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Measurement and Suppression of Tension Waves in Arresting Gear Rope Systems

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Summary.—Experiments were carried out in order to measure the effect of the tension waves which are induced in an arresting gear rope system after engagement, and to try out means of suppressing these waves with a view to application to projected arresting gears suitable for entry speeds of up to 120 and 150 knots.

Rope tensions were recorded for a series of tests covering a range of entry speeds up to 117 knots with a test vehicle weight of 5,400 lb. and up to 151 knots at a weight of 2,450 lb. It is shown that the amplitude of the tension waves becomes relatively greater with increase of entry speed and reaches very serious proportions at the maximum speeds obtained.

The use of resilient rope anchorages has resulted in the suppression of the tension waves to a large extent, reductions in peak tensions of up to 30 per cent under some conditions having been achieved.

1. *Introduction.*—Theoretical investigation[1], together with limited experimental evidence[2], has shown that tension waves are induced in an arresting gear rope immediately following engagement and that these waves may be multiplied by reflection. This results in instantaneous rope tensions considerably greater than is indicated by the standard method of estimating arresting gear characteristics in which an inextensible rope is assumed. The amplitude of these tension waves becomes very significant at high entry speeds.

Very little practical experience has been obtained with entry speeds above 70 to 80 knots and as certain experimental projects will involve the use of arresting gears suitable for speeds up to 120 and 150 knots it was considered necessary that experimental measurement of rope tensions with entry speeds of this order be undertaken.

The use of resilient rope anchorages was considered a possible means of suppressing the reflected tension waves and the experiments described in this note were carried out using a standard arresting gear incorporating this modification.

The opportunity was also taken to obtain some other fundamental data influencing the operation of arresting gears. These form the subjects of Appendices.

2. *Equipment.*—The standard American Mk. IV arresting gear situated on the high-speed track site at the Royal Aircraft Establishment was used for these experiments. This gear is of the 'constant-pressure' type and is shown diagrammatically in Fig. 1. With 10 : 1 reeving and a span of 100 ft between fairlead pulleys, it had a maximum pull-out of 159 ft. It was reeved throughout with $\frac{11}{16}$-in. diameter hemp core steel wire rope. The centre-section of the span, 50 ft in length of the same rope, was connected to the main reeve by shackles.

The normal continuous main reeve was cut at the point furthest from the centre-span and the ends coupled to pistons in a pair of cylinders anchored to the gear foundations. The system is shown diagrammatically in Fig. 2. The cylinders, and an external variable compression space connected to each, could be filled with air to any desired pressure from H.P. air bottles. The 'dampers' operated solely as air springs and had a maximum stroke of 2 ft 6 in. When in use the available pull-out of the arresting gear was reduced to 156 ft.

The mass to be arrested consisted of a rocket-propelled trolley of variable weight running on the high-speed track. A large radius shoe on the front of the trolley engaged the arresting gear centre-span which was supported a few inches above the track. Speed control of the trolley was obtained by varying the number of rockets fired. The run-in distance was chosen to ensure that rocket thrust had ceased before the arresting gear was engaged.

3. *Instrumentation.*—The entry speed was obtained by using a microtimer which measured the time interval between the breaking of two wires, spaced 6 ft to 9 ft apart, by the trolley immediately before engagement.

The trolley carried a C-type accelerometer, range 0 to 13*g*, to record its retardation.

Rope tensions at two points were recorded by Miller oscillograph equipment from strain-gauge pick-ups. At a point immediately outboard of one fairlead pulley, a beam-type rider (illustrated in Ref. 1) was fitted. A pick-up, comprising a hollow beryllium-copper cylinder, loaded in compression, was interposed between one end of the main reeve and the damper. Both these pick-ups were on the same half of the reeving.

The stroke of the damper, also on this half, was obtained from the displacement of a small wooden block clipped on to the rope adjacent to a guide.

Pull-out of the arresting gear was observed visually.

On a few runs the formation of the 'kink wave' in the centre-span and the initial movement of the ropes, one damper and the crosshead were recorded by high-speed ciné cameras (*see* Appendices).

During part of the trials, records of pressure variation in the main cylinder of the arresting gear were obtained by attaching strain-gauges to the cylinder. Accurate measurement of the pressure was not attempted.

4. *Results.*—Full results for Series I to IV (heavy trolley) are given in Table 1, for Series V to VIII (light trolley) in Table 2.

4.1. *Series I.*—The first series of runs was carried out, with the dampers fixed, to determine the basic performance of the arresting gear. These runs were made at entry speeds varying from 65 knots to 115 knots at a mean trolley weight of 5,400 lb. The maximum tensions recorded at the tension measuring rider and the compression cell fitted at the rope anchorage are plotted against entry speed (Fig. 3).

The slopes of the curves show a tendency to rise rapidly at higher entry speeds and at 115 knots a rope tension of 13·5 tons was recorded. This tension was that taken as the working limit for these experiments, the specified minimum breaking load being 20·5 tons.

Oscillograph records of Runs Nos. 1 and 6 are shown in Figs. 8 and 9 and depict the violent oscillations in rope tension, more especially at the higher entry speed. This fluctuation in rope tension, caused by the reflection of stress waves, has also an adverse effect on the retardation diagram. A comparable diagram for Run No. 6 is shown in Fig. 10 and similar oscillations to those recorded by the oscillograph equipment are once again apparent.

4.2. *Series IIA.*—Having obtained a set of basic conditions from Series I, a further series of runs was carried out with the dampers at the rope anchorage in operation. The dampers were set with an available compression ratio at full stroke of 2·96 and the initial pressure for each run was calculated to give a yield load resulting in maximum damper travel for that entry speed. By utilizing the full stroke of the damper it was hoped to reduce the tension wave oscillations to a minimum and thereby achieve the best results. Comparing the curves obtained, Fig. 4 and Fig. 3, it is noticeable that an appreciable reduction in rope tension has been effected at higher entry speeds, a reduction of about 15 per cent.

4.3. *Series IIB, IIIB, IVB.*—In this series of runs the arresting gear settings and trolley weight were similar to the previous series, but entry speed and compression ratio were kept sensibly constant; with the yield load of the damper being the only variable.

Three series were completed at entry speeds of 65 knots with compression ratios set at 2·14, 2·96 and 7·44. The results obtained from these runs are plotted in Fig. 5 and show that there is an optimum yield load for the dampers of approximately 3·1 tons.

At this yield load, rope tensions of the lowest order are recorded irrespective of compression ratio, but it is noticeable that with a compression ratio of 2·96 more favourable rope tensions are recorded throughout the range. Characteristic diagrams recorded by the Miller oscillograph are shown in Fig. 8 where comparison is made between a fixed rope anchorage and varying yield load on the dampers. The effect of the dampers is clearly shown by the form of the rope tension curves which are comparatively smooth when compared with the fixed case.

4.4. *Series IIC, IIIC, and IVC.*—This complete series of runs was carried out at higher entry speeds sensibly constant at 108 knots and once again at compression ratios of 2·14, 2·96 and 7·44. The yield load of the dampers was varied over a range of 1·55 tons to 4·64 tons, the results being plotted in Fig. 6.

At this entry speed the optimum yield load appears to be about 2·5 tons, with lower rope tensions throughout the range occurring at a compression ratio of 2·96. With a compression ratio of 2·14, the optimum yield load was not found, since the full stroke of the damper was being used before reaching the optimum value.

Characteristic oscillograph records for this series are shown in Fig. 9 and comparable retardation diagrams in Fig. 10. The form of the diagrams is appreciably altered with the dampers in operation and the peak oscillations produced by the reflected tension waves considerably reduced in magnitude.

The maximum rope tensions, for a constant damper yield load of 2·70 tons and a compression ratio of 2·96, are shown in Fig. 7 in comparison with the values with dampers fixed. The reduction in peak rope tension effected with these settings is of the order of 23 per cent at the higher entry speeds.

4.5. *Series V.*—The trolley weight was altered for this series and subsequent runs and was sensibly constant at 2,450 lb. This was done mainly to achieve higher entry speeds into the arresting gear. This series of runs was carried out primarily to obtain a basic rope tension/speed curve to determine the performance of the gear without dampers at higher entry speeds. The settings of the arresting gear were constant and entry speeds were varied from 68 knots to 118 knots at which speed the rope tension developed was nearing the working limit of the rope. The results of this test are shown in Fig. 11. The curves of rope tension/speed indicate a rapid increase in rope tensions at speeds in excess of 100 knots.

Comparable oscillograph and retardation records are shown in Figs. 15 and 16, Run No. 39. It is immediately apparent from these diagrams, that the tension wave oscillations have now reached alarming proportions and are a serious handicap to the operation of the arresting gear.

4.6. *Series VI.*—The basic rope tension/entry speed curves having now been obtained, it was decided to use the arresting gear with dampers in operation at the rope anchorage. From previous experience with the heavy trolley, it was decided to operate the dampers at a compression ratio of 7·44 at full stroke and to vary the yield load, keeping the entry speed constant at 118 knots. Results obtained from this set of conditions are shown plotted in Fig. 12 which indicates that the optimum setting of the dampers occurs at a yield load of 2·13 tons.

Typical oscillograph records for this series are shown in Fig. 15 and comparable retardation diagrams Fig. 16.

These records once again depict that considerable reduction in rope tension has been effected by the use of the dampers, and it is noticeable that the violent degree of oscillation previously recorded at this speed has been greatly reduced in magnitude.

4.7. *Series VII.*—In this series of runs the dampers were set at constant settings of 7·44 compression ratio and yield load of 2·13 tons, these values having been determined in Series VI. The entry speed into the arresting gear was gradually increased from 62 knots to 151 knots at which speed the rope tension was rising rapidly, nearing the working limit of the rope and it was considered unsafe to attempt a further increment in speed. The rope tensions recorded are plotted against entry speed in Fig. 13.

Comparison is made between an arresting gear with and without dampers at the rope anchorage under these conditions and the results are plotted against entry speed in Fig. 14. This graph indicates that at 120 knots there is a reduction of 30 per cent effected in rope tension by the use of dampers at the rope anchorage. Maximum permissible entry speed is also increased by about 30 per cent.

The actual oscillograph record for the highest speed into the arresting gear, namely 151 knots is reproduced in Fig. 17 which has been included mainly to show a typical type of record obtained from the Miller equipment.

4.8. *Series VIII.*—To check that the right settings had been determined for the dampers it was decided to carry out a further series of runs at a compression ratio of 2·96 and varying yield load. Three runs were carried out and it was soon apparent that these settings would not produce results comparable with a compression ratio of 7·44, and in consequence no further runs were made. The trend of the curve for this series is shown in Fig. 12.

4.9. *Impact Tension.*—The magnitudes of the initial tension waves due to impact, as measured by the rider, but corrected for initial tension, are plotted in Fig. 18 for all runs, together with a curve representing the calculated values. (*See* Appendix I.)

5. *Discussion.*—It has been shown that the use of dampers can give reductions in peak rope tensions of up to 30 per cent under some conditions or a similar increase in maximum permissible entry speed for a given maximum rope tension. The optimum damper settings for any particular conditions appear to be fairly well defined, but it is not proposed to formulate a theory to cover the results obtained at the present time. Some general trends are apparent, however, which it is necessary to consider in assessing the efficiency of the dampers in suppressing reflection of tension waves.

Study of the actual tension records indicates that the amplitude of the tension waves continues to decrease with damper yield loads but that below a certain value the peak tensions increase. This is considered to be due to the effect of the dampers in delaying the build-up to maximum tension, thus causing a less efficient basic characteristic upon which the oscillations are superimposed. It is demonstrated by the tendency for minimum tensions at the anchorage end of the rope to occur with higher yield loads, since a very small damper travel is, in most cases, sufficient to suppress almost completely the oscillations at this point, so that increase in tension with lower yield loads is due entirely to the less efficient characteristic.

The use of low damper yield loads implies a high compression ratio and hence a very rapid build-up towards the end of the damper stroke. This tends to produce a sharp tension peak at the anchorage and also contributes to an inefficient characteristic. This effect is particularly noticeable in Fig. 9.

Consideration of these effects seems to indicate that the ideal type of damper would be one having the lowest practicable yield load and a linear increase of resistance with stroke. This ideal cannot be realised using a simple air-spring damper and the alternatives of a metal spring or an air-spring with lever linkage would be prohibitively massive. A fairly close approach to a linear load/displacement relationship can be obtained however with a two-stage air-spring embodying two cylinders, one sliding within the other.

6. *Conclusions.*—The experiments have confirmed the existence of oscillatory tension waves in the rope system of an arresting gear after engagement and show that the wave amplitude becomes relatively greater with increase in entry speed causing a serious restriction in the operating limit of the gear.

Resilient rope anchorages have proved to be an effective means of suppressing the tension waves to a large extent and promise to be of considerable assistance in achieving the performance required of future projects.

7. *Further development.*—It is proposed to carry out a similar series of experiments in the near future, using a pair of standard arresting gear units coupled together to provide greater capacity. Two-stage dampers will be fitted. This will enable test conditions to represent the target performance more closely.

Work is proceeding on the mathematical analysis of tension wave formation and suppression.

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TABLE 1

Series No.	Run No.	Trolley weight (lb)	Velocity (knots)	Arresting gear: Pull-out (ft)	Arresting gear: Max. g	Damper: Compression ratio at full stroke	Damper: Yielding load (tons)	Damper: Stroke (in.)	Damper: Max. T (tons)	Rider: Impact T (tons)	Rider: Max. T (tons)	Actual compression ratio	Estimated pressure ratio	Remarks
I	1	5,250	65·8	90	3·6	—	—	—	6·07	2·22	8·15	—	—	
	2	5,250	66·5	90	3·5	—	—	—	6·18	2·20	8·80	—	—	
	3	5,290	81·8	105	4·0	—	—	—	6·54	2·68	9·96	—	—	
	4	5,330	97·3	124	5·2	—	—	—	7·55	3·66	11·26	—	—	
	5	5,390	100·9	133	5·8	—	—	—	8·66	3·83	10·56	—	—	
	6	5,410	107·6	145	5·6	—	—	—	8·72	4·18	11·98	—	—	
	7	5,370	114·6	146	5·5	—	—	—	10·02	4·36	13·52	—	—	
IIA	8	5,250	65·0	85	3·3	2·96	1·55	28·5	5·08	2·18	7·72	2·69	3·13	
	9	5,310	70·2	90	3·9	2·96	1·78	29·7	5·81	2·48	8·49	2·91	3·13	
	10	5,290	82·6	108	3·8	2·96	2·32	25·5	6·63	2·68	8·84	2·29	2·77	
	11	5,370	95·5	126	5·0	2·96	2·86	24·9	7·13	3·55	9·16	2·22	2·44	
	12	5,390	100·9	132	4·7	2·96	2·70	28·4	7·96	4·12	9·43	2·69	2·86	
	13	5,410	109·7	146	5·5	2·96	3·28	22·2	7·54	4·54	10·51	1·96	2·25	
	14	5,430	116·9	157*	6·0	2·96	3·09	N.R.	8·37	4·47	10·59	—	3·34	*Arresting gear bottomed.
IIB 1 run from IIA	15	5,290	64·0	87	3·4	2·96	2·32	22·7	5·19	2·39	7·59	2·03	2·18	
	16	5,290	63·4	86	3·7	2·96	3·09	16·3	5·03	2·27	7·01	1·56	1·60	
	17	5,290	63·4	90	3·4	2·96	3·86	10·0	4·87	2·29	7·61	1·28	1·25	
	18	5,290	63·6	88	3·8	2·96	4·64	4·8	5·17	2·22	8·08	1·12	1·11	
IIIB	19	5,290	63·2	82	3·6	7·44	1·16	24·1	5·44	2·11	7·75	3·28	1·24	
	20	5,290	61·9	81	3·4	7·44	1·93	18·2	4·97	2·33	7·60	2·11	1·22	
	21	5,290	63·7	82	3·6	7·44	3·09	12·5	5·31	2·29	7·01	1·56	1·69	
	22	5,290	63·8	82	3·8	7·44	4·25	6·2	5·20	2·33	8·32	1·22	1·00	

TABLE 1—*continued*

Series No.	Run No.	Trolley weight (lb)	Velocity (knots)	Arresting gear		Damper				Rider		Actual compression ratio	Estimated pressure ratio	Remarks
				Pull-out (ft)	Max. *g*	Compression ratio at full stroke	Yielding load (tons)	Stroke (in.)	Max. *T* (tons)	Impact *T* (tons)	Max. *T* (tons)			
IVB	23	5,290	63·7	82	3·8	2·14	2·70	N.R. 23·0	5·10	2·39	7·57	1·7	1·85	
	24	5,290	63·2	82	3·8	2·14	3·09	Approx. 19·3	5·00	2·12	7·06	Approx. 1·52	1·60	
	25	5,290	63·1	81	3·6	2·14	3·86	11·3	4·92	2·31	7·93	1·25	1·27	
IIC 1 run from IIA	26	5,410	108·7	145	4·9	2·96	2·70	27·5	8·44	4·55	9·90	2·55	3·03	
	27	5,410	108·3	146	5·8	2·96	3·86	17·9	7·04	4·51	11·28	1·65	1·80	
	28	5,410	108·3	146	5·8	2·96	4·64	12·8	6·75	4·56	11·70	1·39	1·44	
IIIC	29	5,410	N.R.	145	5·0	7·44	1·55	26·7	10·17	4·33	10·82	4·35	6·19	
	30	5,410	108·3	145	5·2	7·44	2·32	22·7	9·44	4·41	10·15	2·90	3·93	
	31	5,410	108·9	146	5·6	7·44	3·09	18·2	8·53	4·52	11·26	2·11	2·70	
IVC	32	5,410	110·3	146	5·6	2·14	3·09	28·5	8·12	4·38	10·96	2·02	2·57	
	33	5,410	110·3	149	5·5	2·14	3·48	23·8	7·24	4·57	11·34	1·73	2·05	
	34	5,410	109·3	145	6·3	2·14	3·67	22·9	7·22	4·44	11·25	1·68	1·94	

Arresting gear settings:—Dome valve pressure 750 lb/in.^{2}
Accumulator pressure 700 lb/in.^{2}
Limited-lift valve setting 0·085 in.

TABLE 2

Series No.	Run No.	Trolley weight (lb)	Velocity (knots)	Arresting gear		Damper				Rider		Actual compression ratio	Estimated pressure ratio	Remarks
				Pull-out (ft)	Max. g	Compression ratio at full stroke	Yielding load (tons)	Stroke (in.)	Max. T (tons)	Impact T (tons)	Max. T (tons)			
V	35	2,410	68·7	64	6·6	—	—	—	5·61	2·33	7·42	—	—	
	36	2,450	82·2	75	8·2	—	—	—	5·87	3·02	7·92	—	—	
	37	2,450	103·9	89	10·3	—	—	—	7·09	3·82	9·34	—	—	
	38	2,490	116·5	104	11·7	—	—	—	7·59	4·51	12·27	—	—	
	39	2,490	118·4	104	12·8	—	—	—	8·15	4·49	12·81	—	—	
VI	40	2,490	117·6	106	10·0	7·44	1·55	23·8	6·48	4·80	9·38	3·19	3·97	
	41	2,490	119·2	108	9·2	7·44	1·93	21·3	6·00	4·80	8·81	2·60	2·98	
	42	2,490	116·5	106	8·7	7·44	2·32	17·5	5·49	4·74	8·91	2·02	2·30	
	43	2,490	118·4	105	9·7	7·44	2·70	17·4	6·04	4·88	9·31	2·01	2·18	
VII	44	2,430	68·3	62	6·2	7·44	2·13	15·4	4·50	2·47	6·05	1·80	2·06	
	45	2,430	85·0	75	7·5	7·44	2·13	19·7	5·82	3·16	7·37	2·32	2·65	
	46	2,450	102·7	88	8·1	7·44	2·13	20·7	6·09	3·96	7·98	2·48	2·77	
	47	2,490	133·6	120	10·5	7·44	2·13	20·0	6·64	5·82	9·68	2·36	3·01	
	48	2,510	149·9	136	12·0	7·44	2·13	21·6	7·00	6·68	12·25	2·65	3·18	
	49	2,510	151·3	148	10·8	7·44	2·13	23·5	7·35	6·86	11·15	3·05	3·33	Limited lift valve set at 0·138 in.
VIII	50	2,470	115·7	108	9·4	2·96	2·13	27·7	6·60	5·74	9·68	2·57	3·00	
	51	2,470	118·0	105	9·4	2·96	2·32	25·3	6·60	4·77	9·59	2·27	2·76	
	52	2,470	118·0	105	10·0	2·96	2·70	21·0	5·92	4·71	9·53	1·87	2·14	

Arresting gear settings:—Dome valve pressure 600 lb/in.^{2}
Accumulator pressure 700 lb/in.^{2}
Limited-lift valve setting 0·085 in.

APPENDIX I

Analysis of Impact Tensions

Introduction.—At high entry speeds the inertia of the arresting rope plays an important part and the tensions due to the impact effects are considerable. An opportunity presents itself in this series of tests to compare the theoretical values with those obtained in practice. In addition to measuring the impact tension on each run, during Run No. 50 a high-speed camera was used to photograph the rope configuration after impact. A selection of these photographs is shown in Fig. 19.

It will be seen that the predicted kink is most marked, especially before wave reflections occur at the shackles and fairlead pulleys. A trace of the rope position for each frame of the film record is shown in Fig. 20, in which the wave reflections from the shackles and pulleys can be followed.

Experimental Results.—The theory of impact effects on a rope is given by Stevens[3] who obtains the following relations

$$e^{1/2} = 1 - \cos\theta$$

$$\frac{V}{a} = e^{1/2}\sin\theta$$

where e is the strain

V is the velocity of engagement

a is the velocity of a tension wave in the rope

θ is the kink angle in the rope.

Table 3 gives values of e and θ tabulated against values of V/a.

On analysis of the photographic record (Fig. 20) of Run No. 50 a value for θ of 19·7 deg and a value for V of 204·5 ft/sec were obtained.

The corresponding values of a and e are

$$a = 10{,}370 \text{ ft/sec} \qquad e = 0 \cdot 00342\,.$$

The velocity of a tension wave is also given by the formula

$$a = \sqrt{\left(\frac{EA}{m}\right)}$$

where E is the modulus of elasticity

A is the cross-sectional area of rope

m is the mass of rope per unit length.

Neglecting the core of the rope, the area of cross-section of the steel is 0·172 sq in. The total mass per foot is found to be 0·70 lb, i.e., $m = 0 \cdot 0217$ slugs per ft.

Thus E is found to be $13 \cdot 6 \times 10^6$ lb/sq in.

Table 4 shows the agreement between theory and the experimental records of impact tensions. Columns 1 and 2 give the run numbers and entry speed in knots. Column 3 gives the value of V/a based on a value for a of 10,370 ft/sec, *i.e.*, 6,140 knots. The corresponding value of e, column 4, is found from interpolating in Table 3. Column 5 gives the value of T_1 which is the impact tension induced in a rope of zero initial tension and is found from the relation

$$T_1 = eEA \ .$$

When the rope has an initial tension T_0, Thomlinson[1] has shown that the maximum tension in the rope is given by $T_1 + \frac{2}{3}T_0$, provided T_0 is small compared with T_1. Column 7 of the table accordingly gives the maximum tensions recorded at the rider less two-thirds of the initial tension.

So far the effect of the pulleys and shackles has been neglected. Ringleb[4] has considered in some detail the effects of reflections at such points. In a similar series of experiments the experimental values obtained for the tensions exceeded the theoretical by 23 per cent. This was explained by assuming part of the tension wave reflected by the pulley. In the case considered here it seems reasonable to suppose a similar effect is obtained from the first pulley on the moving crosshead of the arresting gear. In addition, reflections from the shackles and fairlead pulleys travelling to the centre of the span and being reflected a second time may also increase the recorded tensions. These increases are partly offset by the losses round the fairlead pulley. It is obviously impracticable to analyse completely the reflection effects of the complete system and a factor of 1·30 has been introduced to allow for these effects. This factor was obtained by fitting by 'least squares' the best curve to the experimental results. The values of $1 \cdot 30T_1$ are given in column 6 for comparison with column 7. The experimental results are shown plotted in Fig. 18 together with the theoretical curve.

TABLE 3

V/a	e	θ
0·001	0·000063	7° 12′
0·002	0·000159	9° 6′
0·003	0·000274	10° 25′
0·004	0·000403	11° 31′
0·005	0·000543	12° 24′
0·006	0·000692	13° 10′
0·007	0·000851	13° 53′
0·008	0·001018	14° 29′
0·009	0·001193	15° 6′
0·010	0·001374	15° 39′
0·011	0·001561	16° 9′
0·012	0·001755	16° 39′
0·013	0·001955	17° 6′
0·014	0·002159	17° 31′
0·015	0·002369	17° 56′
0·016	0·002584	18° 21′
0·017	0·002803	18° 43′
0·018	0·003027	19° 5′
0·019	0·003256	19° 27′
0·020	0·003489	19° 48′
0·021	0·003726	20° 7′
0·022	0·003967	20° 27′
0·023	0·004211	20° 45′
0·024	0·004460	21° 4′
0·025	0·004713	21° 21′
0·026	0·004969	21° 39′
0·027	0·005229	21° 55′
0·028	0·005493	22° 7′
0·029	0·005759	22° 28′
0·030	0·006029	22° 44′

TABLE 4

Run	V (knots)	V/a	e	T_1 (tons)	$1\cdot30T_1$	Recorded impact T_1 less $\frac{2}{3}T_0$
Prelim. run	65·8	0·01071	0·001507	1·57	2·04	1·85
1	65·8	0·01071	1507	1·57	2·04	2·01
2	66·5	0·01083	1529	1·60	2·07	1·99
3	81·8	0·01332	2020	2·11	2·74	2·47
4	97·3	0·01584	2550	2·66	3·46	3·45
5	100·9	0·01642	2676	2·79	3·63	3·62
6	107·6	0·01752	2919	3·05	3·96	3·97
7	114·6	0·01866	3178	3·32	4·31	4·15
8	65·0	0·01059	1484	1·55	2·01	1·85
9	70·2	0·01143	1644	1·72	2·23	2·15
10	82·6	0·01345	2047	2·14	2·78	2·35
11	95·5	0·01555	2487	2·60	3·37	3·22
12	100·9	0·01642	2676	2·79	3·63	3·79
13	109·7	0·01786	2996	3·13	4·07	4·21
14	116·9	0·01903	3263	3·41	4·43	4·14
15	64·0	0·01042	1453	1·52	1·97	2·06
16	63·4	0·01032	1434	1·50	1·95	1·94
17	63·4	0·01032	1434	1·50	1·95	1·96
18	63·6	0·01035	1439	1·50	1·95	1·89
19	63·2	0·01029	1428	1·49	1·94	1·78
20	61·9	0·01008	1389	1·45	1·89	2·00
21	63·7	0·01037	1443	1·51	1·96	1·96
22	63·8	0·01039	1447	1·51	1·96	2·00
23	63·7	0·01037	1443	1·51	1·96	2·06
24	63·2	0·01029	1428	1·49	1·94	1·79
25	63·1	0·01028	1426	1·49	1·94	1·98
26	108·7	0·01770	2960	3·09	4·02	4·22
27	108·3	0·01763	2944	3·07	4·00	4·18
28	108·3	0·01763	2944	3·07	4·00	4·23
29	N.R.	—	—	—	—	—
30	108·3	0·01763	0·002944	3·07	4·00	4·08
31	108·9	0·01772	2964	3·10	4·02	4·19
32	110·3	0·01796	3018	3·15	4·10	4·05
33	110·3	0·01796	3018	3·15	4·10	4·24
34	109·3	0·01780	2982	3·11	4·05	4·11
35	68·7	0·01119	1598	1·67	2·17	2·12
36	82·2	0·01339	2035	2·13	2·76	2·81
37	103·9	0·01691	2783	2·91	3·78	3·61
38	116·5	0·01896	3247	3·39	4·41	4·30
39	118·4	0·01928	3321	3·47	4·51	4·28
40	117·6	0·01915	3291	3·44	4·47	4·47
41	119·2	0·01941	3352	3·50	4·55	4·47
42	116·5	0·01896	3247	3·39	4·41	4·41
43	118·4	0·01928	3321	3·47	4·51	4·55
44	68·3	0·01112	1584	1·65	2·15	2·14
45	85·0	0·01384	0·002126	2·22	2·89	2·83

APPENDIX II

Travel of Tension Wave through Rope System

During Run No. 50 a high-speed film record was made of the moving crosshead; typical examples are shown in Fig. 21. The ropes were marked individually to measure the movement of each separately. The following points are immediately noted.

(i) Before the crosshead has moved appreciably the first rope (nearest camera) shows a marked movement due to the extension of the rope caused by the tension wave

(ii) The ropes move off from rest successively as the tension wave travels along the rope system

(iii) The tensions in the first few ropes are sufficient to cause crosshead movement even before the tension wave has travelled the length of the rope and this causes the last ropes to slacken. This effect is very marked in Fig. 21b.

A further analysis of the motion is made in Fig. 22 where the ropes and crosshead displacement are plotted against time, the origin of the time scale being arbitrary. It will be seen that the slackening of the later ropes increases the time lag between their successive movements. A reasonable estimate of the tension wave velocity in the reeving is however obtained from ropes Nos. 1 and 2. The time lag is found to be 0·0069 sec giving a velocity of 9,600 ft/sec. This value is in reasonably good agreement with the value of 10,370 ft/sec found in Appendix I, the discrepancy being no doubt due to the effect of the pulleys.

The slopes of the curves give the particle velocities in the rope. From rope 1 the particle velocity is found to be 36·5 ft/sec at the steepest part of the curve. The particle velocity calculated from the kink wave angle is found to be 35·5 ft/sec. (Particle velocity = ea.)

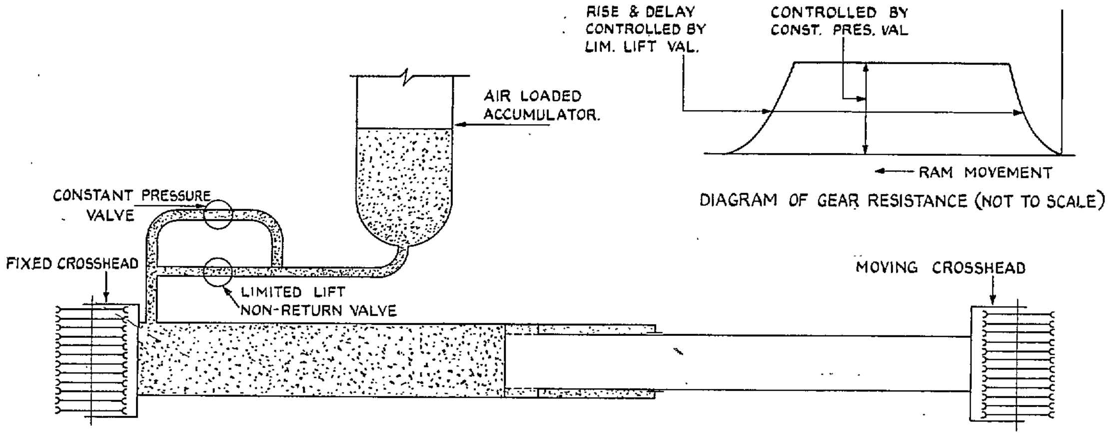
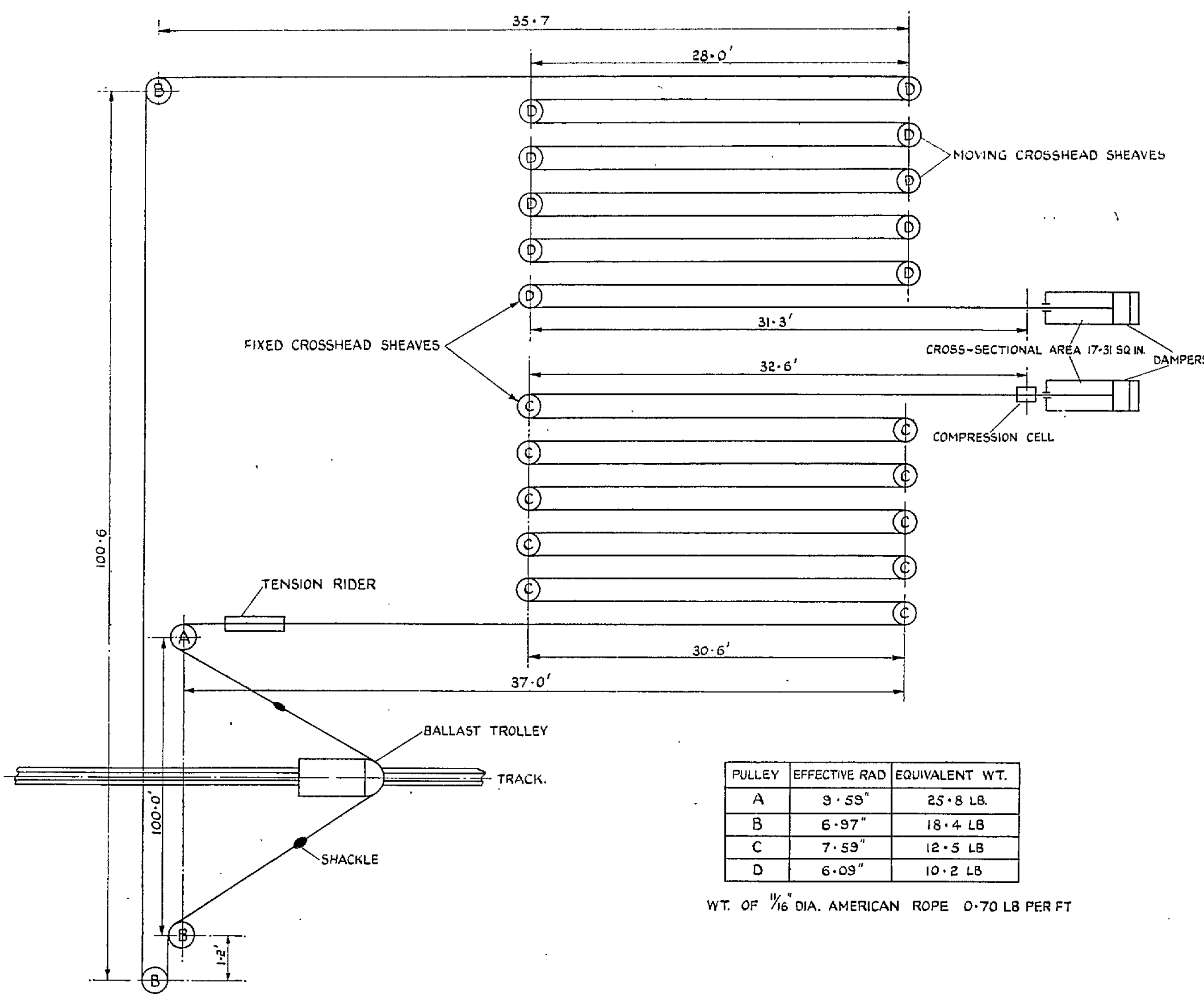


FIG. 1. Diagrammatic arrangement of American Mk. IV unit.



PULLEY	EFFECTIVE RAD	EQUIVALENT WT.
A	9·59"	25·8 LB.
B	6·97"	18·4 LB
C	7·59"	12·5 LB
D	6·09"	10·2 LB

FIG. 2. Diagrammatic arrangement of rope layout.

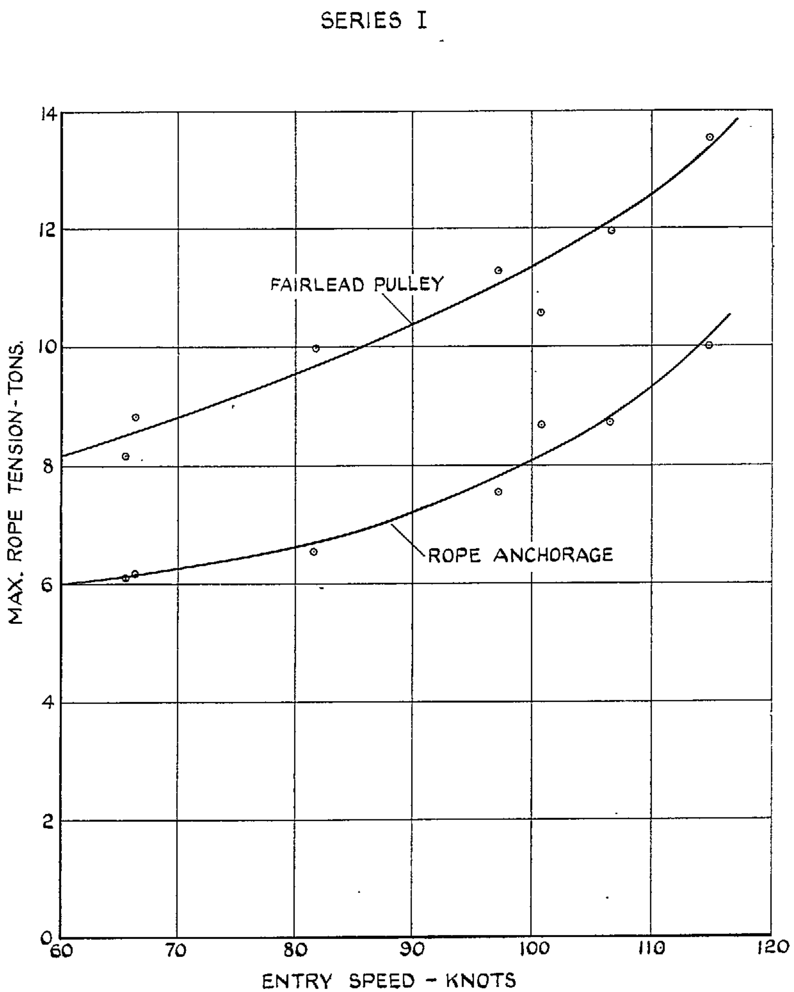


FIG. 3. Basic performance of arresting gear at 5,400 lb.

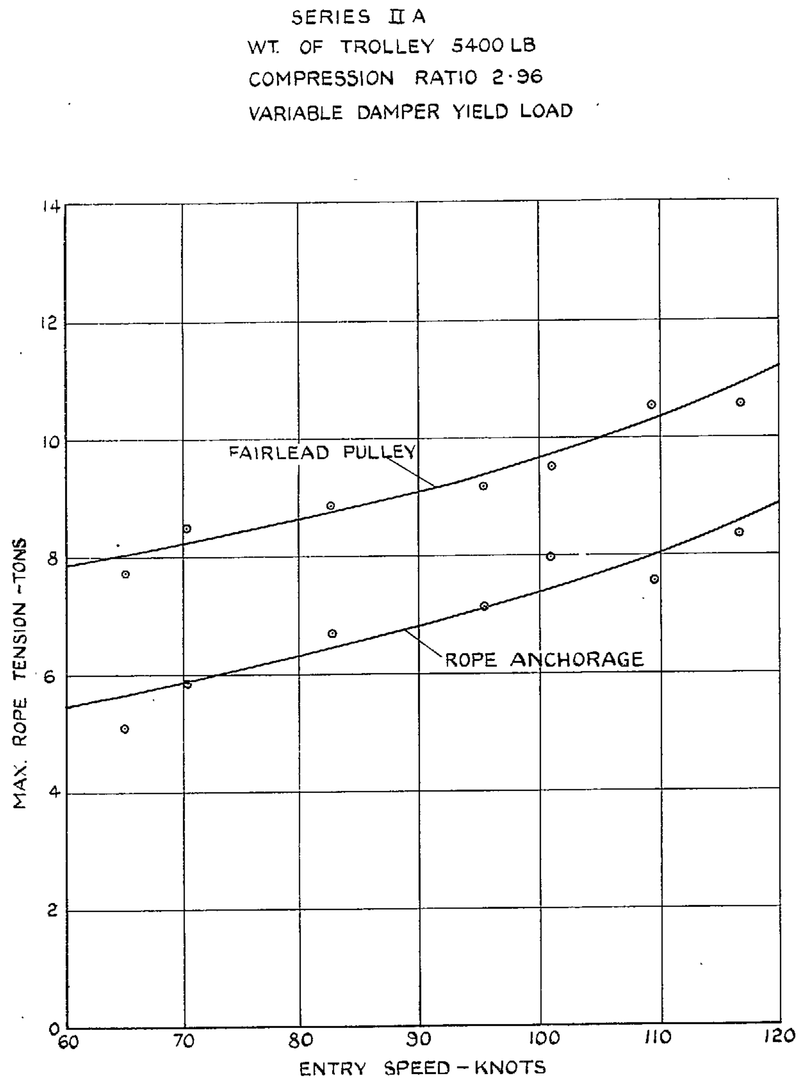


FIG. 4. Arresting gear performance with full damper stroke.

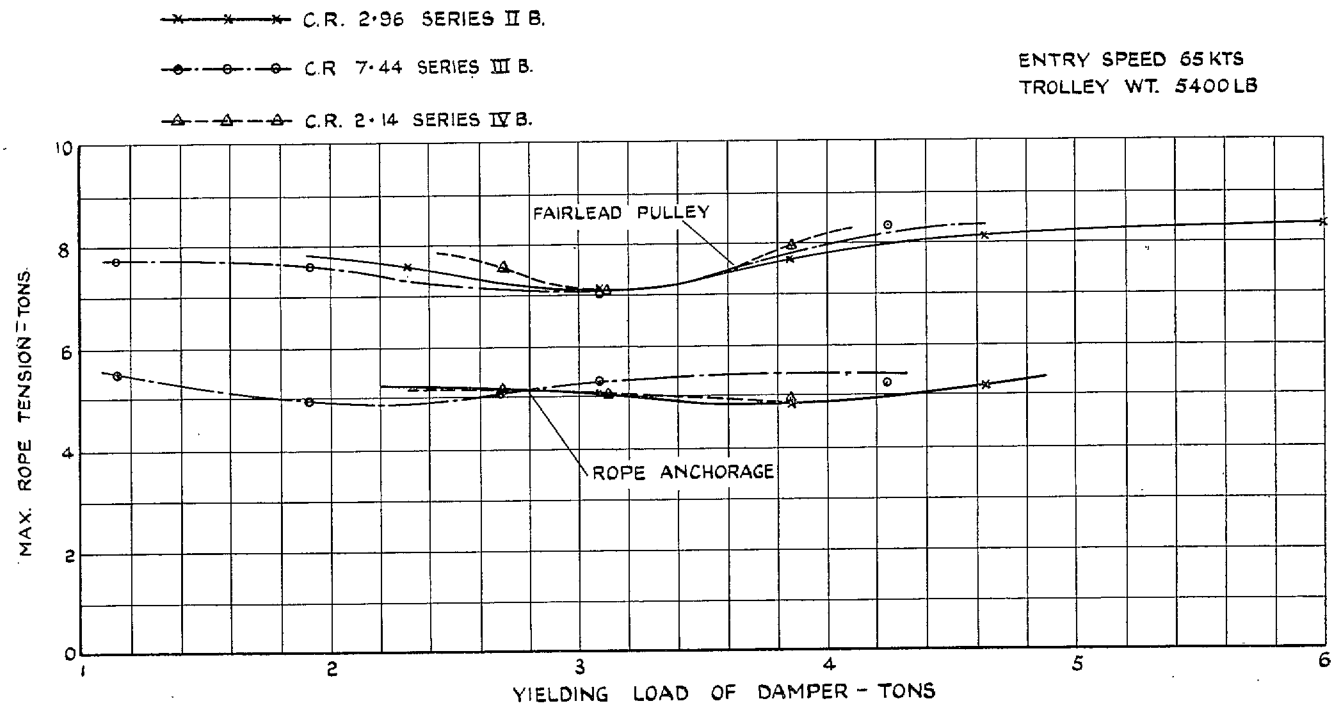


FIG. 5. Variation of maximum rope tension with damper yield load (5,400 lb at 65*K*).

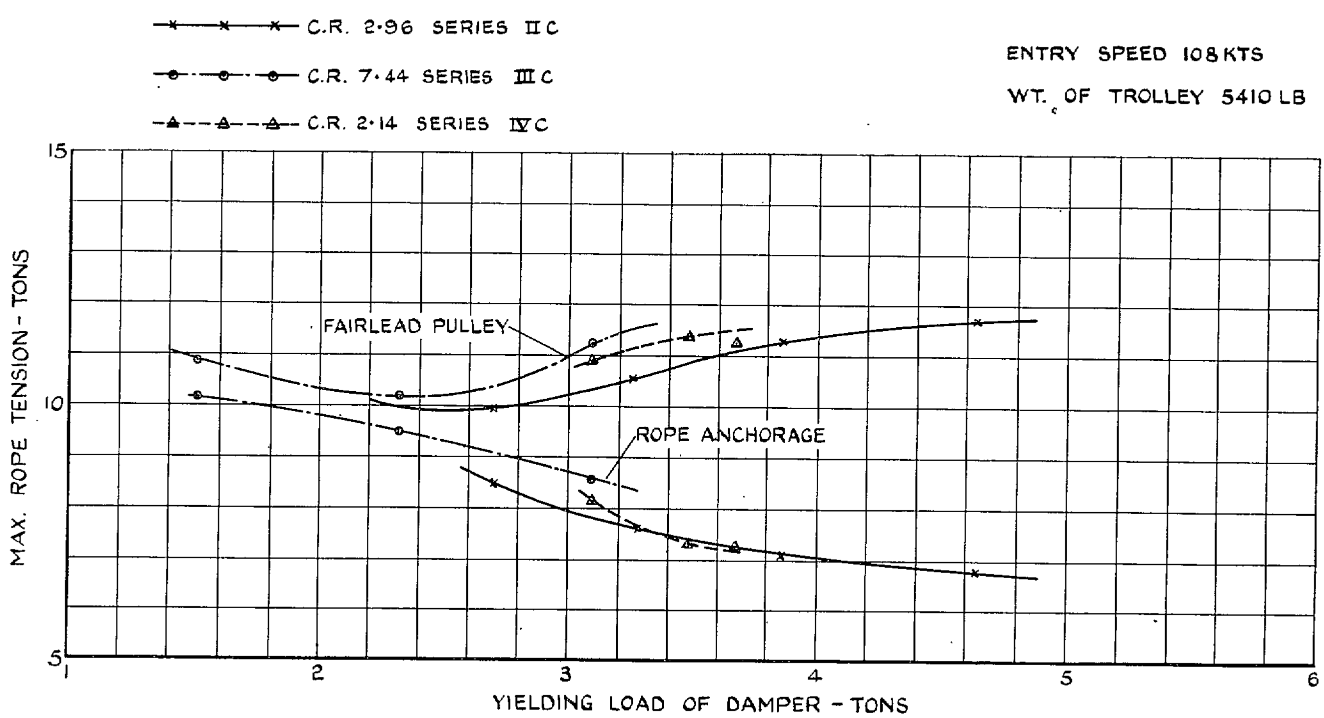


FIG. 6. Variation of maximum rope tension with damper yield load (5,400 lb at 108*K*).

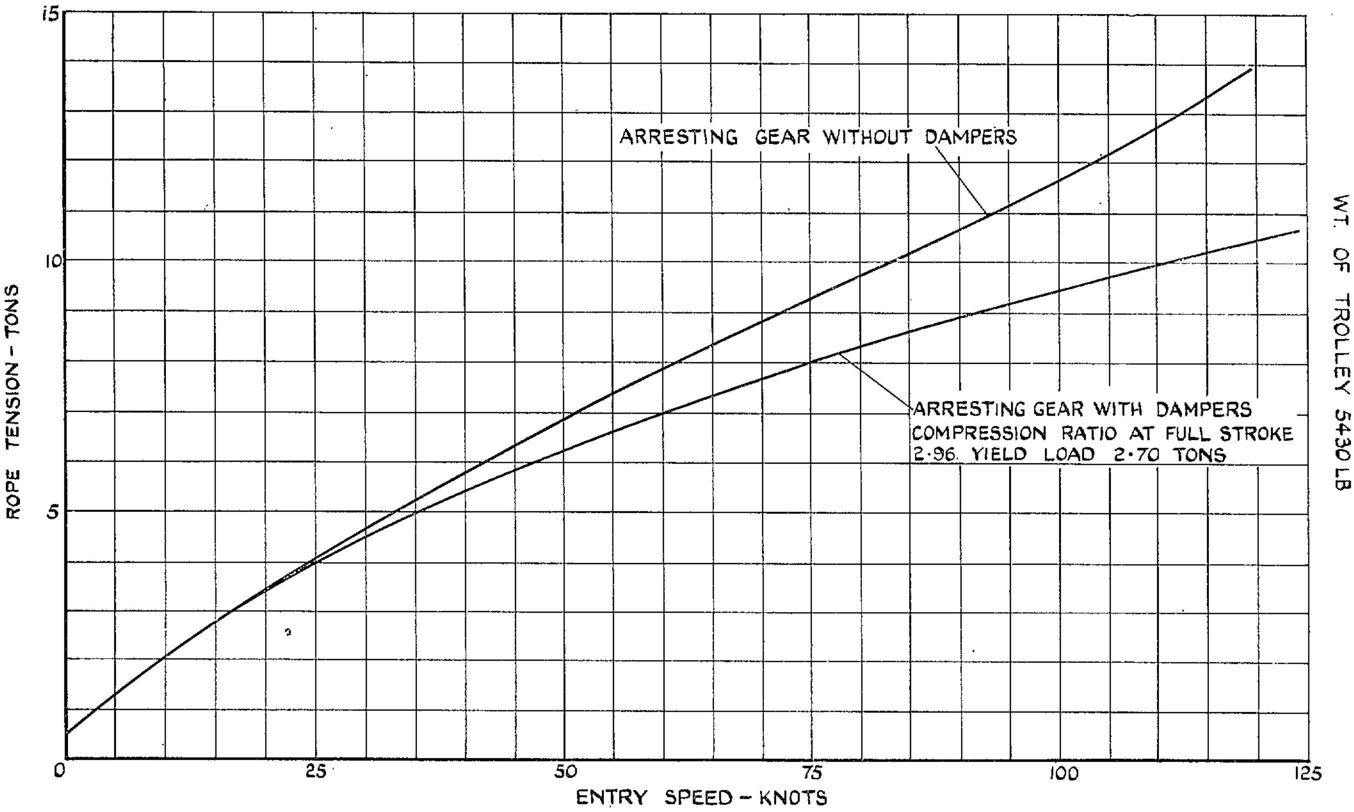


FIG. 7. Effect of dampers at a constant yield load (5,400 lb at 64K to 115K).

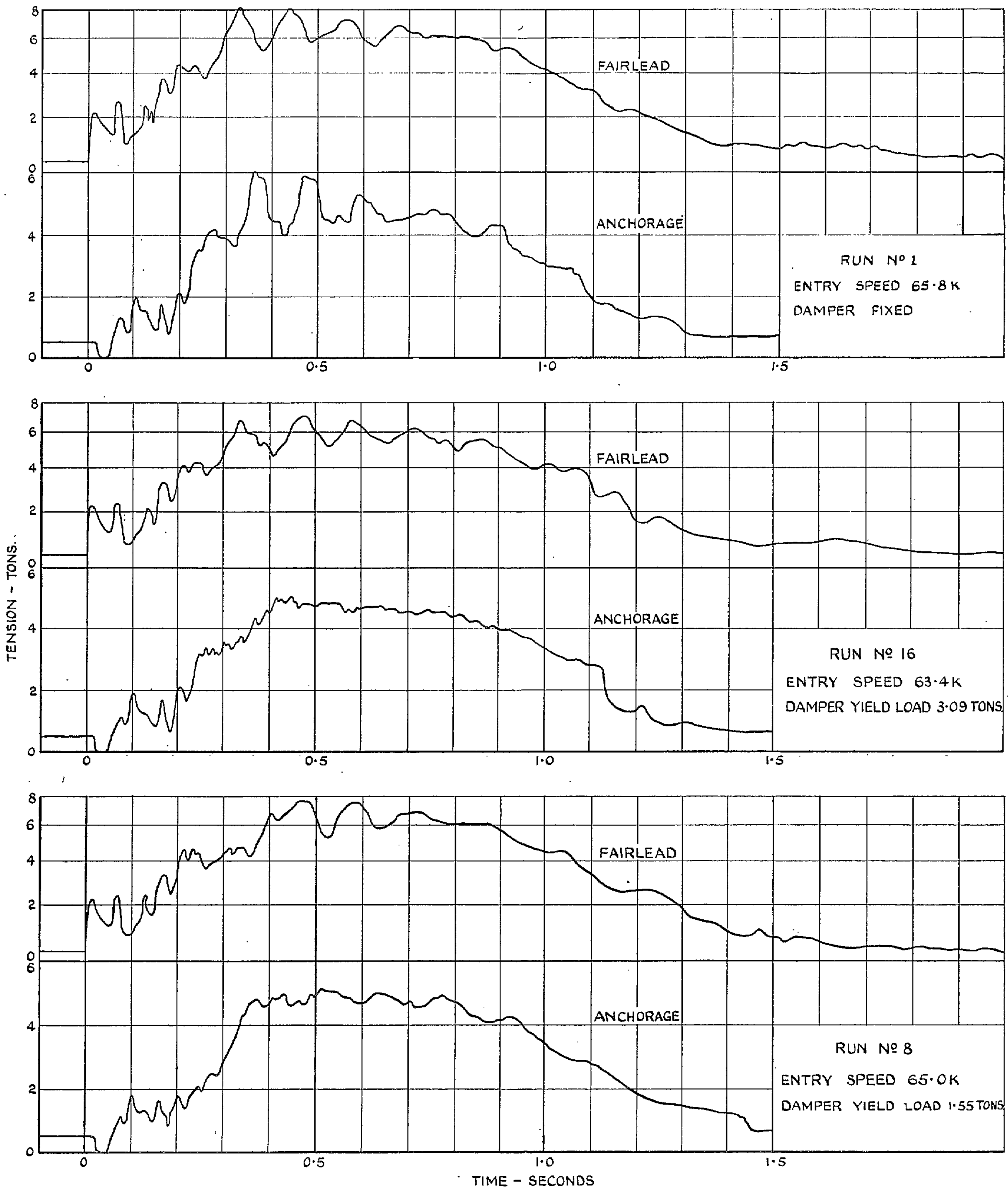


FIG. 8. Rope tension records. Effect of varying yield load (5,400 lb at 65K).

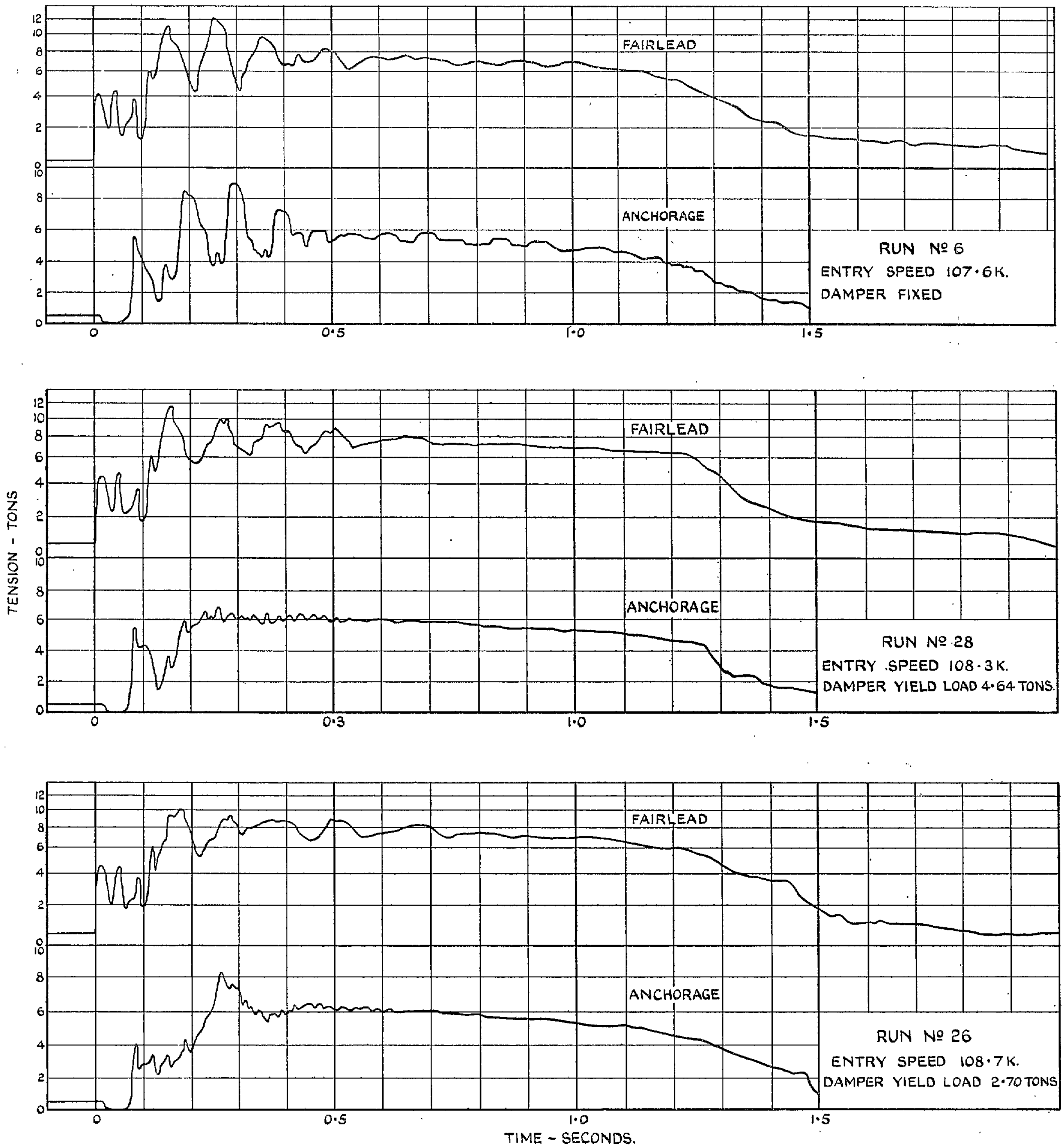


FIG. 9. Rope tension records. Effect of varying yield load (5,400 lb. at 108K).

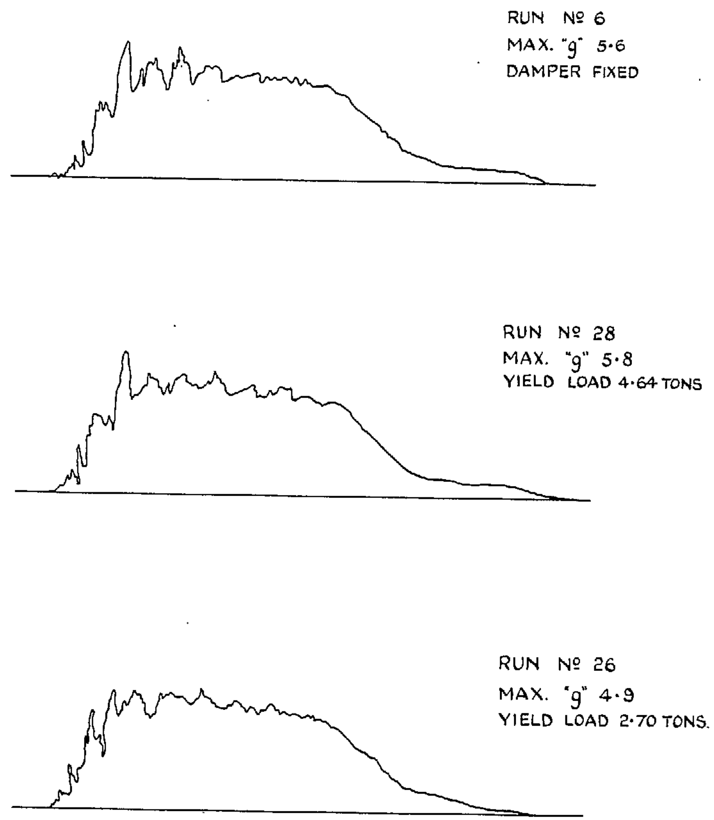


FIG. 10. Trolley retardation records. Effect of varying yield load (5,400 lb. at 108K).

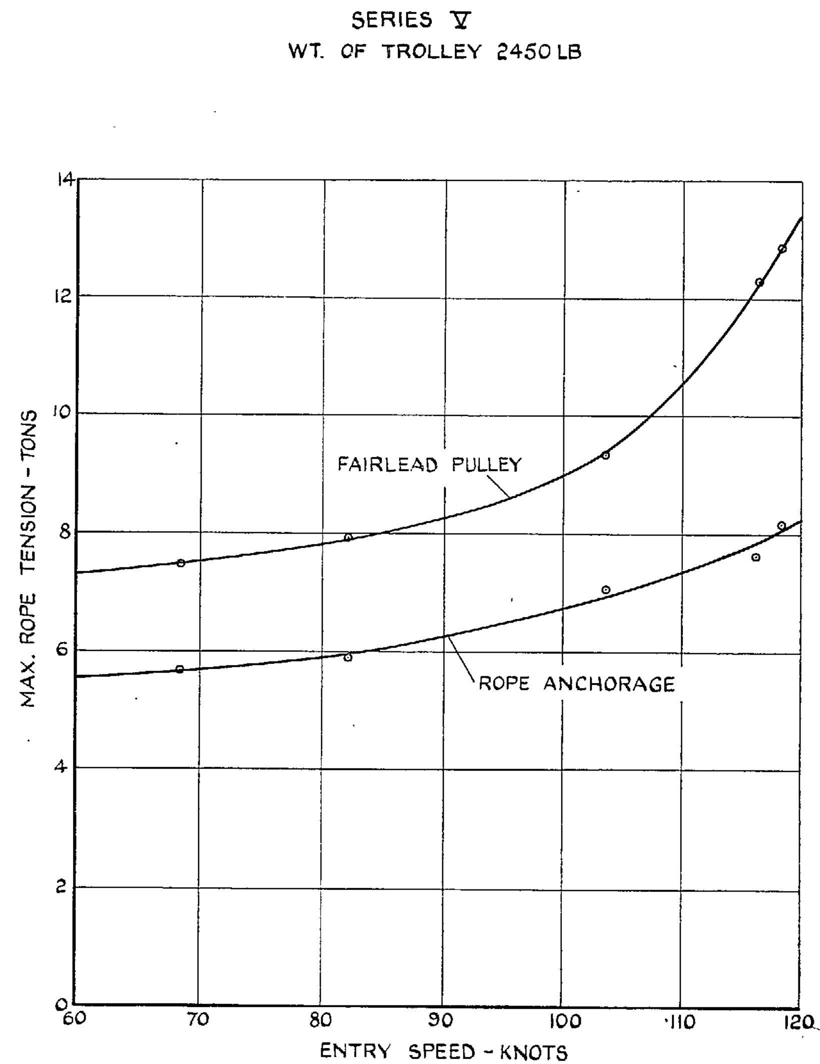


FIG. 11. Basic performance of arresting gear at 2,450 lb.

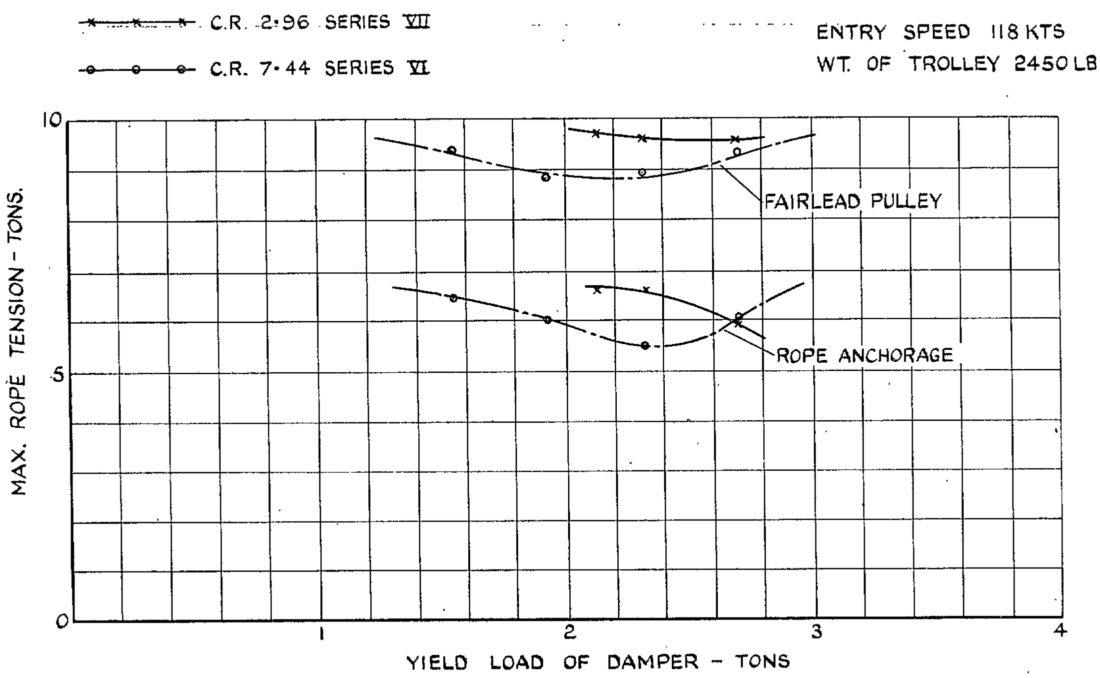


FIG. 12. Variation of maximum rope tension with damper yield load (2,450 lb at 118K).

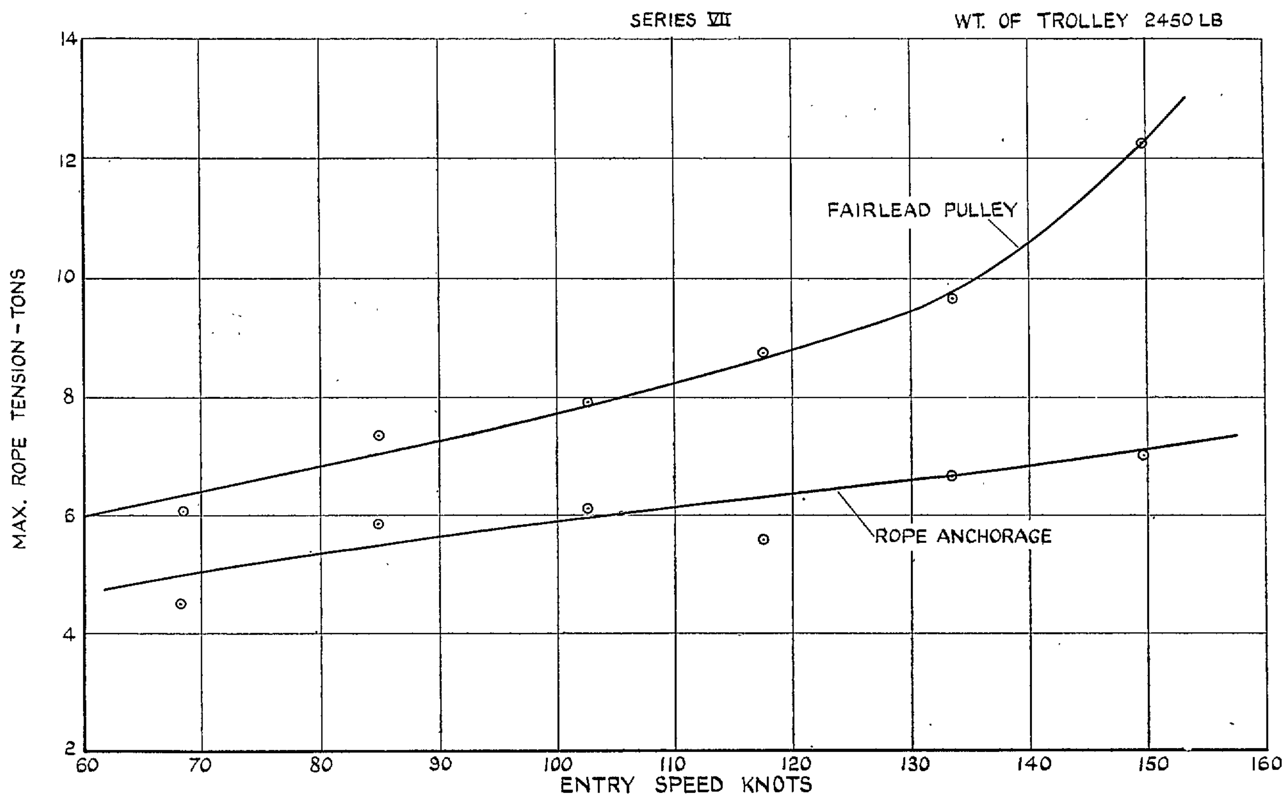


FIG. 13. Arresting gear performance at 2,450 lb with a constant yield load.

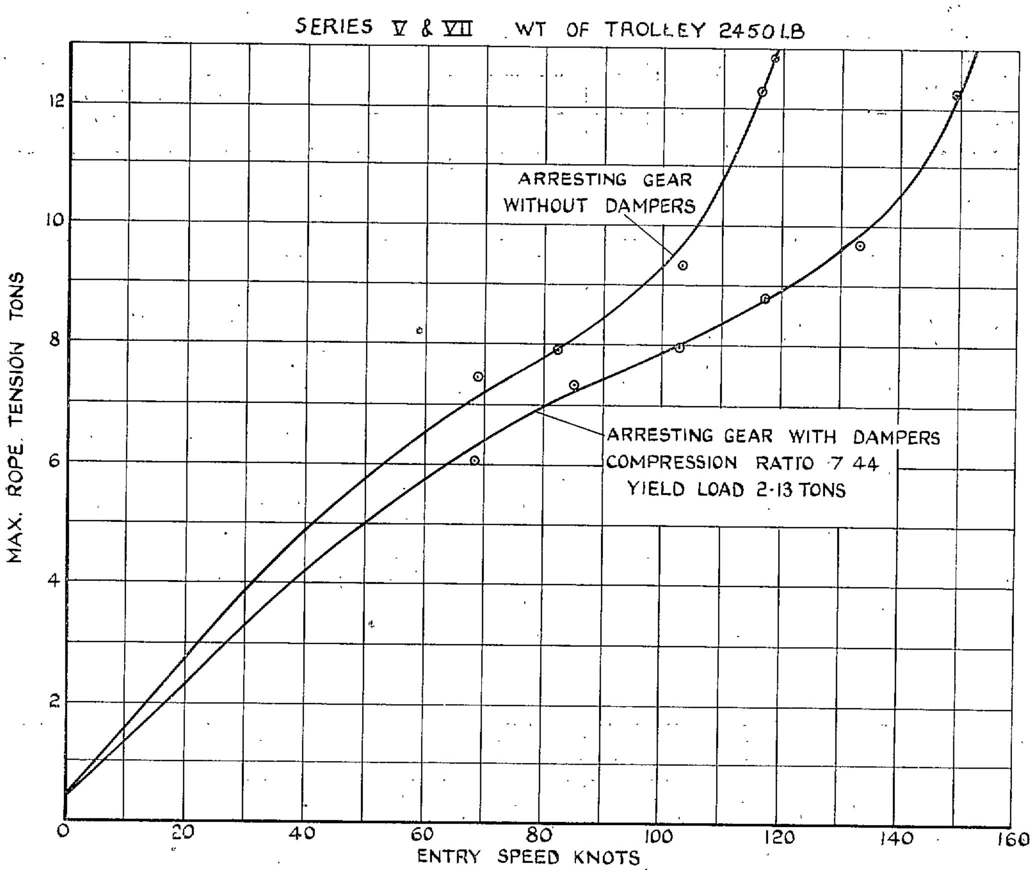


FIG. 14. Effect of dampers at a constant yield load (2,450 lb at 68K to 151K).

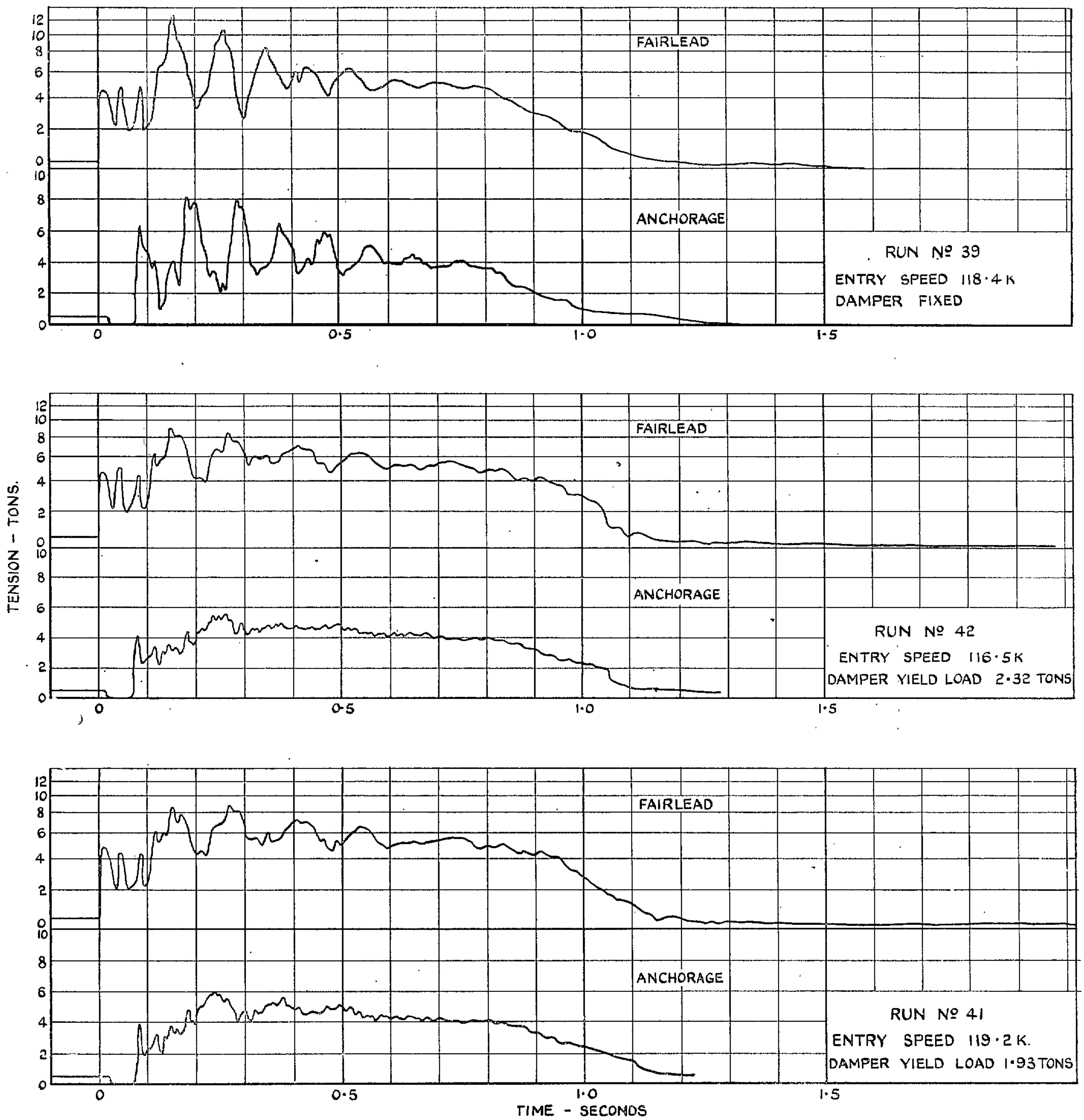


FIG. 15. Rope tension records. Effect of varying yield load (2,450 lb at 118K).

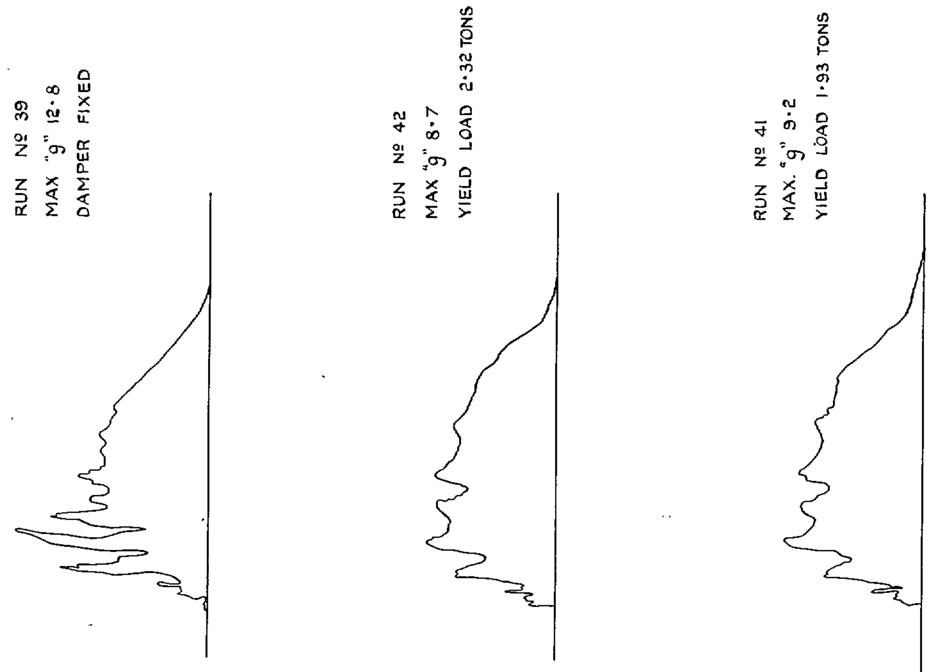


FIG. 16. Trolley retardation records. Effect of varying yield load (2,450 at 118K).

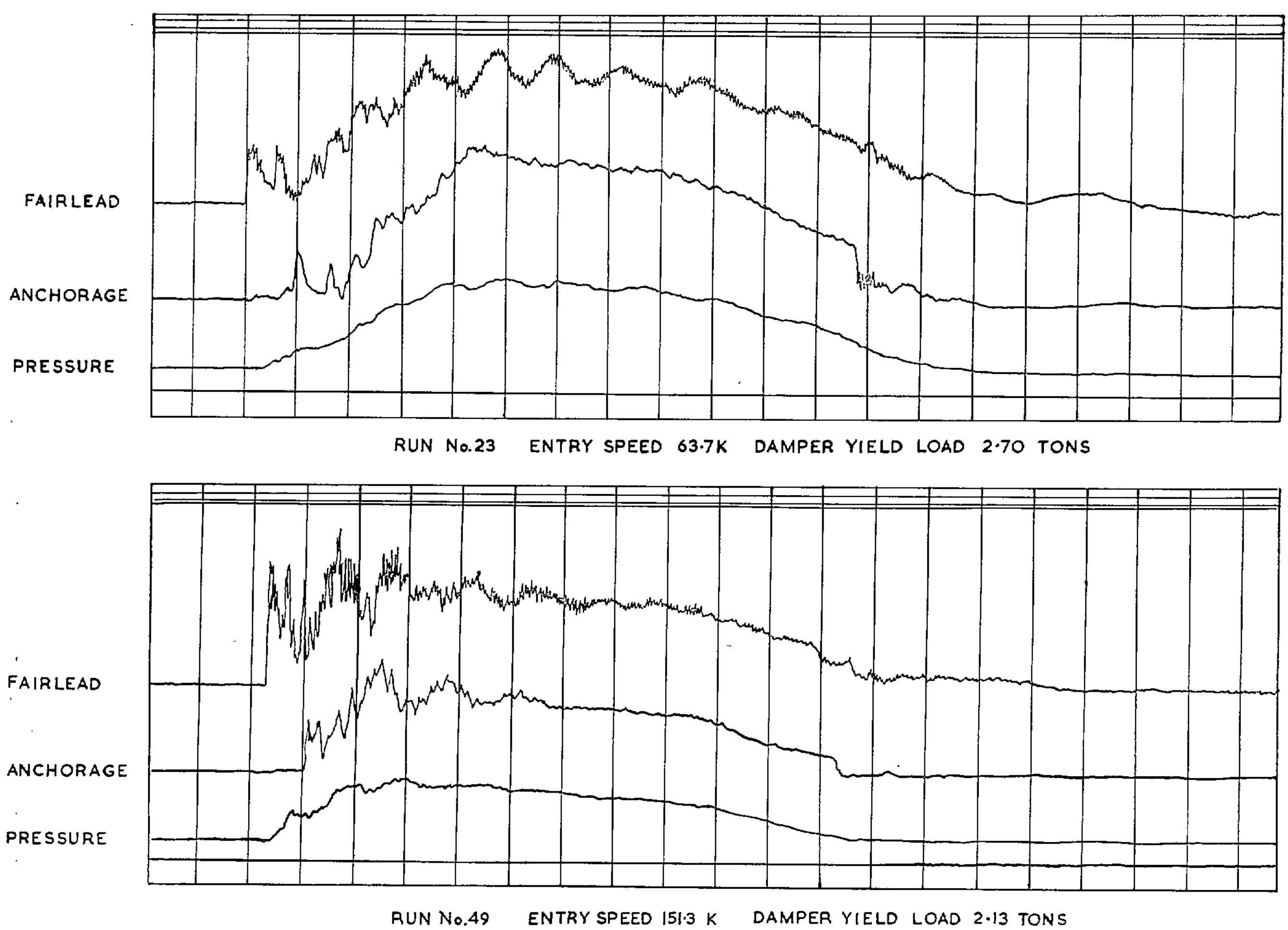


FIG. 17. Reproductions of typical oscillograph records.

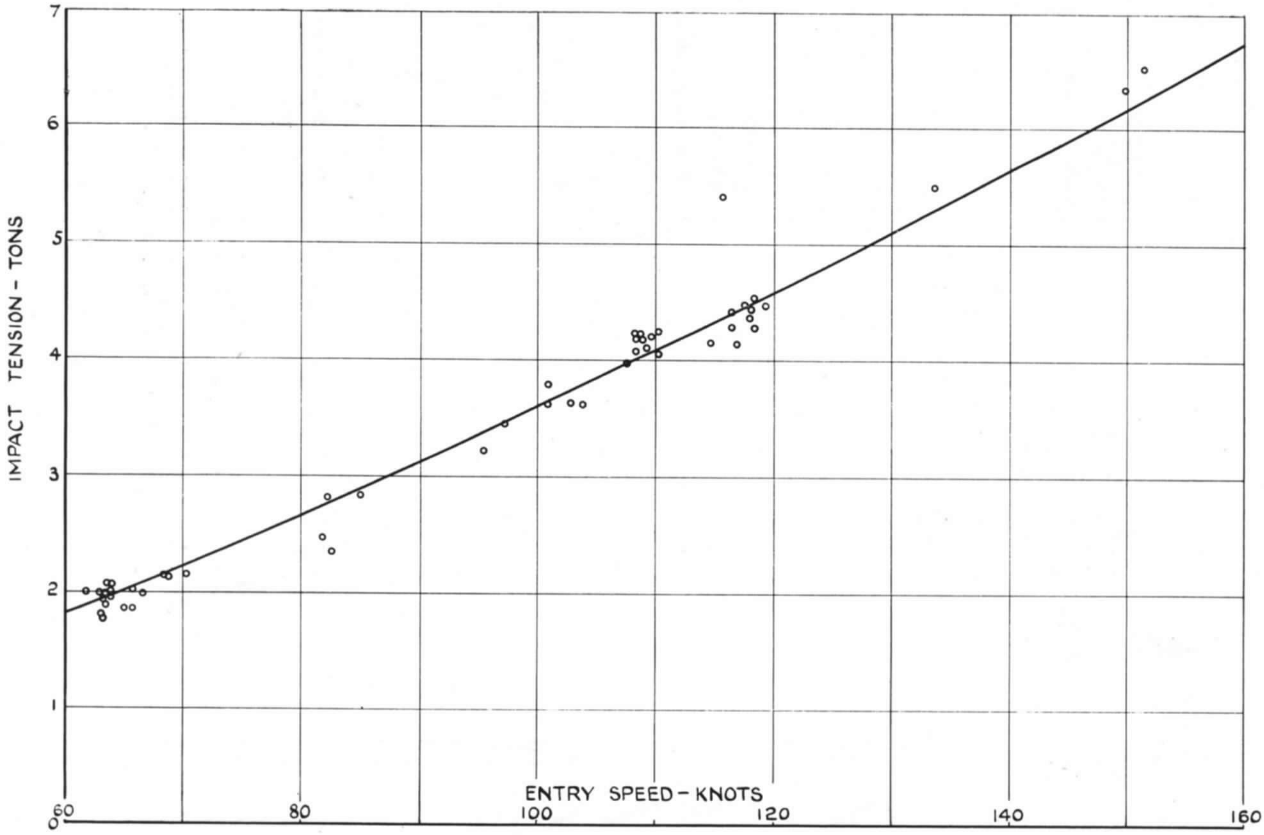


FIG. 18. Comparison of actual and theoretical impact tensions.

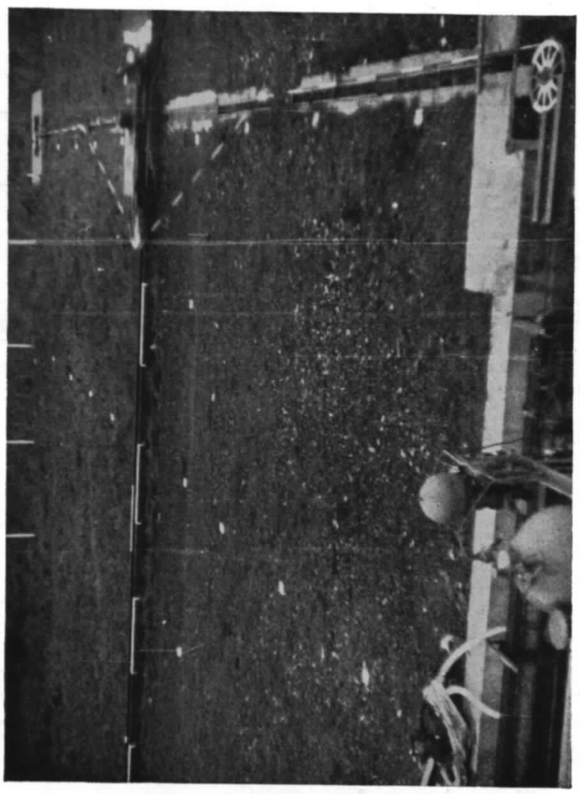


FIG. 19a.

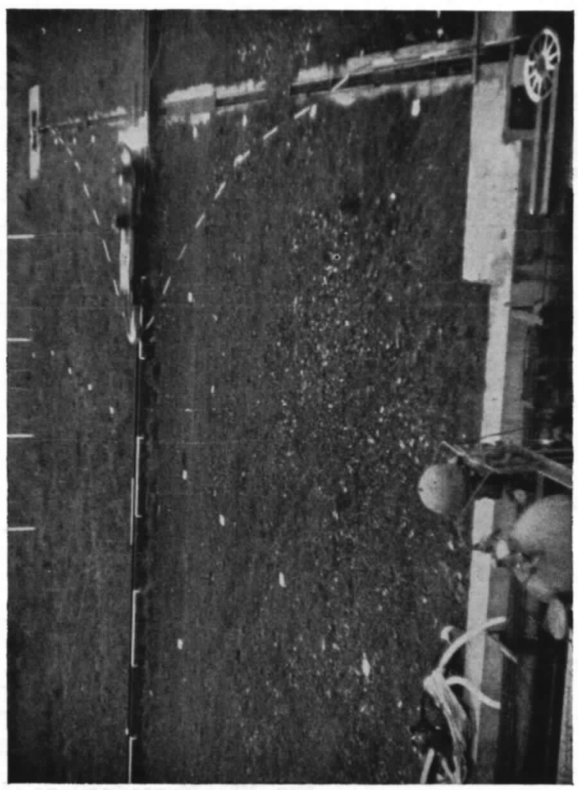


FIG. 19b.

FIGS. 19a and 19b. Impact ' kink ' wave. Entry speed 204·5 ft/sec.

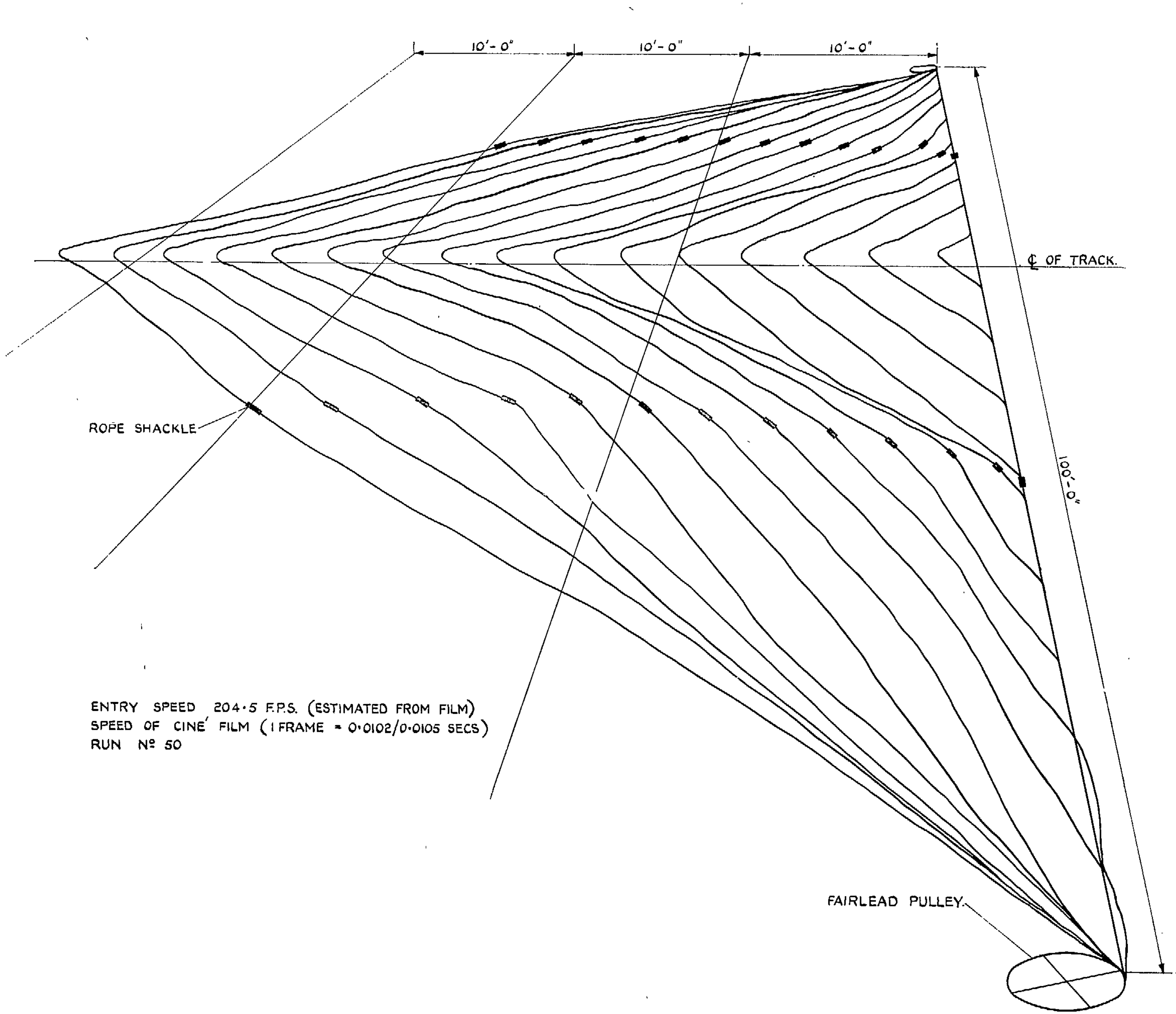


FIG. 20. Development of ' kink ' wave in an arresting gear centre span.

FIG. 21a.

FIG. 21b.

FIGS. 21a and 21b. Initial movement of rope reeving and crosshead. Entry speed 204·5 ft/sec.

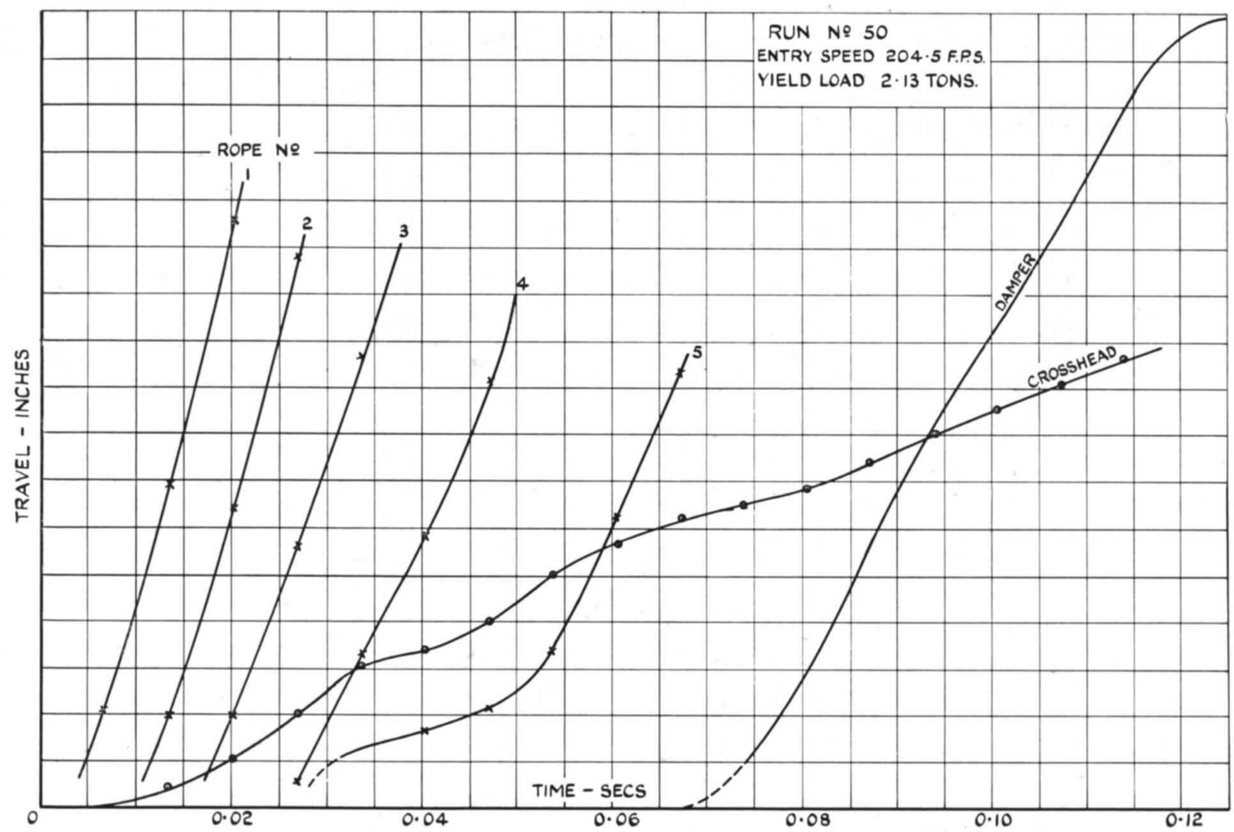


FIG. 22. Initial movement of rope reeving and crosshead. Entry speed 204·5 ft/sec.

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