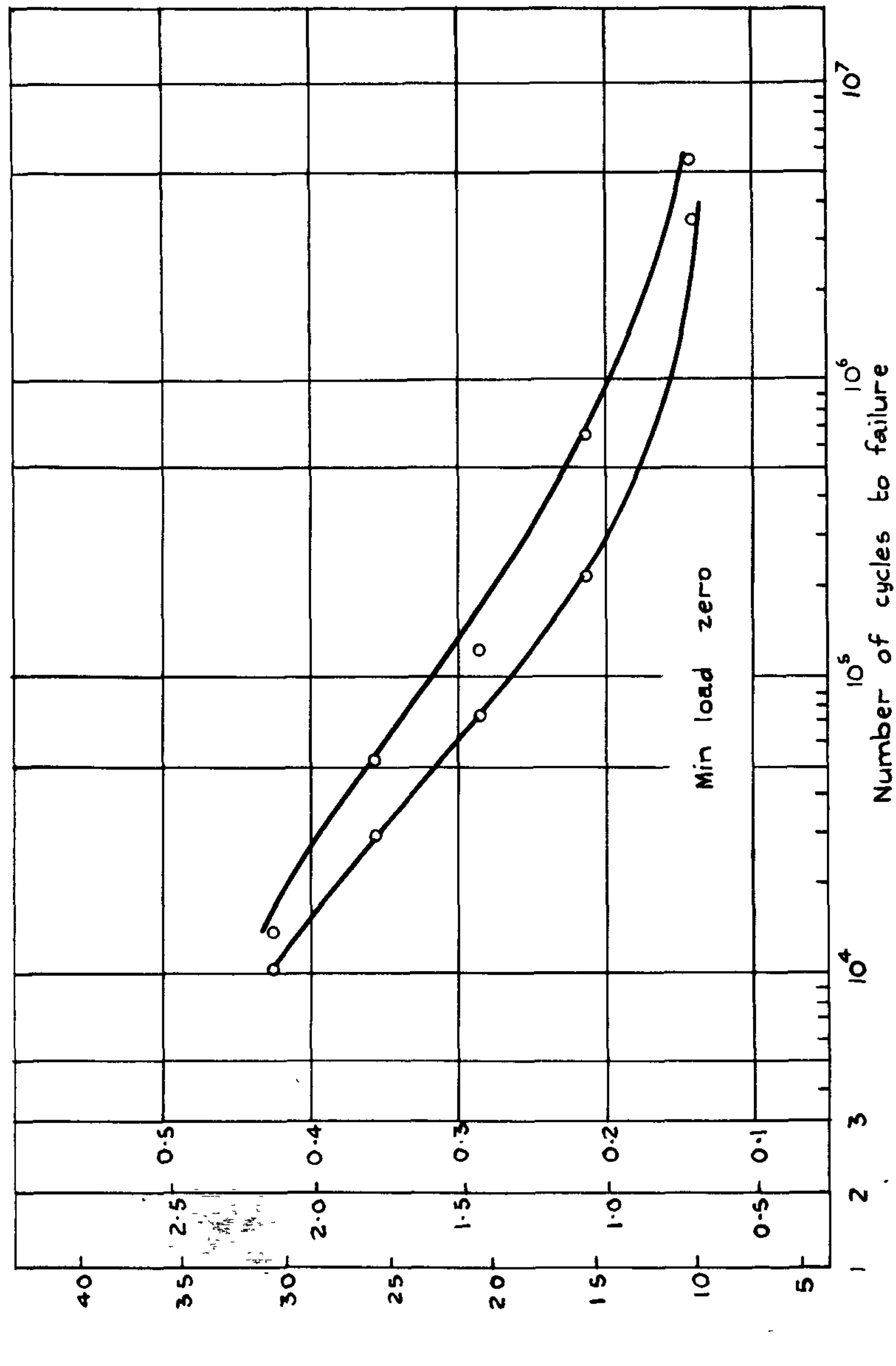
DTD 610 riveted 3 row



DTD 610 riveted 3 row.

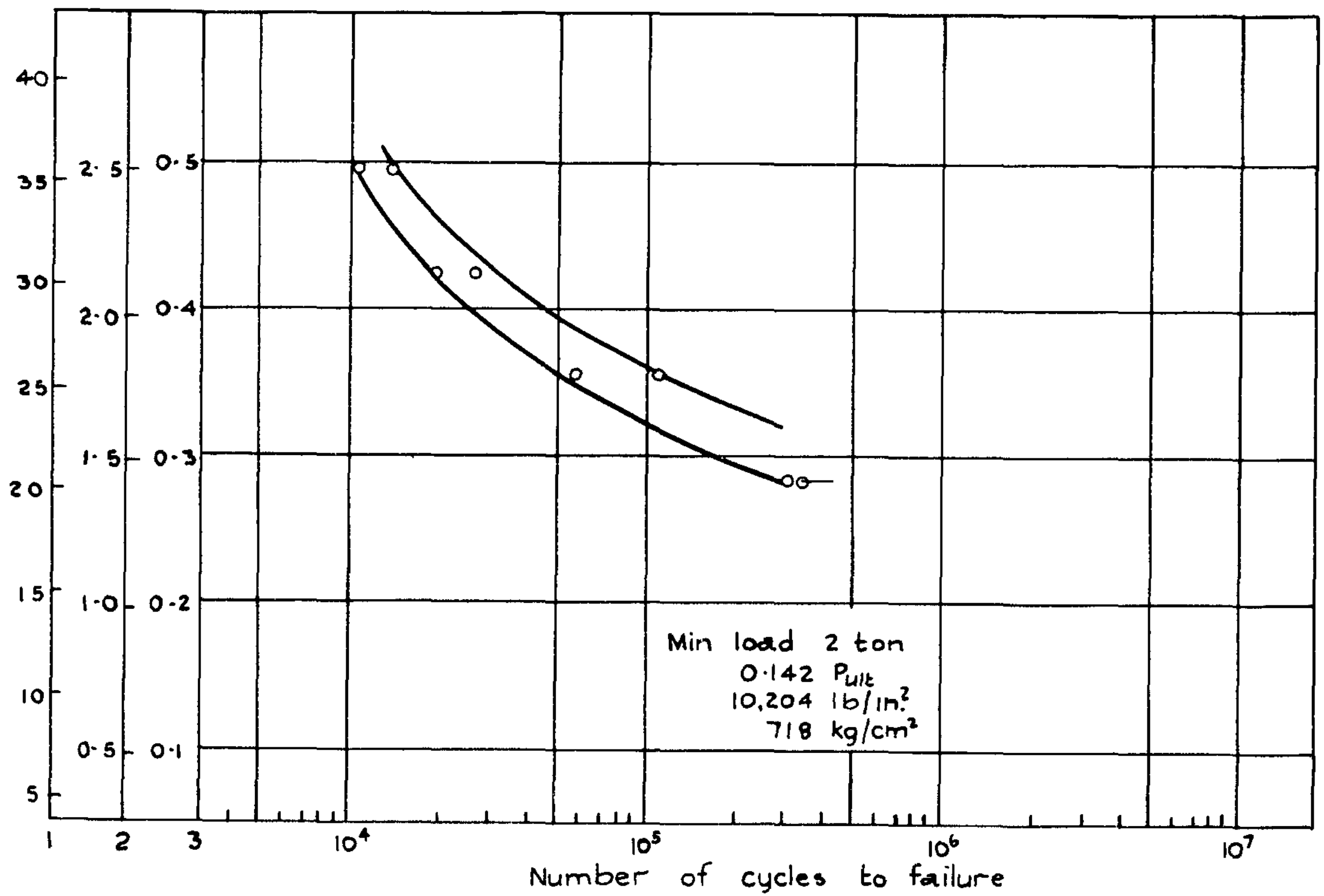
FIG 26

FIG.27.



DTD 687 riveted 3 row

FIG 28



DTD 687 riveted 3 row

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