Stress measurements on Boiler Frames, dated 18th June 1969. Applicable to 15th Class Garratt locomotive No.411 operating on Rhodesia Railways

Notes to readers

The source document for this file was the Office Copy of the Report held in the National Railways of Zimbabwe Drawing Office in Bulawayo. It was discovered, in March 1998, while I was helping with searching for a complete set of drawings of the 15th Class locomotives after No. 398 had been purchased by a private group in New Zealand for eventual export to that country.

The original documents were duplicated copies and photocopies of hand written calculations, hence the slightly indistinct type in some places. These were photocopied (with permission) on to A4 size paper while in the Drawing Office and the photocopies scanned when we were back in New Zealand.

The scanned files have been lightly "Photoshopped" to remove most of the artefacts resulting from the photocopying and scanning processes and to increase the contrast to make them more readable.

Any alterations, amendments or corrections done by hand have all been left in place and this file is a reasonably accurate reproduction of the original.

The original copies of the graphs contained in the report were slightly larger than A4 size and some critical information at the tops of the pages is missing. I have assumed that our copies are filed in the correct order and have marked them 1?, 2?, etc.

I cannot answer any queries regarding the veracity of the tests or the accuracy of the calculations given in this report.

Alan Bailey
December 2010

REPORT TO THE SENIOR MECHANICAL ENGINEER. (DESIGN AND DEVELOPMENT).

CRACKING OF THE 15, 15A CLASS LOCOMOTIVE BOILER FRAME. LOCOMOTIVE TRIAL NO: 270.

1.0. Cracks appeared in the above locomotive boiler frames shortly after entering service. Previous attempts have been made to prevent the cracking (Reference L.T. 238), but have been unsuccessful.

1.1. This investigation was carried out by first determining with strain gauges, the stresses which were causing the frame to crack and then designing the new ends of the frame so that they would be strong enough to withstand these stresses.

2.0. INITIAL TESTS.

Locomotive No. 411 was selected a few days before it entered the Workshops for a General repair. Strain gauges were fitted to the right hand hind end (which are more prone to cracking), and dynamic values were obtained between Bulawayo - Gwelo - Bulawayo. Three gauges were fitted in the region where the cracks occur, as shown in the appendix. One on the top surface, the second one directly below it on the under surface and the third one was on the side of the frame and just next to the second gauge. Unfortunately the frame had a crack which was not visible when the gauges were fitted, it extended 2.1/2" up from the lower surface. This crack prevented the strain being transmitted to the two lower gauges. All the calculations shown in the appendix were therefore based on the results obtained from the top gauge. These calculations determined the dimensions for the new ends which were fitted during the General repair. The drawing numbers of the new ends are: L-7628 and L-7629. Similar new ends were proposed and drawn in 1960 but were never implemented.

3.0. AIMS OF THE DESIGN.

3.1. The depth of the frame where the cracks occur was deepened downwards to give additional strength and also to reduce the large moment, which is produced by the pull of the front unit, and the pivot centre being lower than the centre line of the frame. The effects of this moment were clearly seen on the strain measuring bridge; producing negative readings at position No. 2 and positive at No. 3.

3.2. The deepening of the frame also removed the stress concentration on the lower surface just where the moment in the above paragraph is the largest.

3.3. The lower horizontal stiffening flanges were omitted to enable the frame to bend lateraly without causing high stresses. L.T. 238 showed that these flanges would have to be large, to be of sufficient strength to stop the lateral bending. Therefore, if it wants to flex, let it flex, but keep the stresses to an acceptable limit.

3.4. The small flats on the lower surface at the ends of the frames are for the pedestals in the Workshops.

4.0. Checking the design of the new ends with strain gauges.

Strain gauges were fitted at nine different positions on the new ends as shown on the attached sketch.

4.1. Static Tests.

Static readings were taken as the boiler was lowered into the frame. Some of these readings were high and subsequent tests found three wire contacts to be faulty. The static tests were repeated twice in the running shed by placing jacks under the frame below the fire box and lifting until the pivot centre just lifted free. These two readings agree with each other and gave more realistic figures.

4.2. Dynamic Tests.

The dynamic tests between Gwelo and Bulawayo clearly showed that there were three forces acting on the frame, they were:-

1. The tractive effort from the front unit when the locomotive pulled. This was a steady pull.

2. When the locomotive negotiated a bend and the boiler canted over causing the weight to change on the frame.

3. The out of balance effects of the wheels, i.e. the swaying couple, hammer blow etc., could only be seen on the Oscilloscope, as the frequency at 30 m.p.h. and above was too high to be picked up by the damped needle on the strain measuring bridge. These out of balance forces were always noticeable from about 20 m.p.h. upwards.

4.3. Strain gauge Nos. 8 and 9 were in a rosette, to measure the shear stresses.

5.0. Results.

The results of the static and three dynamic readings were plotted on the attached graphs, and their resultants were obtained for the Goodman fatigue graphs. The factor of safety is shown on each graph.

The strain gauges at positions 5, 6 and 7 were to see if the frame bent lateraly in an even curve and did not have a "hinging" effect at a point. The results showed that there is slightly more bending nearer the firebox than towards the pivot centre, but the stress from this bending is acceptable.

6.0. Conclusion.

The results show that the stresses in the new ends are acceptable and that the factors of safety are in the order of two, which was what they were designed for.

The tractive effort stresses will be slightly higher when hauling a full load as the load hauled during the test was only 484 tons x 52 and the full load is 1000 x 30.

Further strain gauge tests will be conducted later as the locomotive wears.

3/.........

7.0. Recommendations.

7.1. Locomotive No. 411 should be fitted with the modified rounded brick arch (The "Rees" brick arch). Some 9th Class locomotive bricks have been cut which will give the desired shape. This locomotive should then be put on a 12, or if possible, 15 day tube blow period so that the maximum number of miles per month can be obtained.

7.2. When the "Star Jet" blast pipe cap has been made; also fit it to this locomotive in order to determine what benefits can be achieved by introducing these modifications and then assess whether their expenses are necessary.

W.A. O'Shann.
ASSISTANT MECHANICAL ENGINEER.
(DESIGN AND DEVELOPMENT).

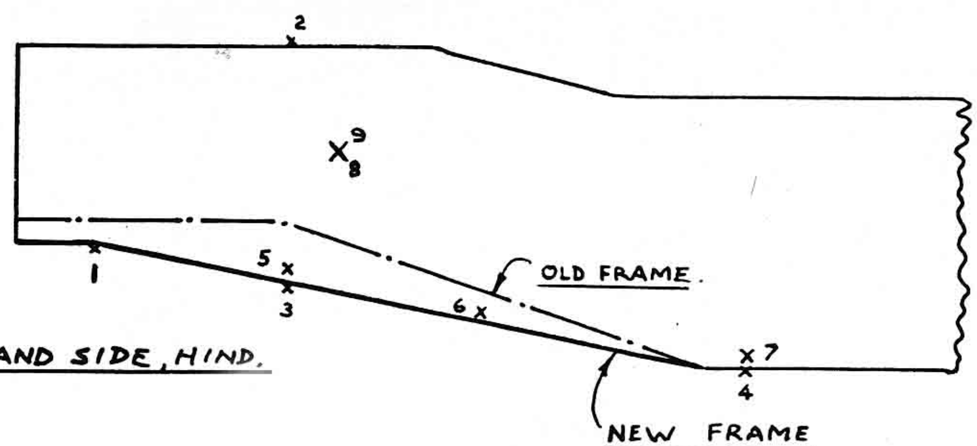
Ref: M.6.

18th June, 1969.

AMED/jd

X. POSITIONS OF STRAIN GAUGES.

8 & 9 IS A STRAIN ROSETTE. THE LINES SHOW THE ANGLES.



RIGHT HAND SIDE, HIND.

SKETCH SHOWING THE STRAIN GAUGE POSITIONS ON THE NEW FRAME.

RESULTS OBTAINED FROM THE STRAIN GAUGES.

INITIAL TESTS BEFORE GENERAL. REPAIR		
BRIDGE READING.	STRESS	REMARKS.
-1·0	- 3000 psi	STARTING.
-2·8	- 8,400 psi.	PULLING 20 mph.
+1·5	4,500 psi	" "
-3·0	-9,000 psi	" 30 mph
-2·5	-7,500 psi	" " "
+1·5	4500 p.si.	COASTING " "
-2·0	-6000 psi	" 35 "
* +3·0	9,000 psi.	BRAKING 20 mph.
-1·5	-4500 psi	COASTING 15 mph.
* -4·0	-12,000 psi.	PULLING 15 mph.
-3·6	-10,800 psi.	PULLING 20 mph.

OLD FRAME

STATIC TESTS IN RUNNING SHEDS.				
POSITION.	BRIDGE READING.		STRESS.	
	TEST 1	TEST 2	TEST 1.	TEST 2
1	-0·5	+0·6	-1500 psi.	1800 p.si.
2	-0·5	+0·5	-1500 psi.	1500 p.si.
3	-0·7	+0·8	-2100 psi	2400 p.si.
4	-3·9	+4·0	-11700 psi	12,000 psi.
5	-0·8	+0·8	-2400 psi	2400 psi.
6	-2·6	+2·7	-7800 psi	8100 psi.
7	-3·8	+3·8	-11,400 psi	11,400 psi.
8	-0·6	+0·5	-1800 psi	1500 psi.
9	+0·7	-0·6	+2100 psi.	-1800 psi.

TEST 1. WERE STRESSES RELIEVED BY JACKING UP THE BOILER.
TEST 2. WERE " IMPOSED BY RELIEVING THE JACKS.

DYNAMIC TESTS. TRAIN 8 UP. LOAD 484 x 52. 10/6/69.			
POSITION	TRACTIVE EFFORT.	BANKS & CURVES.	WHEEL OUT OF BALANCE.
1	1500 psi.	± 1800 psi.	± 600 psi.
2	3300 psi	± 1800 psi.	± 1500 psi
3	4200 psi	± 1800 psi.	± 1500 psi
4	1200 psi	± 1500 psi	± 1200 psi
5	4200 psi	± 1900 psi	± 1800 psi
6	2700 psi	± 1500 psi	± 1800 psi
7	1800 psi	± 1200 psi	± 1800 psi
8		± 1500 psi	± 1500 psi.
9		± 1500 psi	± 1500 psi.

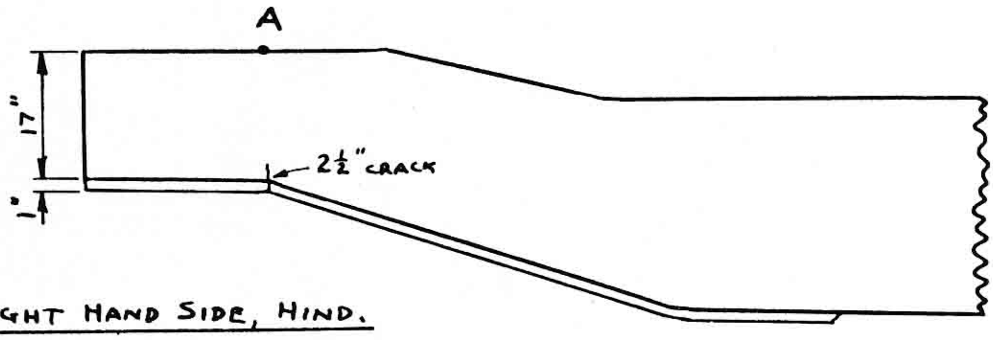
NEW FRAME

MAXIMUM SHEAR STRESS AT 8 OR 9 : 2100 + 1500
= 3600 psi. Acceptable

STRESSES RECORDED ON LOCOMOTIVE Nº 411 PRIOR TO THE BOILER FRAME MODIFICATION. TRAIN 8UP. LOAD 980 x 80.

MAXIMUM STRESSES RECORDED AT POSITION "A"

- 12,000 p.s.i.
+ 9,000 p.s.i. } DYNAMIC ONLY.



RIGHT HAND SIDE, HIND.

CALCULATIONS TO DETERMINE THE DEPTH OF THE NEW FRAME, SO THAT IT WILL GIVE A FACTOR OF SAFETY OF 2. AT THE SECTIONS WHERE THE FRAMES CRACK.

EXISTING FRAME.

EFFECTIVE DEPTH OF CRACKED FRAME = 18" - 2½" = 15.5"

$$I = \frac{1 \times 15.5^3}{12} = 373 \text{ ins}^4.$$

FULL BEAM WITH NO FLANGE.

$$I = \frac{1 \times 17^3}{12} = 500 \text{ ins}^4.$$

DYNAMIC BENDING MOMENTS TO PRODUCE THE RECORDED STRESSES.

$$\text{MAX.} = -\frac{373 \times 12000}{7.75 \times 2240} = \frac{I f}{y} = -258 \text{ Ton ins.}$$

$$\text{MIN.} = +\frac{373 \times 9000}{7.75 \times 2240} = +193.2 \text{ Ton ins.}$$

∴ THESE B.M. WOULD PRODUCE THE FOLLOWING STRESSES IN A 17" FRAME.

$$\text{STRESSES IN FULL FRAME} = -\frac{258 \times 8.5}{500} = -4.4 \text{ Tons/in}^2$$

$$= -9,860 \text{ p.s.i.}$$

$$= +\frac{193.2 \times 8.5}{500} = 3.28 \text{ Tons/in}^2.$$

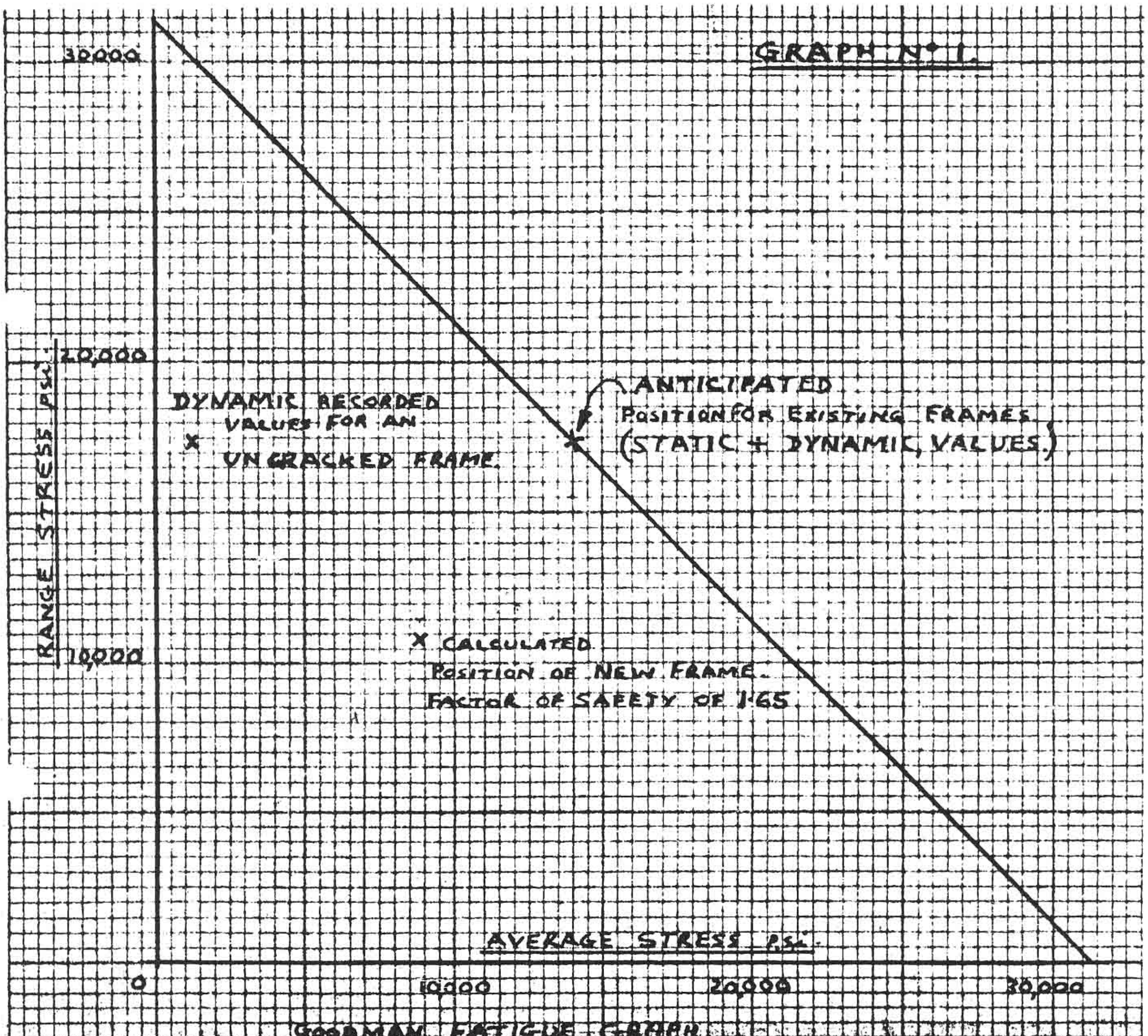
$$= 7350 \text{ psi.}$$

∴ RANGE STRESS = (−9860) + (7350) = 17,210 psi

AVERAGE STRESS = $\frac{17210}{2}$ − 9860 = −1260 psi

WHICH WILL BE +ve IF CONSIDERED ON THE LOWER SURFACE.

THESE TWO VALUES WHERE PLOTTED ON THE ATTACHED GOODMAN FATIGUE GRAPH. AS SHOWN. GRAPH No1.



GOODMAN FATIGUE GRAPH

NOW THESE FRAMES DO CRACK, ∴ THE STATIC STRESSES FROM THE WT. OF THE BOILER MUST INCREASE THE AVERAGE STRESS BY AT LEAST 14,000 − 1260

= 12740 psi.

∴ B.M FROM STATIC LOAD = $\frac{500 \times 12740}{8{\cdot}5 \times 2240}$ = 335 Ton ins.

B.M. FROM AVERAGE DYNAMIC STRESSES.

$$= \frac{500 \times 1240}{8.5 \times 2240} = \underline{33 \text{ Ton ins.}}$$

TOTAL AVERAGE BM. : 335 + 33 = 368 Ton ins.

Now $\frac{M}{I} = \frac{f}{y} = \frac{12M}{1 \times d^3} = \frac{2f}{d}$

$\therefore d^2 = \frac{12M}{2f}$ where d is the depth of the beam.

& f is the allowable average stress for a Factor of Safety of 2.

ie $f = 7,000$ psi.

$$\therefore d^2 = \frac{12 \times 368}{2 \times 7000} = 7,070 \text{ in}^2$$

$$d = \underline{26.5''}$$

NOW THIS 26.5" DEPTH WILL ALSO DECREASE THE RANGE STRESS AND ∴ INCREASE THE FACTOR OF SAFETY GREATER THAN 2, AND IS NOT NECESSARY.

∴ TRY $d = 23.5''$

$$I = \frac{1 \times 23.5^3}{12} = 1084 \text{ ins}^4$$

$$y = \quad = 11.75 \text{ ins.}$$

AVERAGE B.M. = 368 Ton ins.

$$\therefore \text{AVERAGE STRESS} = \frac{368 \times 2240 \times 11.75}{1084} = \underline{8,940 \text{ psi}}$$

TO FIND RANGE STRESSES WHEN B.M's = +258 Ton ins
−193.2 Ton ins.

$$\therefore \text{MAX. STRESS} = \frac{258 \times 2240 \times 11.75}{1084} = \underline{6,270 \text{ psi.}}$$

$$\text{MIN. STRESS} = \frac{-193.2 \times 2240 \times 11.75}{1084} = \underline{-4,680 \text{ psi.}}$$

$$\therefore \text{RANGE STRESS} = 6270 - (-4680)$$

$$= \underline{10,950 \text{ p.si.}}$$

THESE WERE PLOTTED ON THE GRAPH Nº1. TO GIVE A FACTOR OF SAFETY OF 1.65. WHICH BY REDUCING THE STRESS CONCENTRATION, SHOULD PRODUCE A VALUE OF 2.

B.M. FROM AVERAGE DYNAMIC STRESSES.

$$= \frac{500 \times 1240}{8 \cdot 5 \times 2240} = \underline{33 \text{ Ton ins.}}$$

TOTAL AVERAGE BM. : 335 + 33 = 368 Ton ins.

Now $\frac{M}{I} = \frac{f}{y} = \frac{12\,M}{1 \times d^3} = \frac{2f}{d}$

$$\therefore d^2 = \frac{12\,M}{2f}$$

where d is the depth of the beam.
& f is the allowable average stress for a Factor of Safety of 2.
ie f = 7,000 psi

$$\therefore d^2 = \frac{12 \times 368}{2 \times 7000} = 7070 \text{ in}^2$$

$$d = \underline{26 \cdot 5''}$$

NOW THIS 26·5" DEPTH WILL ALSO DECREASE THE RANGE STRESS AND ∴ INCREASE THE FACTOR OF SAFETY GREATER THAN 2, AND IS NOT NECESSARY.

∴ TRY d = 23·5"

$$I = \frac{1 \times 23 \cdot 5^3}{12} = 1084 \text{ ins}^4.$$

$$y = \quad = 11 \cdot 75 \text{ ins.}$$

AVERAGE B.M. = 368 Ton ins.

$$\therefore \text{AVERAGE STRESS} = \frac{368 \times 2240 \times 11 \cdot 75}{1084} = \underline{8{,}940 \text{ psi}}$$

TO FIND RANGE STRESSES WHEN B.M's = +258 Ton ins
−193·2 Ton ins.

$$\therefore \text{MAX. STRESS} = \frac{258 \times 2240 \times 11 \cdot 75}{1084} = \underline{6{,}270 \text{ psi.}}$$

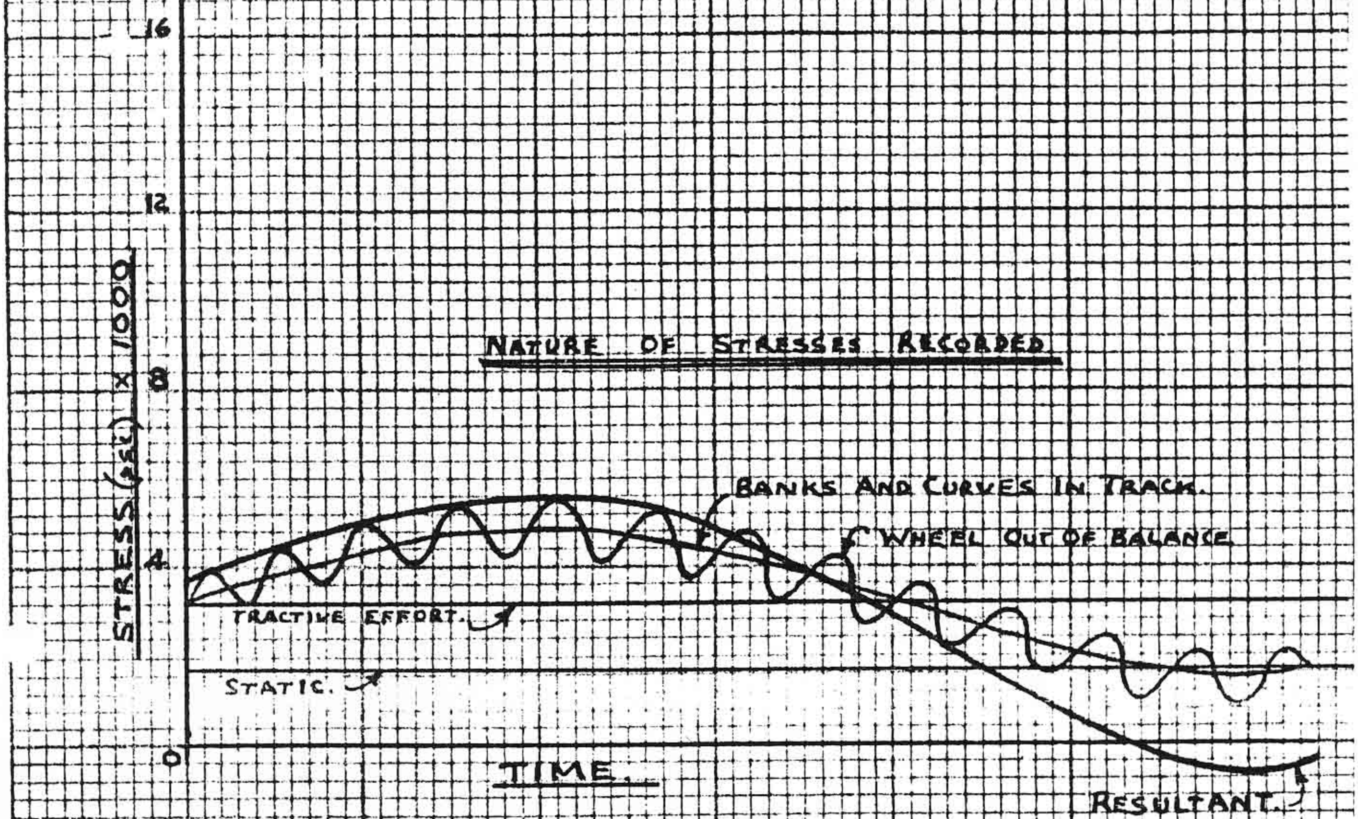
$$\text{MIN. STRESS} = \frac{-193 \cdot 2 \times 2240 \times 11 \cdot 75}{1084} = \underline{-4{,}680 \text{ psi.}}$$

$$\therefore \text{RANGE STRESS} = 6270 - (-4680)$$

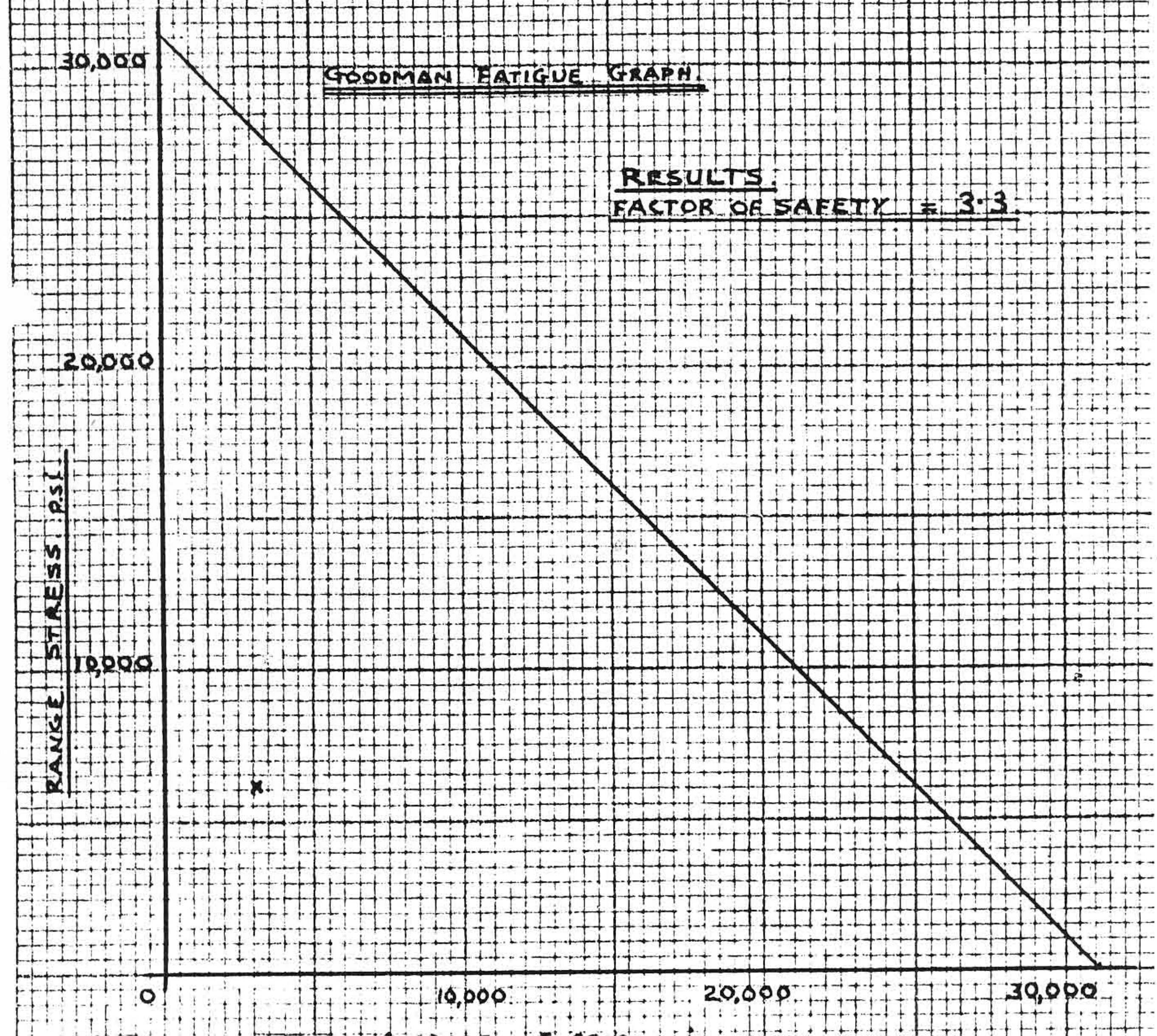
$$= \underline{10{,}950 \text{ p.si.}}$$

THESE WERE PLOTTED ON THE GRAPH No 1. TO GIVE A FACTOR OF SAFETY OF 1·65. WHICH BY REDUCING THE STRESS CONCENTRATION, SHOULD PRODUCE A VALUE OF 2.

1?



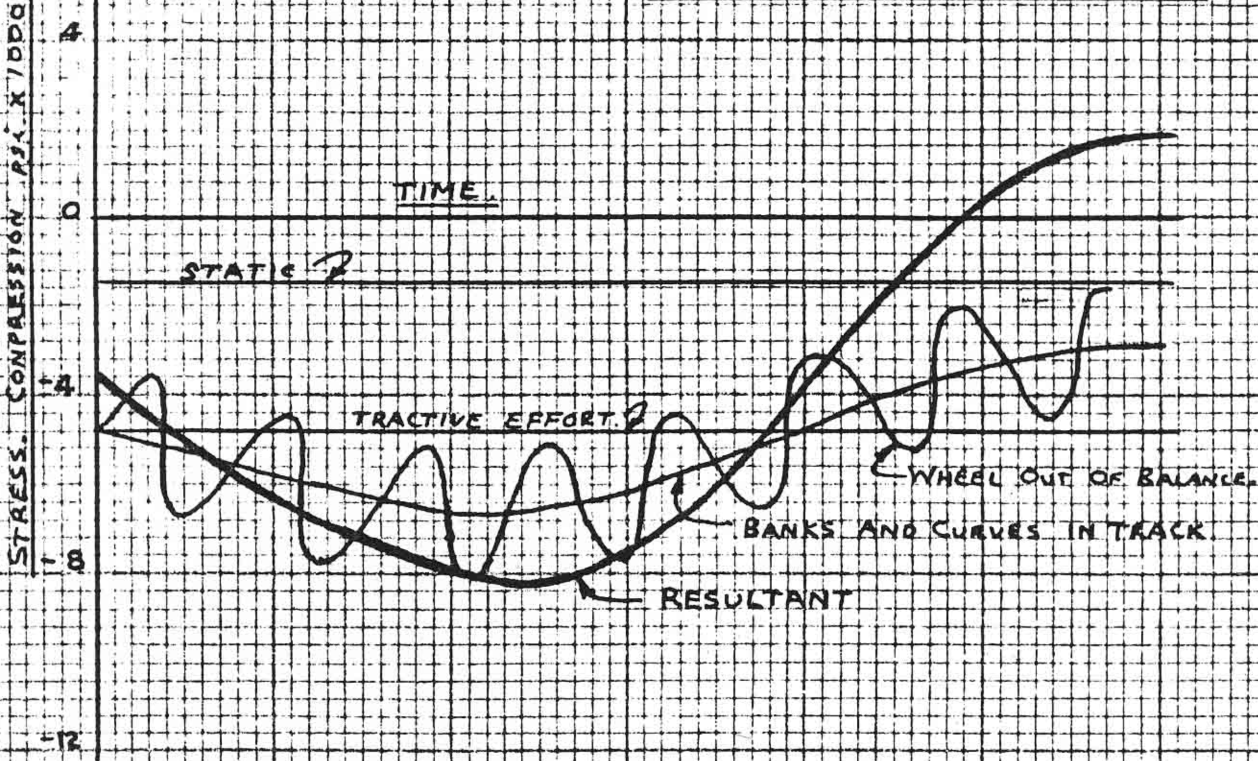
NATURE OF STRESSES RECORDED
STRESS (psi) x 1000
16
12
8
4
0
BANKS AND CURVES IN TRACK.
WHEEL OUT OF BALANCE
TRACTIVE EFFORT.
STATIC.
TIME.
RESULTANT.



GOODMAN FATIGUE GRAPH.
RESULTS.
FACTOR OF SAFETY = 3·3.
RANGE STRESS P.S.I.
30,000
20,000
10,000
0
10,000
20,000
30,000

2?

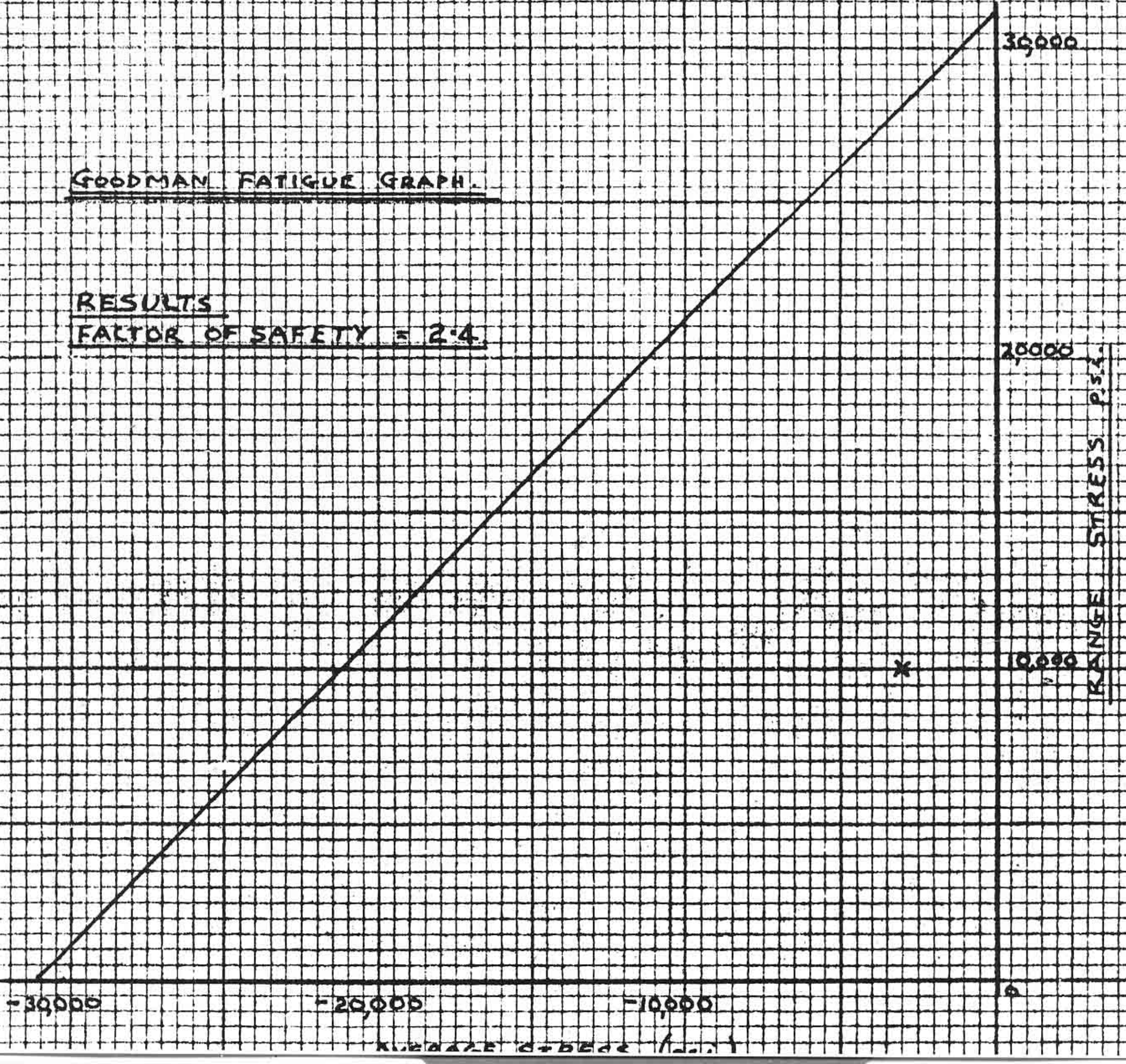
NATURE OF STRESSES RECORDED.



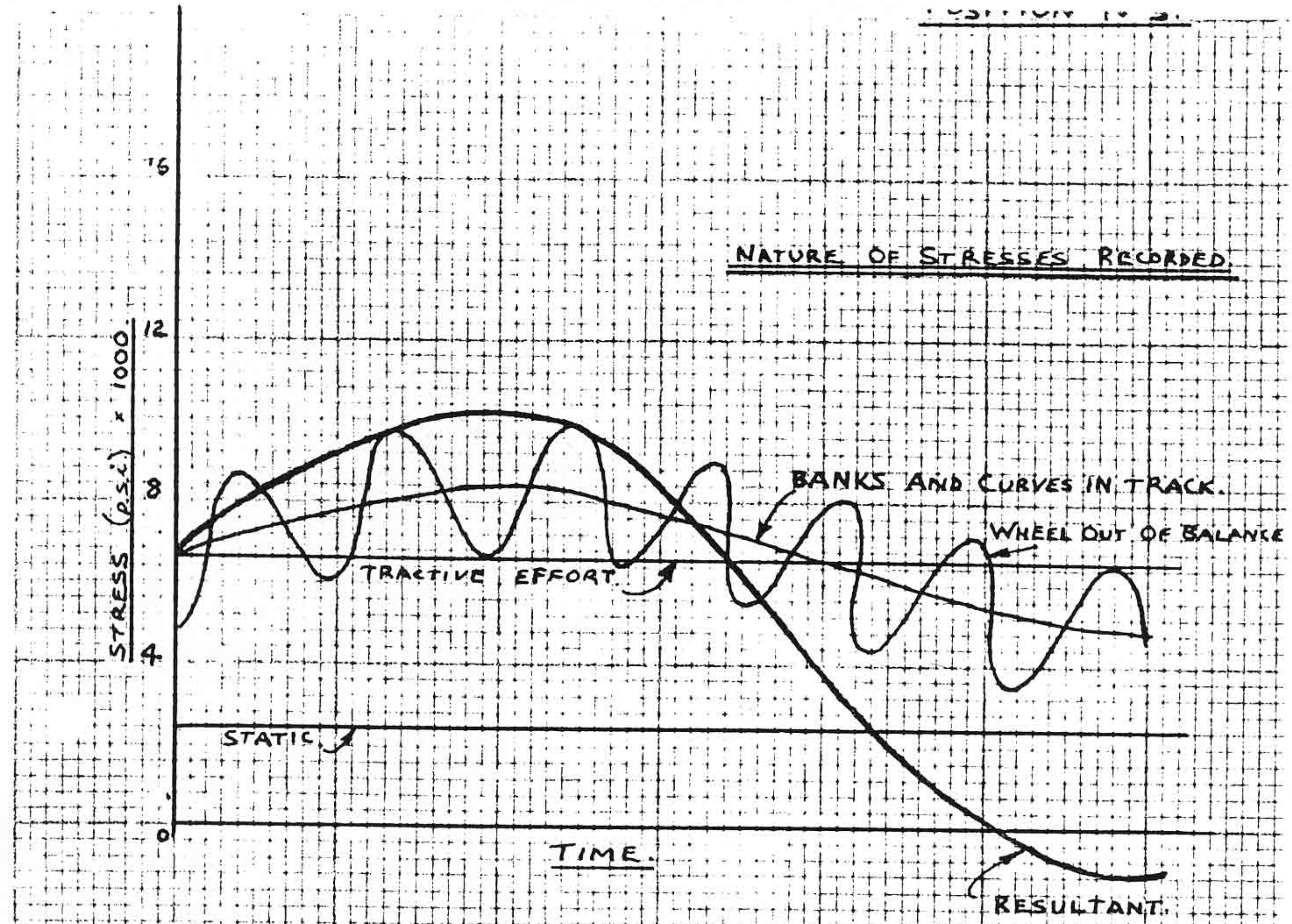
GOODMAN FATIGUE GRAPH.

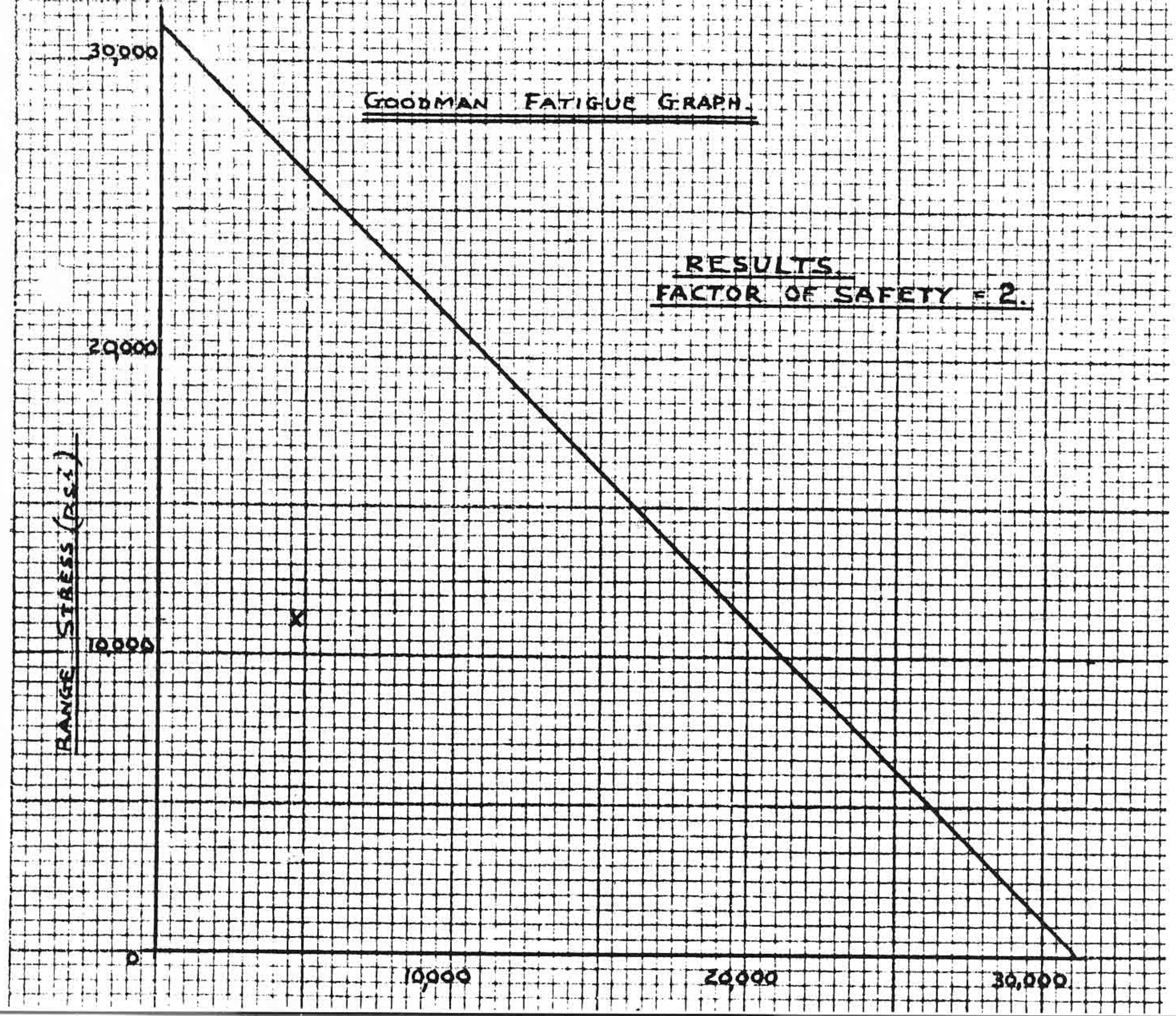
RESULTS

FACTOR OF SAFETY = 2·4

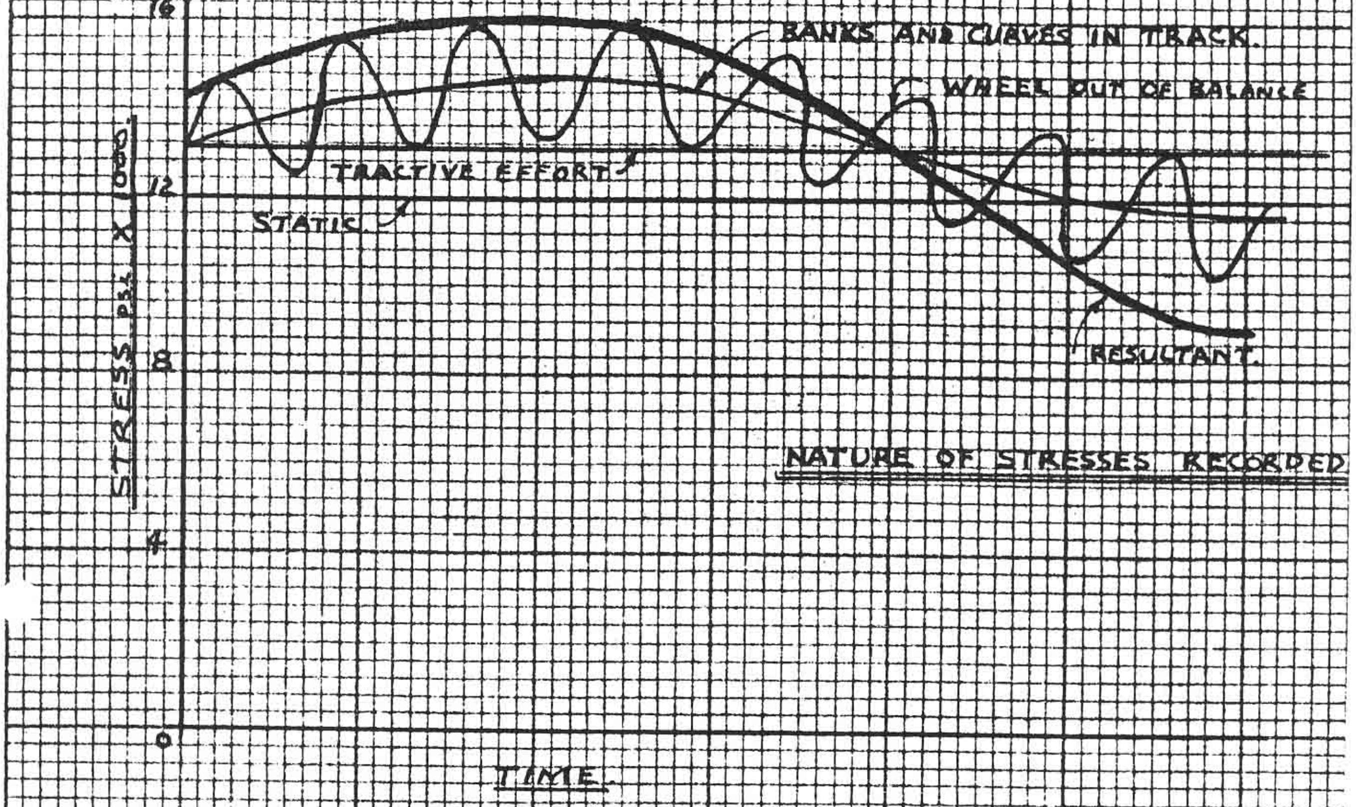


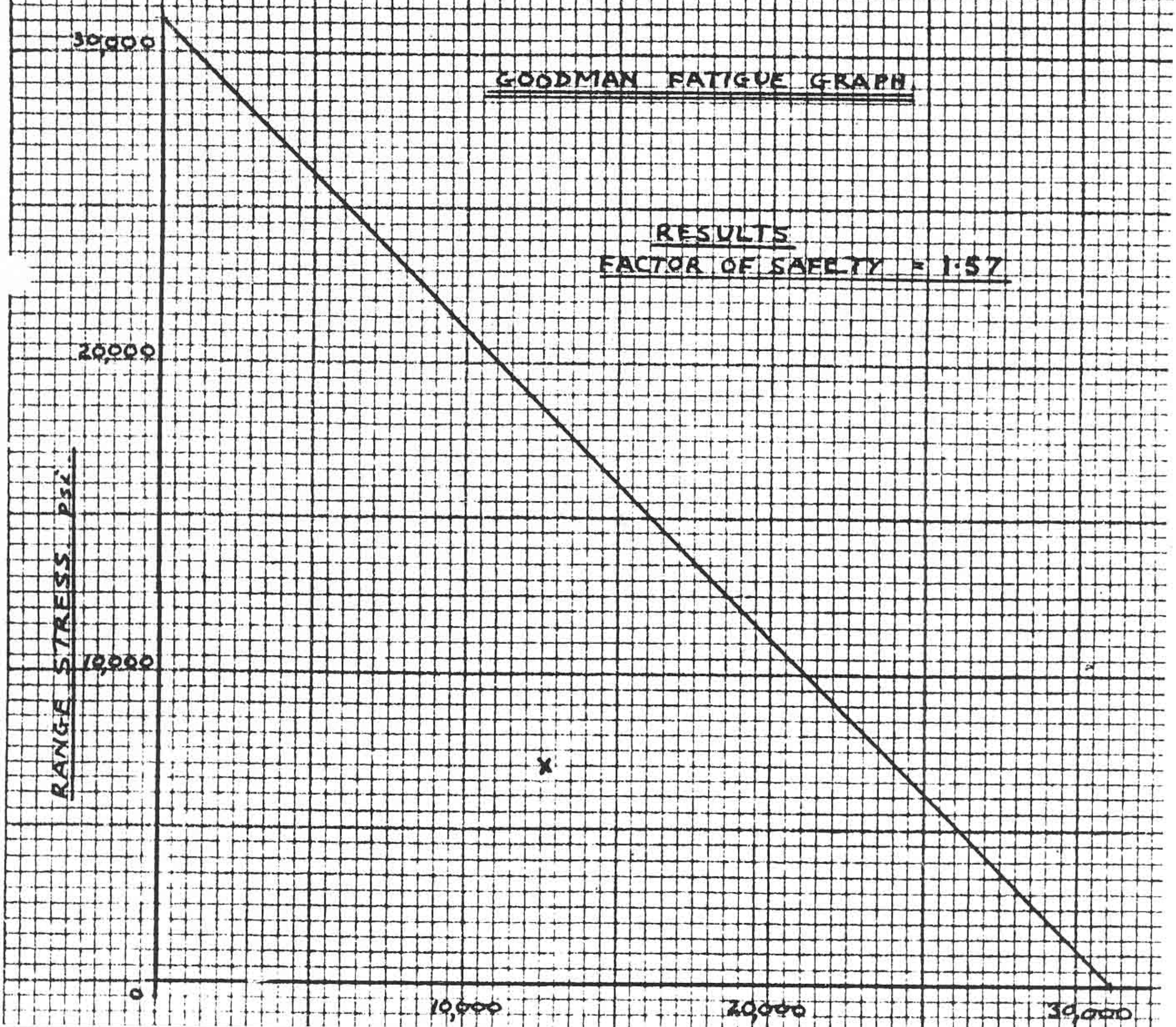
3?


NATURE OF STRESSES RECORDED.
16
12
8
4
0
STRESS (p.s.i.) × 1000.
BANKS AND CURVES IN TRACK.
WHEEL OUT OF BALANCE
TRACTIVE EFFORT.
STATIC.
TIME.
RESULTANT.

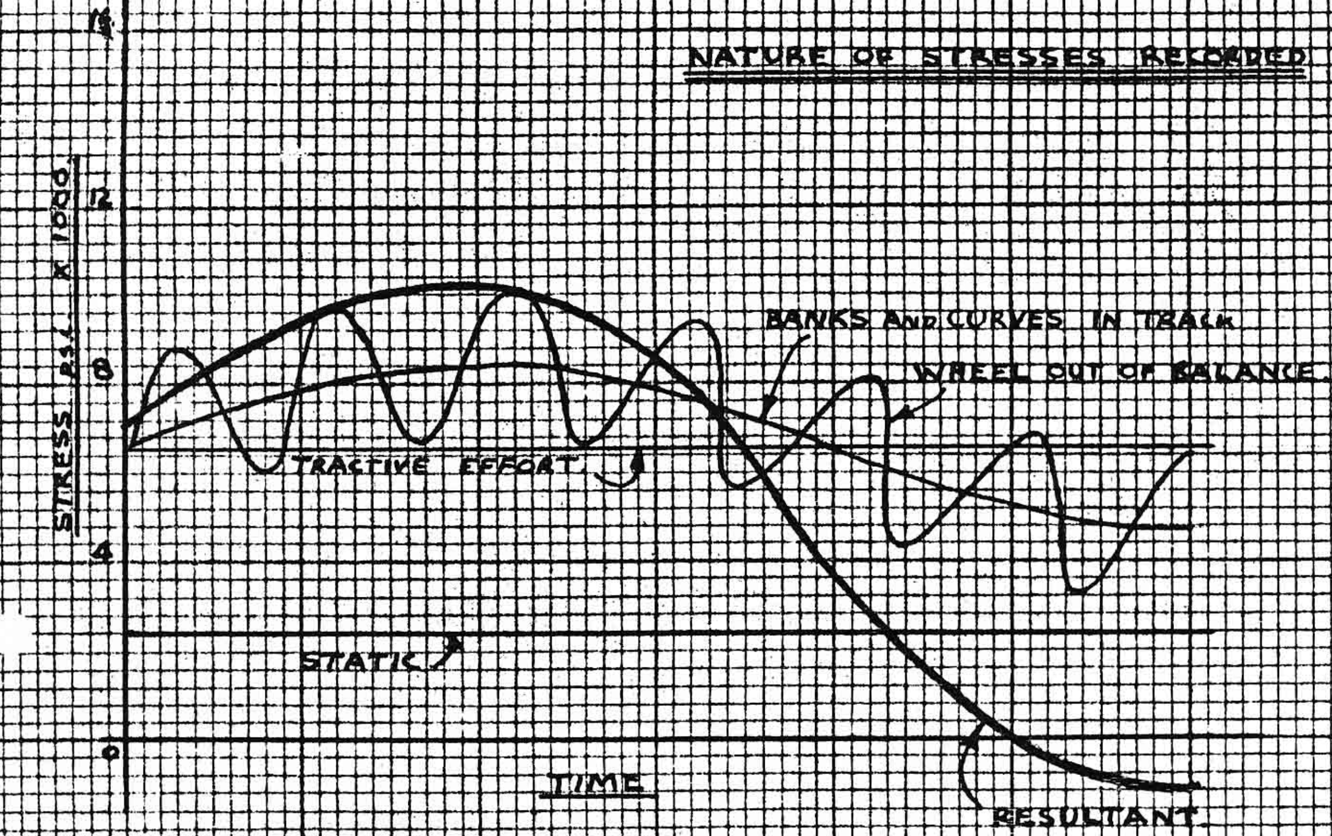

30,000
GOODMAN FATIGUE GRAPH.
RESULTS.
FACTOR OF SAFETY = 2.
20,000
RANGE STRESS (p.s.i.)
10,000
X
0
10,000
20,000
30,000.

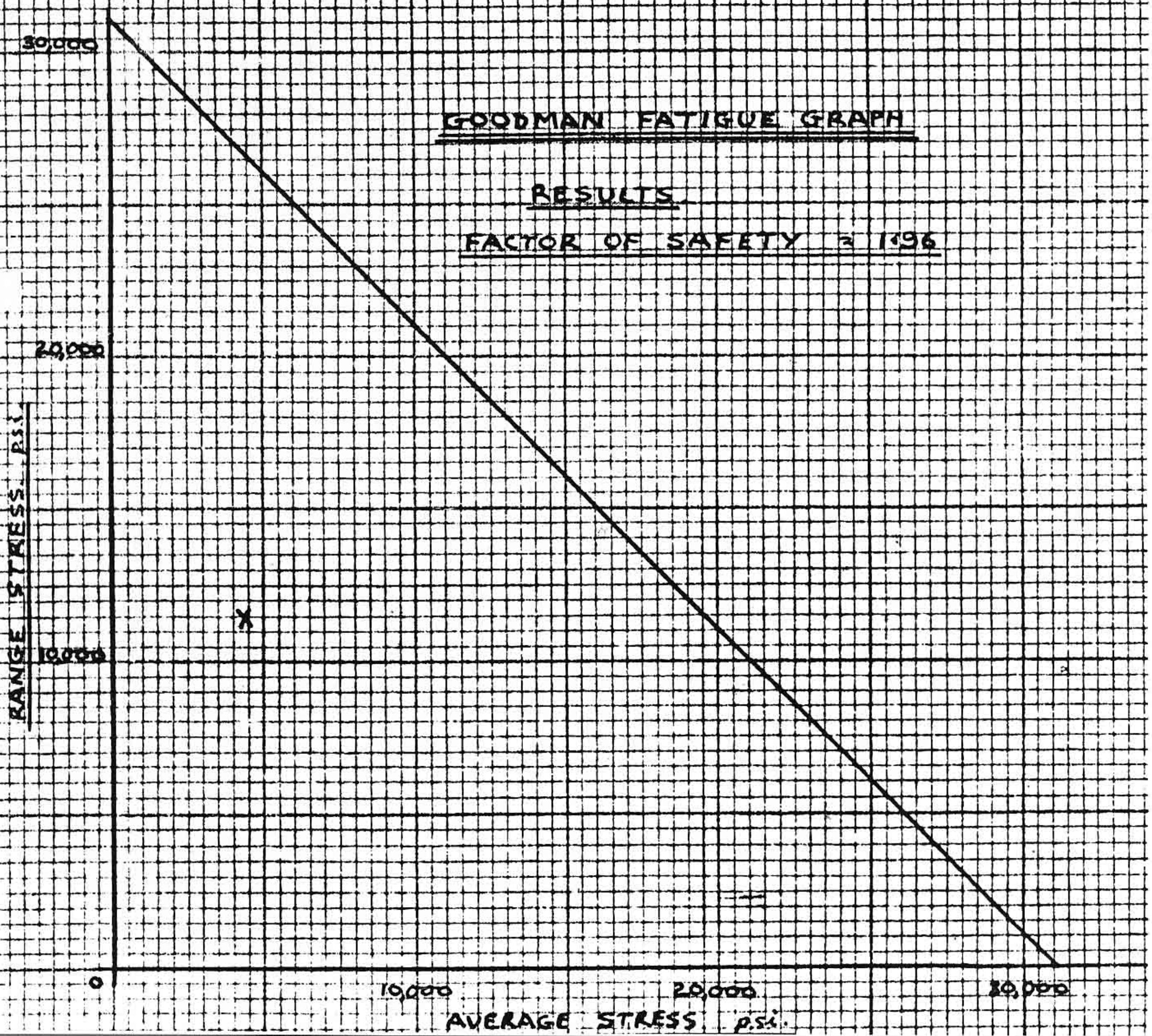
POSITION N°4.


16
12
8
4
0
STRESS PSI. X 1000
BANKS AND CURVES IN TRACK.
WHEEL OUT OF BALANCE
TRACTIVE EFFORT
STATIC
RESULTANT.
NATURE OF STRESSES RECORDED
TIME.


30,000
20,000
10,000
0
RANGE STRESS PSI.
GOODMAN FATIGUE GRAPH.
RESULTS
FACTOR OF SAFETY = 1:57
10,000
20,000
30,000

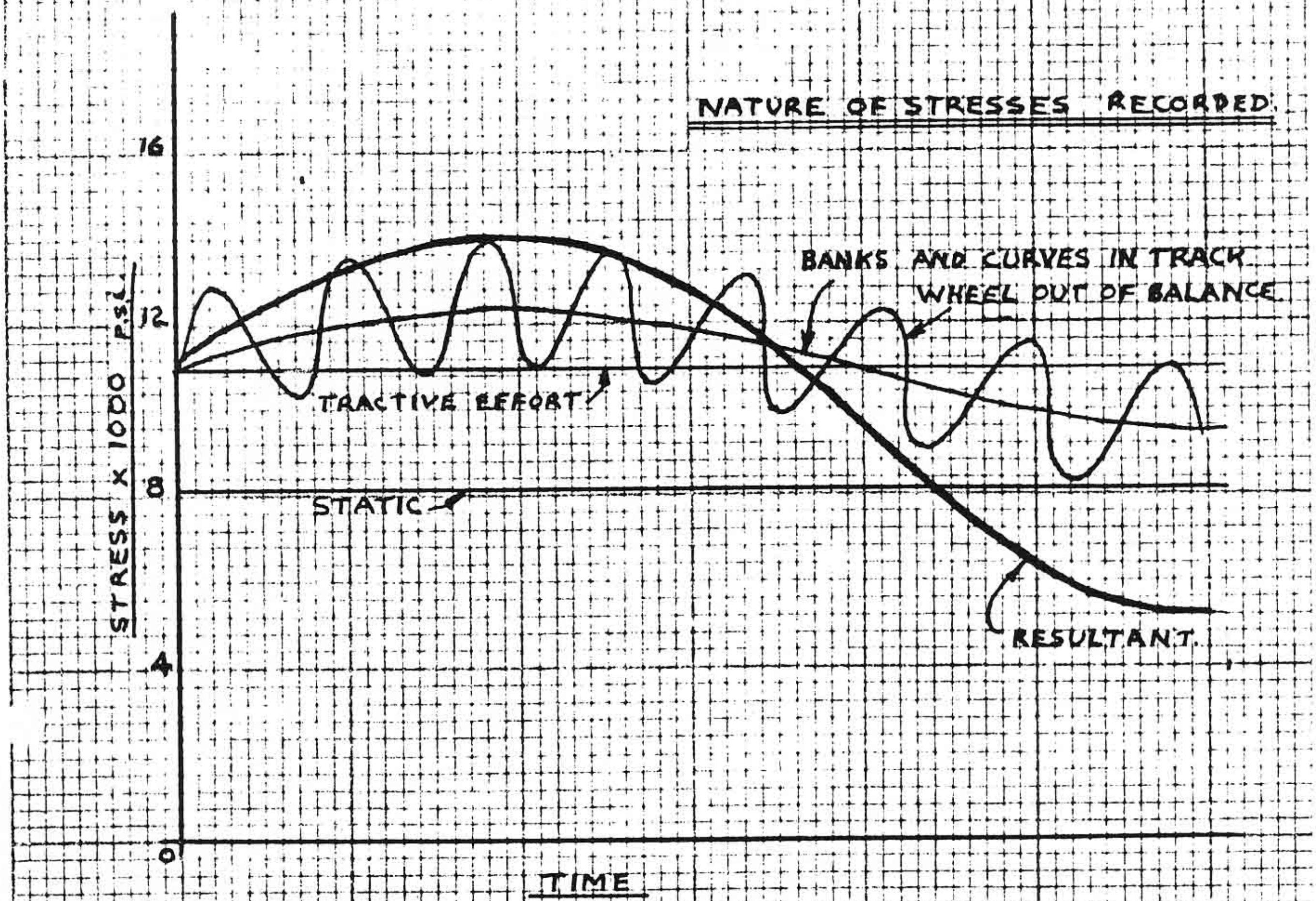
5?

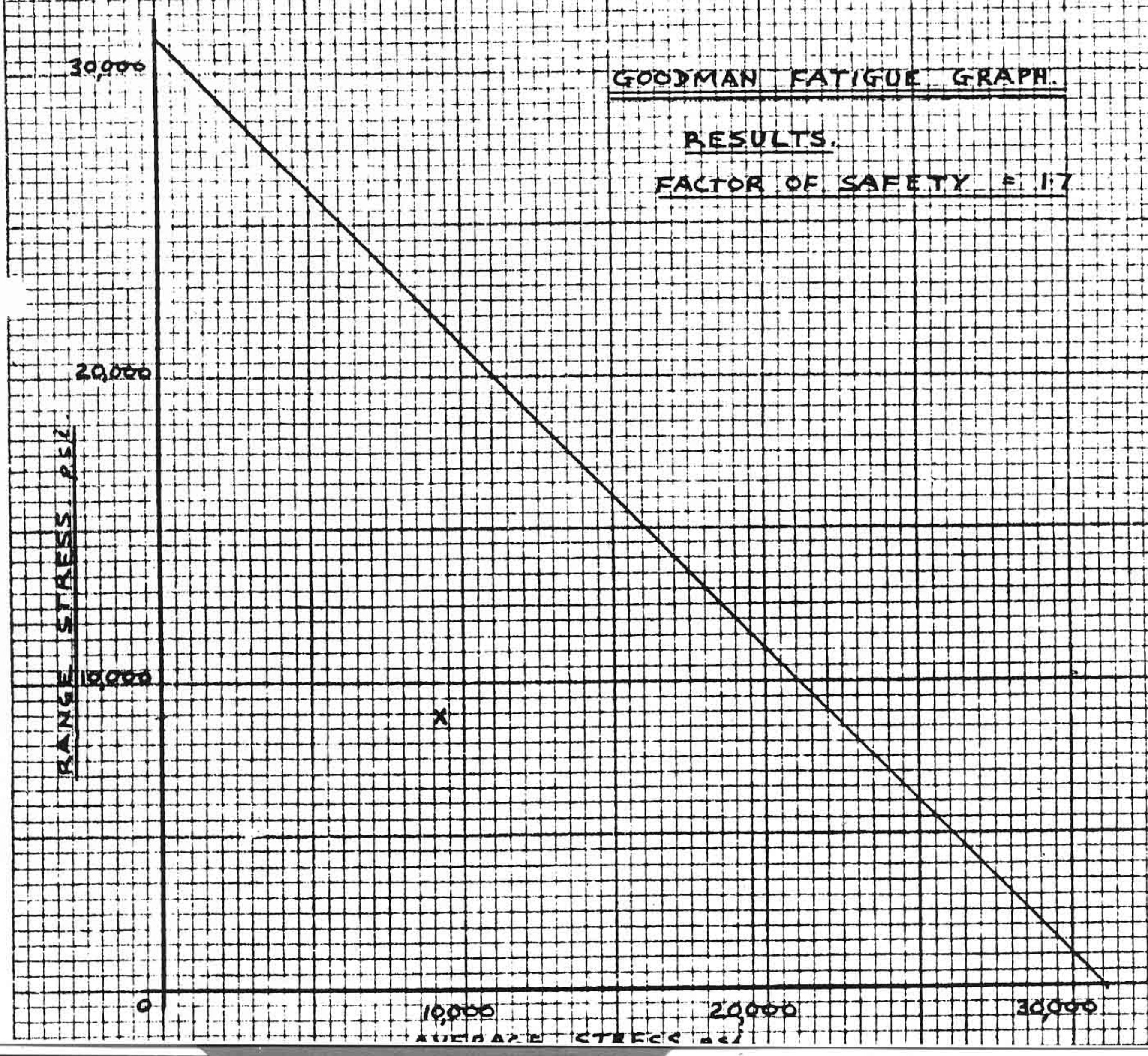

NATURE OF STRESSES RECORDED
STRESS p.s.i. X 1000
16
12
8
4
0
BANKS AND CURVES IN TRACK
WHEEL OUT OF BALANCE
TRACTIVE EFFORT
STATIC
TIME
RESULTANT


GOODMAN FATIGUE GRAPH
RESULTS
FACTOR OF SAFETY = 1·96
RANGE STRESS p.s.i.
30,000
20,000
10,000
0
10,000
20,000
30,000
AVERAGE STRESS p.s.i.

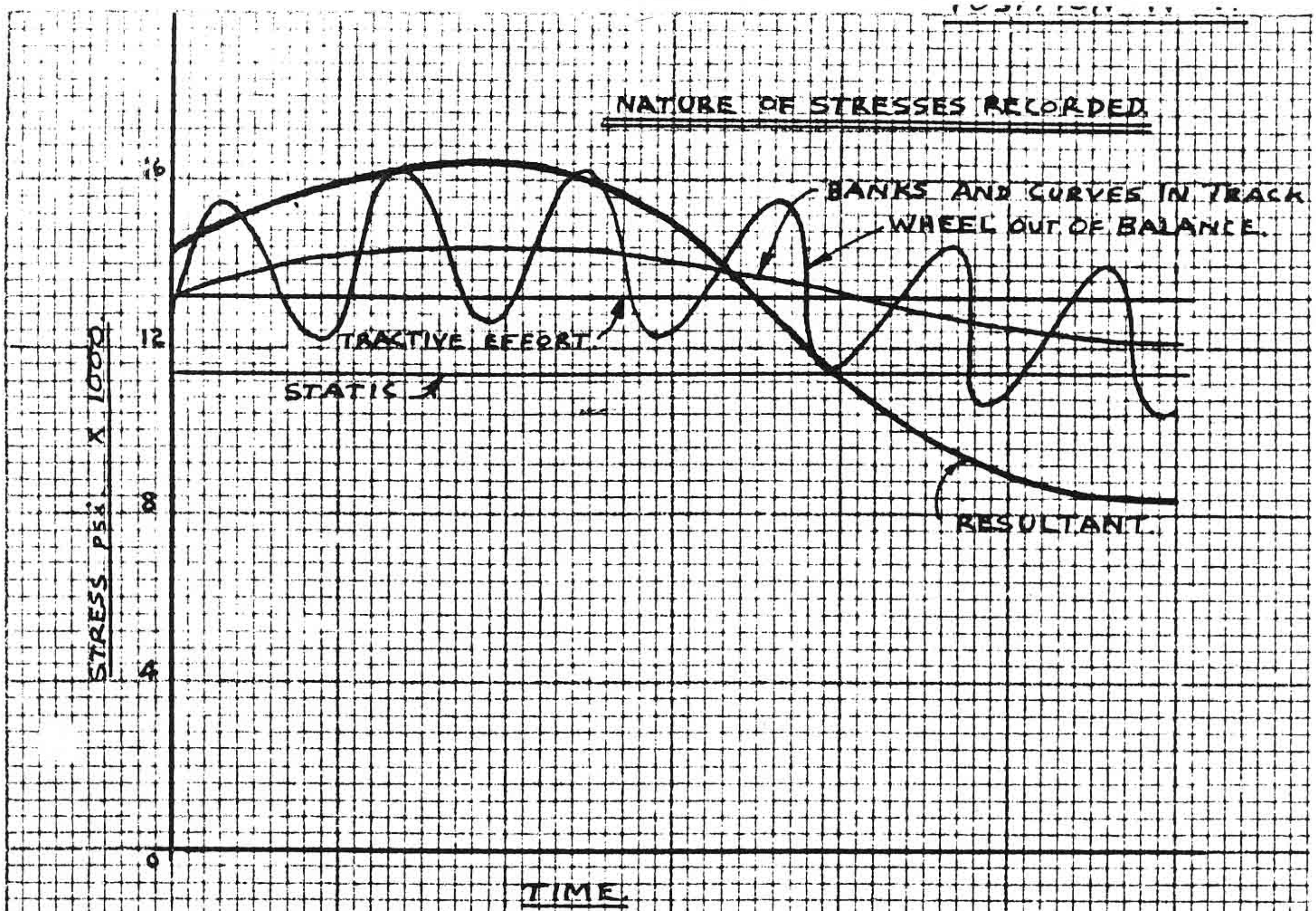
6?

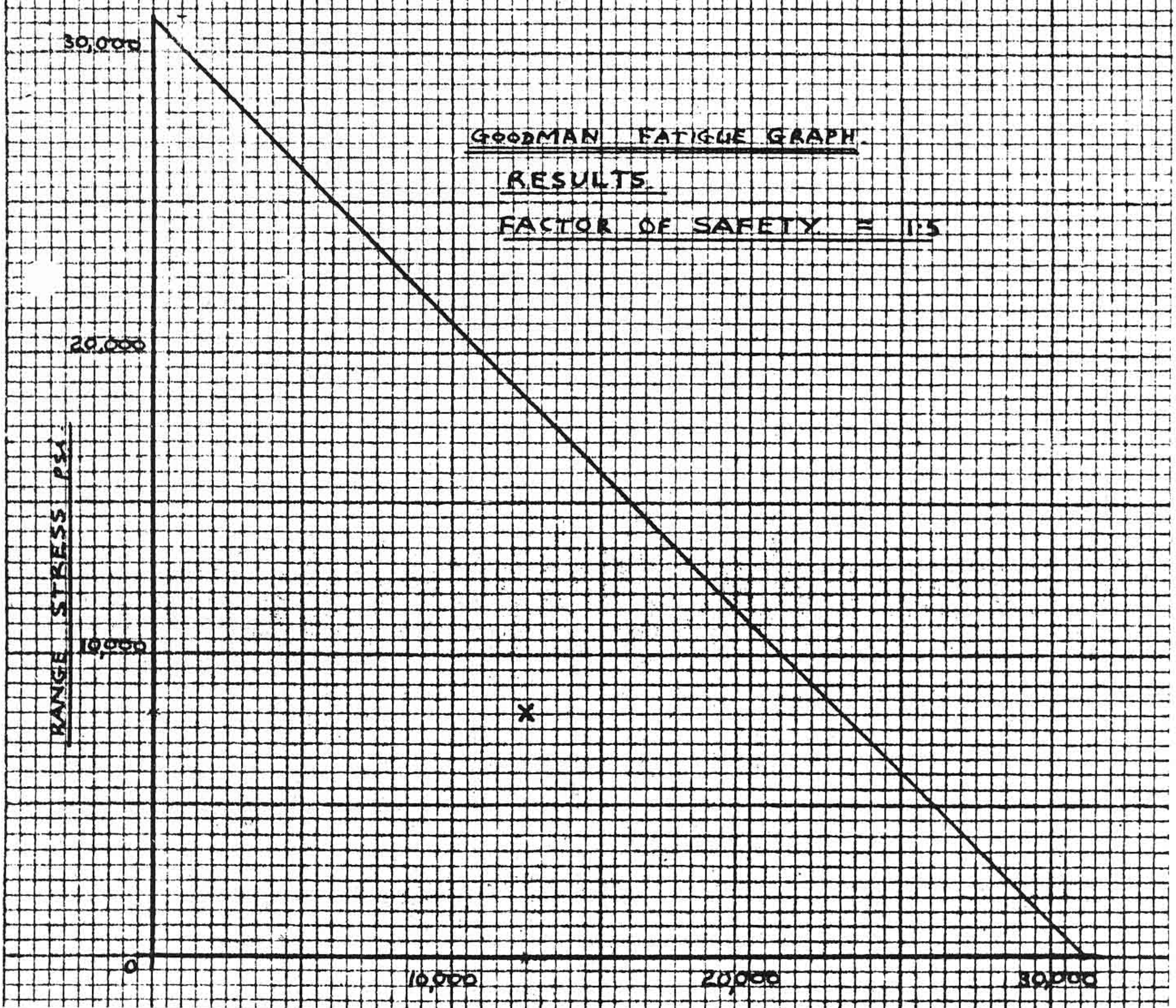
POSITION N° 6.





7?


NATURE OF STRESSES RECORDED
BANKS AND CURVES IN TRACK
WHEEL OUT OF BALANCE
TRACTIVE EFFORT
STATIC
RESULTANT
STRESS PSI. X 1000
16
12
8
4
0
TIME


GOODMAN FATIGUE GRAPH
RESULTS
FACTOR OF SAFETY = 1·5
RANGE STRESS PSI.
30,000
20,000
10,000
0
10,000
20,000
30,000