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Civil Aircraft Airworthiness Data Recording Programme Study of Severe Turbulence Encountered by Civil Aircraft

by

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CIVIL AIRCRAFT AIRWORTHINESS DATA RECORDING PROGRAMME

STUDY OF SEVERE TURBULENCE ENCOUNTERED BY CIVIL AIRCRAFT

by

G. E. King

SUMMARY

Continuous trace records of airworthiness data have been taken from a small number of aircraft in normal airline service since October 1962.

The acceleration trace on a sample of records covering 3284 flying hours has been read to give peak values. The durations of the patches of turbulence have been estimated and an attempt has been made to distinguish between gust and manoeuvre loads.

The most severe of these patches of turbulence have been studied in detail; it is found that the largest acceleration in a patch is often larger than would be predicted from a Rayleigh distribution of peaks, which is the distribution normally used in spectral analysis of turbulence.

* Replaces R.A.E. Technical Report 67106 - A.R.C. 29535

CONTENTS

1 INTRODUCTION

The collection of data on atmospheric turbulence affecting normal civil operations is usually done in the U.K. by means of the Counting Accelerometer[1]. Analysis of these records necessarily involves assumptions about the loads over short time intervals. With continuous trace records it is possible to study individual patches of turbulence in detail and an attempt can be made to distinguish between gust and manoeuvre loads.

It is the purpose of this paper to examine the peak acceleration distributions of the most severe patches of turbulence taken from a sample of CAADRP[2] continuous trace records, and also to present the full acceleration distributions of the sample.

In addition, the accelerations have been divided into manoeuvre and turbulence, and the durations of the patches of turbulence have been measured.

The airspeed trace at the time of a turbulence encounter can give an indication of the degree of warning of turbulence, as the aircraft in question have recommended rough air speeds which differ from the normal operating speeds. For each of the patches of severe turbulence presented in this Report the degree of warning is discussed.

2 TYPE OF FLYING

The records analysed were a random selection from three aircraft types. All the aircraft are four engined pure jet civil transports and are fitted with storm warning radar.

Aircraft type III is a later version of type I whilst type II is of a different manufacture.

The number of flying hours and the routes covered by each type are as follows:-

Type I 882 hours 325 flights	Flying from London to Europe, Africa, India, Far East, Australia and South America.
Type II 1351 hours 388 flights	Flying from London to Europe, India, Far East, Australia, North America and West Indies.
Type III 1051 hours 686 flights	Flying from London to Europe and the near East.

3 METHOD OF TRACE READING

3.1 Measurement

Each acceleration trace peak greater than 0.25 g increment was measured according to the mean crossing peak count method[5]. This method ignores small changes in acceleration by measuring the largest peak between successive zero crossings. In turbulence however, the trace becomes a series of alternate positive and negative acceleration levels; successive zero crossings cannot be seen but, by measuring each peak, the mean crossing peak count method is still in effect being used. The interval between successive acceleration peaks of the same sign in turbulence is between 3 and 4 seconds. This does not vary greatly unless there are manoeuvres present.

3.2 Separation of gusts from manoeuvres

The distinction between gusts and manoeuvres was drawn by taking accelerations lasting more than approximately two seconds as manoeuvres. An acceleration thought to be a manoeuvre using the above distinction was further examined in conjunction with the elevator trace. As there is no simple elevator displacement-acceleration relationship, a particular manoeuvre was confirmed if the elevator moved in the correct sense; this is thought to work well for manoeuvres in fairly smooth air. When flying manually at low altitude there are often considerable elevator movements and associated accelerations and, although these are thought to be induced by the atmosphere, the loads have been classed as manoeuvres, because the significant loads are clearly produced by the elevator movements. Within a patch of turbulence, however, any manoeuvre contribution to the peak accelerations has not been separated, and the total distributions of counts due to turbulence must necessarily include some manoeuvres.

For the most severe patches of turbulence, which are presented separately, the extent of manoeuvre contribution to the maximum acceleration increment in each patch is discussed.

3.3 Duration of turbulence

The duration of a patch of turbulence was taken as the time to the nearest $\frac{1}{2}$ minute over which the counts were of fairly uniform frequency and above 0.25 g increment. However, these criteria cannot be applied precisely and the durations of individual patches are based on human judgment. This is smoothed out to a large extent in the addition of the individual patches to form the total time spent in turbulence.

3.4 Acceleration counts

The acceleration counts given in this paper are the number of peaks exceeding the specified level; that is the number of counts at say 0.5 g refers to actual values of 0.51 g and above in the case of a cumulative distribution. If the cumulative counts are differenced then the number of counts at say 0.5 g is for actual accelerations of 0.51, 0.52, 0.53, 0.54 and 0.55 g.*

4 DATA

4.1 Presentation

The cumulative distributions of acceleration counts for each aircraft type were obtained for both positive and negative gust and manoeuvre loads in climb, cruise and descent. These data are given in Tables 1-3. Figs.1-4 represent data from aircraft type I, Figs.5-8 from type II and Figs.9-12 from type III.

4.2 Turbulence encounters

Figs.1, 5 and 9 are plots using data from Tables 1-3 of the cumulative distributions of acceleration increments due to turbulence (log counts against g) positive and negative increments being taken together. The patches of severe turbulence which form the high g end of these distributions were selected for further study as follows:-

Aircraft type I - patches containing over 0.80 g increment
Aircraft type II - patches containing over 0.60 g increment
Aircraft type III - patches containing over 0.75 g increment.

The use of the above selection levels produced a total of 24 patches of turbulence which are described individually in para.4.5.

The distributions obtained by the summation of these patches for each aircraft type are given in Figs.3, 7 and 11 whilst the distributions resulting from the remaining turbulence which has not been divided into separate patches are given in Figs.2, 6 and 10.

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*These counting levels have been used for the distributions although to be precise the levels should have been 0.495, 0.505, 0.515 g, etc., but the accuracy of the original data does not warrant this refinement.

4.3 Manoeuvre loads

The manoeuvre data in Tables 1, 2 and 3 are plotted (log counts against g) in Figs.4, 8 and 12, and show positive and negative loads for each aircraft type in climb and descent. The cruise manoeuvre loads have not been plotted as these are too few in number.

On a visual assessment, without fitting calculated distributions, the plots show an exponential distribution with a lower severity than for the turbulence distributions.

4.4 Duration of turbulence

Distributions of durations are given in Table 4 for all patches of turbulence and for the 24 most severe patches which had been separated using the method given in para.4.2. This table was used to give Fig.13 which shows the number of patches per hour of duration t minutes or more plotted against t.

In addition, the durations of the patches have been summed for each aircraft type and flight phase, and the percentages of time spent in turbulence in climb, cruise and descent are given in Table 5.

It should be noted that these durations are for turbulence patches containing over 0.25 g increment. If a lower g level was used, many of the short patches would join to form longer patches and some extra patches would be included, thereby changing the distribution presented here.

4.5 Studies of the most severe patches of turbulence

The circumstances giving rise to the 24 patches of turbulence separated by the method given in para.4.2 are described individually. The equivalent gust velocity (for a 100ft ramp shaped leading edge gust) corresponding to the largest acceleration in a patch is given only where there is no manoeuvre contribution to the largest count.

Reproductions* of the original traces are given in Figs.14-37.

Aircraft type I - 8 patches a to h

Aircraft type I normally cruises in excess of the recommended rough air speed, and if severe turbulence is suspected the airspeed is reduced.

*Definition is necessarily lost in reproduction of the traces and many acceleration spikes can only be seen on the original record. The largest spike has been marked by a dot.

The airspeed handling can thus be taken as an indication of the degree of warning available to the pilot. Information concerning height, weight, speed and acceleration counts is given in Table 6.

(Ia) Sector: Kuala Lumpur - Singapore (See Fig.14)

During climb out in generally heavy turbulence the airspeed was held down before the largest acceleration (+0.80 g) was encountered. Any manoeuvre contribution appears to be small.

(Ib) Sector: Nairobi - Khartoum (See Fig.15)

A sudden short patch of severe turbulence was encountered during an otherwise normal climb out. The airspeed was reduced after the largest acceleration (+0.85 g) was encountered and it is likely that this patch occurred without warning. There is no elevator input and the largest increment is more in the nature of a discrete gust. The equivalent gust velocity is 32 ft/sec.

(Ic) Sector: Colombo - Kuala Lumpur (See Fig.16)

The normal cruise airspeed was reduced slightly, because of moderate turbulence, about 3 minutes before the most extreme acceleration (-0.80 g) was encountered, but this severe patch apparently occurred without warning. There is a rapid elevator input corresponding to the most extreme acceleration, which may have increased the maximum increment.

(Id) Sector: Darwin - Sydney (See Fig.17)

A completely unexpected patch of turbulence followed a long period of smooth cruise. The airspeed was reduced during the event, but was increased again afterwards. There is some elevator input which appears to have moved the g trace in the positive direction and probably increased the maximum increment (+0.95 g) by about 0.2 g.

(Ie) Sector: Recife - Sal (See Fig.18)

The normal cruise airspeed was reduced five minutes before the encounter, showing that some warning was available. There is a small elevator input corresponding to the largest acceleration (+0.90 g), but the manoeuvre produced by this is probably less than 0.1 g.

(If) Sector: Kuala Lumpur - Colombo (See Fig.19)

The airspeed was reduced 24 minutes before the event, at the start of a turbulent descent, and the degree of warning cannot be assessed. There is some elevator movement corresponding to the most extreme acceleration (-0.95 g) and this may have contributed about 0.4 g to the increment.

(Ig) Sector: Melbourne - Brisbane (See Fig.20)

During the initial part of descent, following a period of smooth cruise, turbulence was encountered which was almost certainly unexpected, as the airspeed was reduced after the event. There is no elevator input corresponding to the maximum acceleration (+0.90 g). The equivalent gust velocity is 36 ft/sec.

(Ih) Sector: Colombo - Bombay (See Fig.21)

The descent airspeed was reduced before the event and was further reduced after the event, making it difficult to assess the degree of warning. There is no elevator input corresponding to the maximum acceleration (+0.80 g) and this patch is similar in character to patch b, with an equivalent gust velocity of 42 ft/sec.

Aircraft type II - 11 patches a to k

Aircraft type II normally cruises below the recommended rough air speed and little indication of the degree of warning of turbulence is available from the airspeed handling.

Information concerning height, weight, speed and acceleration counts is given in Table 7.

(IIa) Sector: London - Frankfurt (See Fig.22)

The climb out airspeed was reduced slightly before the most extreme acceleration (-0.65 g) was encountered. The counts are displaced to the negative side by about 0.1 g manoeuvre, and this probably increased the increment.

(IIb) Sector: Delhi - Bangkok (See Fig.23)

This was a climb out in turbulence and the loads are a mixture of gust and manoeuvre. The patch of turbulence contains some manoeuvre loads, but the most extreme acceleration (-0.60 g) has the character of a gust. It is not possible to assess the manoeuvre contribution to this acceleration, or the degree of warning.

(IIc) Sector: Darwin - Hongkong (See Fig.24)

Turbulence was encountered following a period of smooth cruise and was probably unexpected. The largest acceleration (+0.65 g) has little manoeuvre contribution, but the other accelerations contain a considerable amount of manoeuvre.

(IId) Sector: Manila - Sydney (See Fig.25)

A short extremely severe and unexpected patch of turbulence was encountered following a period of smooth cruise. The initial elevator movement occurs just before the most extreme acceleration (-0.95 g), which probably contains no manoeuvre contribution. The equivalent gust velocity is 68 ft/sec.

(IIe) Sector: New York - London (See Fig.26)

Continuous turbulence lasting 24 minutes was encountered during cruise. The counts presented in Fig.41 are for the period of highest intensity which lasted $4\frac{1}{2}$ minutes. There are elevator inputs throughout the patch, but these do not appear to have influenced the two most extreme increments (-0.80 g and -0.85 g). The equivalent gust velocities are 46 and 49 ft/sec respectively.

(IIf) Sector: Calcutta - Singapore (See Fig.27)

Towards the end of a period of light turbulence, a patch of greater severity was encountered. The normal cruise airspeed was reduced during the event, so it is probable that this intensity was unexpected. There is no elevator input corresponding to the most extreme acceleration (-0.60 g). The equivalent gust velocity is 42 ft/sec.

(IIg) Sector: London - New York (See Fig.28)

This seven minute period of turbulence, which occurred in cruise, has been treated as one patch, but could also have been regarded as several shorter patches. The largest acceleration in each short patch is in the nature of an isolated gust and any manoeuvre contribution is small. It is not possible to assess the degree of warning.

(IIh) Sector: Frankfurt - Zurich (See Fig.29)

During the descent, the airspeed was reduced before the largest acceleration (+0.70 g) was encountered and it is probable that some warning was available. There is some elevator input which may have increased the maximum increment.

(IIi) Sector: Bahrain - Delhi (See Fig.30)

The airspeed was fluctuating during this part of the descent, and it is difficult to assess the degree of warning. There is an elevator input corresponding to the most extreme acceleration (-0.70 g) which may have contributed to the increment.

(IIj) Sector: Beirut - Rome (See Fig.31)

A patch of turbulence was encountered during the descent, producing an extreme increment of -0.60 g, of which about 0.2 g was manoeuvre. The degree of warning cannot be assessed, in fact the airspeed increased during the encounter.

(IIk) Sector: Hongkong - Bangkok (See Fig.32)

The last part of the descent was carried out in general turbulence, and there is considerable elevator activity. It is not possible to assess either the manoeuvre contribution to the most extreme increment (-0.60 g), or the degree of warning.

Aircraft type III - 5 patches a to e

Aircraft type III normally cruises in the region of the recommended rough air speed but an indication of the degree of warning of turbulence is available from the airspeed handling. Information concerning height, weight, speed and acceleration counts is given in Table 8.

(IIIa) Sector: Madrid - London (See Fig.33)

A patch of turbulence was encountered during climb which produced an extreme increment of -0.85 g. There was probably no warning of the event as the airspeed, which was increasing at the time, was held down afterwards. Any manoeuvre contribution is small.

(IIIb) Sector: Naples - London (See Fig.34)

The airspeed was increasing during climb at the time of the largest acceleration (+0.75 g), but was reduced afterwards. Although some turbulence was present before the event, it is unlikely that this severity was expected. The maximum increment contains about 0.2 g manoeuvre and the aircraft may have been in a turn.

(IIIc) Sector: Rome - Paris (See Fig.35)

The normal cruise airspeed was reduced before the turbulence was encountered, indicating that some warning was available. An elevator movement corresponding to the most extreme acceleration (-1.20 g) may have contributed to the increment.

(IIId) Sector: London - Athens (See Fig.36)

Moderate turbulence, for which the normal cruise airspeed was reduced, was encountered some 10 minutes before the severe patch, and it is not possible to assess the degree of warning. The turbulence is superimposed on a ±0.1 g manoeuvre oscillation of 2 cycles/min, and the largest increment (+0.75 g) may contain 0.1 g manoeuvre.

(IIIe) Sector: London - Gibralter (See Fig.37)

The airspeed during descent was reduced two minutes earlier for a patch of turbulence which was probably unexpected. The airspeed was still at the reduced level when the second patch was encountered. There is no elevator input corresponding to the most extreme acceleration (-0.80 g). The equivalent gust velocity is 25 ft/sec.

5 DISCUSSION

5.1 Peak distributions of the most severe patches of turbulence

The crossing distribution of a stationary random Gaussian process of rms a can be described[3] by the following expression:-

$$N_x = N_o \exp\left(-\frac{x^2}{2a^2}\right) \qquad (1)$$

where N_o is the number of positive slope zero crossings

N_x is the number of positive slope x crossings.

If the response of an aircraft to random excitation is linear, then expression (1) will describe the normal acceleration history of an aircraft over a short constant rms value interval, if the turbulence is Gaussian in character.

In order to compare the patches of severe turbulence in this Report with (1), it is necessary to make two assumptions, as crossings have not been counted. The first is that expression (1) is a good approximation to the cumulative distribution of peak values. This has been investigated by Press and others[4] who consider that for gust loads on flexible aircraft, the use of expression (1) to derive the peak distribution gives values 10-15% low at $\frac{x}{a} = 1$ and 2-3% low at $\frac{x}{a} = 2$. The second assumption is that the mean crossing peak count method gives values compatible with a full peak count, and this is shown to be so in Ref.5.

If a patch of turbulence follows expression (1), i.e. a Rayleigh distribution, then the plot of log counts (N) against acceleration increment squared (x^2) is a straight line of slope $2a^2$. Figs.38-44 show such plots for the patches of severe turbulence described in para.4.5, together with fitted Rayleigh distributions of rms a. The distributions were fitted by maximum likelihood through the largest values of N, using the following expression to obtain a:-

$$a^2 = \frac{1}{2} \frac{\sum_{p=1}^{N} x_p^2}{N} - c^2$$

where c is the distance from zero to the x counting threshold; in this case 0.25.

Figs.38-44 also show for each plot a value of P, which is the probability that any other patch of turbulence with similar values of a and N will contain an increment exceeding the observed maximum x_m. Values of P were obtained as follows:-

Probability that a single random value exceeds x_m is

$$\exp\left(\frac{c^2 - x_m^2}{2a^2}\right) \quad . \qquad (2)$$

From (2) probability P that at least one of N random values exceeds x_m is

$$1 - \left(1 - \exp\left(\frac{c^2 - x_m^2}{2a^2}\right)\right)^N \quad .$$

In view of the small number of counts in some of the patches, the precise values of a and P should be treated with caution, but it can be seen that 22 of the 24 values of P are less than 0.5, and that 14 are below 0.2. In some instances, as stated in para.4.5, the largest acceleration in a patch can be caused by a manoeuvre contribution to an already large gust load, but it is thought that patches Ib, Ig, Ih, IId, IIe, IIf and IIIe contain no such contribution. For these seven patches, all the values of P are less than 0.5 and 5 values are less than 0.2.

The difference between the largest observed increment and the expected maximum has been calculated for each of the 24 severe patches; on average the largest increment is about 30% greater than expected for both the manoeuvre influenced and pure gust cases.

The severe patches examined in this Report were picked out on a maximum load basis only, but it is possible that there are other patches of turbulence of similar mean severity where the largest load did not meet the selection criterion.

5.2 Warning of turbulence

The deductions made in para.4.5 regarding the degree of warning of turbulence are summarised below:-

Aircraft type I - 4 patches unexpected, 2 patches expected and 2 patches where the airspeed was already reduced because of turbulence met previously.

Aircraft type II - 3 patches unexpected, 3 patches expected. For the remaining 5 patches, it was not possible to assess the degree of warning.

Aircraft type III - 2 patches unexpected, 1 patch expected and 2 patches where the airspeed was already reduced because of turbulence met previously.

Thus approximately 40% of the turbulence patches which produced the largest loads on these aircraft were encountered without warning.

6 FURTHER WORK

This paper has isolated on a maximum load basis the most severe patches of turbulence which were encountered in a relatively small number of hours. It is hoped to isolate the most severe patches of turbulence from CAADRP records covering approximately 40000 flying hours, but only simple measurements of the type used in this paper can be made on each patch.

The introduction of mandatory recorders brings within reach 100 000 hours per year of more comprehensive data from each aircraft type; airspeed, height and heading are recorded every second together with pitch and acceleration every fifth of a second. If a simple method can be devised for finding the most severe patches of turbulence, then a more refined study can be made on each patch, but no information will be available on structural modes of vibration. In order to derive maximum benefit from such a study a pilot and meteorological report would be required.

7 CONCLUSIONS

From an examination of 24 of the most severe patches of turbulence experienced in 3284 hours of normal civil operations, the following conclusions can be drawn.

(1) The largest acceleration in a patch is on average about 30% greater than would be expected from a Gaussian distribution. This can be caused by a manoeuvre contribution to the largest load in a patch having random characteristics, but the primary explanation must be found elsewhere.

(2) Nine of the twenty-four patches of turbulence examined occurred without warning as to their severity. Thus, although the technique of reducing airspeed in turbulence benefits fatigue life and passenger comfort, it cannot ensure that the largest gusts are always met at the reduced airspeed.

Table 1

CUMULATIVE DISTRIBUTIONS OF ACCELERATIONS FOR AIRCRAFT TYPE I - 325 FLIGHTS

Flight phase	Climb				Cruise				Descent			
Duration	148 hours				611 hours				123 hours			
Duration of turbulence	32 minutes				90 minutes				61 minutes			
Acceleration exceeded (g)	Gust		Man		Gust		Man		Gust		Man	
	+	-	+	-	+	-	+	-	+	-	+	-
0.25	117	101	123	65	228	194	4	1	239	190	345	108
0.30	79	66	53	23	132	85	2	1	155	94	176	40
0.35	38	37	15	9	55	47	1	1	87	62	53	10
0.40	23	22	8	3	27	30	1		60	30	20	3
0.45	11	13		2	13	20	1		28	19	4	2
0.50	10	5		1	7	6	1		17	11	1	
0.55	5	4			3	4	1		9	7		
0.60	4	3			3	3			7	3		
0.65	3	1			3	1			6	1		
0.70	2				3	1			3	1		
0.75	2				3	1			2	1		
0.80	2				3	1			2	1		
0.85	1				2				1	1		
0.90					2				1	1		
0.95					1					1		
1.00					1							

Table 2

CUMULATIVE DISTRIBUTIONS OF ACCELERATIONS FOR AIRCRAFT TYPE II - 388 FLIGHTS

Flight phase	Climb				Cruise				Descent			
Duration	142 hours				1038 hours				171 hours			
Duration of turbulence	7 minutes				84 minutes				44 minutes			
Acceleration exceeded (g)	Gust		Man		Gust		Man		Gust		Man	
	+	-	+	-	+	-	+	-	+	-	+	-
0.25	27	20	217	125	190	253	10	11	162	145	379	132
0.30	19	13	105	53	96	154	5	3	103	95	204	54
0.35	7	9	40	21	37	83	1	1	53	52	63	19
0.40	3	6	24	9	16	41		1	39	35	30	3
0.45		2	10	6	9	30			22	18	10	1
0.50		2	6	4	6	14			14	12	4	1
0.55		2	2		2	8			9	7		
0.60		2	1		2	5			4	3		
0.65		1			2	3			2	1		
0.70						3			2	1		
0.75						3						
0.80						3						
0.85						2						
0.90						1						
0.95						1						

Table 3

CUMULATIVE DISTRIBUTIONS OF ACCELERATIONS FOR AIRCRAFT TYPE III - 686 FLIGHTS

Flight phase	Climb				Cruise				Descent			
Duration	215 hours				609 hours				227 hours			
Duration of turbulence	33 minutes				70 minutes				47 minutes			
Acceleration exceeded (g)	Gust		Man		Gust		Man		Gust		Man	
	+	-	+	-	+	-	+	-	+	-	+	-
0.25	247	129	455	283	441	387	13	3	323	214	770	259
0.30	125	78	203	108	280	227	12	2	222	119	354	94
0.35	74	46	82	36	180	130	9		148	73	153	29
0.40	38	25	27	7	97	72	2		77	36	53	13
0.45	16	15	11	1	60	52	1		42	24	20	2
0.50	11	8	2	1	35	38	1		23	13	8	1
0.55	6	7	1		21	24			13	8	4	
0.60	3	5	1		13	17			10	6	1	
0.65	2	2			9	8			5	3	1	
0.70	1	1			5	7			3	2		
0.75	1	1			3	4				1		
0.80		1			2	1						
0.85		1			2	1						
0.90						1						
0.95						1						
1.00						1						
1.05						1						
1.10						1						
1.15						1						
1.20						1						

Table 4

DISTRIBUTION OF DURATIONS OF TURBULENCE PATCHES FOR ALL AIRCRAFT

Duration of patch	$\frac{1}{4}$ min	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5	7	10
Total number of patches	373	170	111	18	24	6	4	3	6	1	4	1	1
Number of severe patches	8	6	4	2	1	1				1		1	

Table 5

PERCENTAGE OF TIME SPENT IN TURBULENCE

	Climb	Cruise	Descent
Type I	0.36	0.25	0.83
Type II	0.08	0.13	0.43
Type III	0.26	0.19	0.34
All aircraft	0.24	0.18	0.49

Table 6

AIRCRAFT TYPE I - TURBULENCE PATCHES CONTAINING 0.81 g INCREMENT OR OVER

Patch	Ia	Ib	Ic	Id	Ie	If	Ig	Ih
Phase	CL	CL	CR	CR	CR	DES	DES	DES
Duration minutes	$1\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{4}$	$2\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{4}$
Aircraft height ft x 1000	5.5	9.2	34.2	31.0	32.3	6.0	29.0	23.6
Aircraft weight kg x 1000	50	62	51	56	61	52	53	53
Indicated airspeed knots	212	263	240	265	235	220	260	220
Recommended rough air-speed knots	208	230	210	219	228	211	213	213
0.25	23	7	8	5	25	11	9	5
0.30	22	3	8	4	13	11	9	3
0.35	15	1	5	4	10	8	9	3
0.40	7	1	3	4	6	4	5	2
0.45	4	1	1	3	4	3	5	1
0.50	2	1	1	3	3	3	4	1
0.55	1	1	1	2	2	2	3	1
0.60	1	1	1	2	2	2	2	1
0.65	1	1	1	2	1	1	2	1
0.70	1	1	1	2	1	1	1	1
0.75	1	1	1	2	1	1	1	1
0.80	1	1	1	2	1	1	1	1
0.85		1		1	1	1	1	
0.90				1	1	1	1	
0.95				1		1		
1.00				1				
Acceleration increment (g)	Number of times acceleration exceeded							

Table 7

AIRCRAFT TYPE II - TURBULENCE PATCHES CONTAINING 0.61 g INCREMENT OR OVER

Patch	IIa	IIb	IIc	IId	IIe	IIf	IIg	IIh	IIi	IIj	IIk
Phase	CL	CL	CR	CR	CR	CR	CR	DES	DES	DES	DES
Duration minutes	½	¼	¼	¼	4½	½	7	1	1	1½	½
Aircraft height ft × 1000	9.5	3.2	40.0	33.8	34.0	38.0	33.0	15.0	4.4	12.6	8.4
Aircraft weight kg × 1000	97	105	98	111	98	102	117	96	91	89	88
Indicated airspeed knots	252	256	250	274	288	259	288	240	262	268	258
Recommended rough air-speed* knots	280	280	242	278	278	254	280	280	280	280	280
0.25	6	4	3	11	37	11	27	17	15	35	12
0.30	5	2	3	7	33	10	11	12	10	29	7
0.35	4	2	3	7	22	7	9	10	8	16	6
0.40	3	2	3	7	17	4	6	7	5	12	6
0.45	1	1	2	7	12	2	5	5	4	9	5
0.50	1	1	2	5	4	2	3	3	3	9	4
0.55	1	1	1	3	2	2	1	3	3	6	2
0.60	1	1	1	2	2	1	1	2	2	2	1
0.65	1		1	2	2			2	1		
0.70				1	2			2	1		
0.75				1	2						
0.80				1	2						
0.85				1	1						
0.90				1							
0.95				1							
Acceleration increment (g)	Number of times acceleration exceeded										

*The Flight Manual recommends approximately 280 kt ias or 0.8 M, whichever is the lower.

Table 8

AIRCRAFT TYPE III - TURBULENCE PATCHES CONTAINING 0.76 g INCREMENT OR OVER

Patch	IIIa	IIIb	IIIc	IIId	IIIe
Phase	CL	CL	CR	CR	DES
Duration minutes	¼	1	1	2	½
Aircraft height ft × 1000	8.6	5.5	32.0	33.4	8.8
Aircraft weight kg × 1000	61	63	58	58	52
Indicated airspeed knots	286	268	255	250	270
Recommended rough air-speed knots	280	280	254	250	280
0.25	7	10	34	33	7
0.30	6	6	31	19	6
0.35	4	4	28	11	5
0.40	1	2	26	6	3
0.45	1	2	22	4	2
0.50	1	1	17	2	1
0.55	1	1	16	2	1
0.60	1	1	13	1	1
0.65	1	1	8	1	1
0.70	1	1	6	1	1
0.75	1	1	6	1	1
0.80	1		3		
0.85	1		3		
0.90			1		
0.95			1		
1.00			1		
1.05			1		
1.10			1		
1.15			1		
1.20			1		
Acceleration increment (g)	Number of times acceleration exceeded				

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4	H. Press May T. Meadows I. Hadlock	Estimates of probability distribution of root-mean-square gust velocity of atmospheric turbulence from operational gust load data by random process theory. NACA Technical Note 3362
5	J. Schijve	Random load-time histories with relation to fatigue tests. Fatigue of aircraft structures. W. Barrois/E. L. Ripley (Pergamon Press)

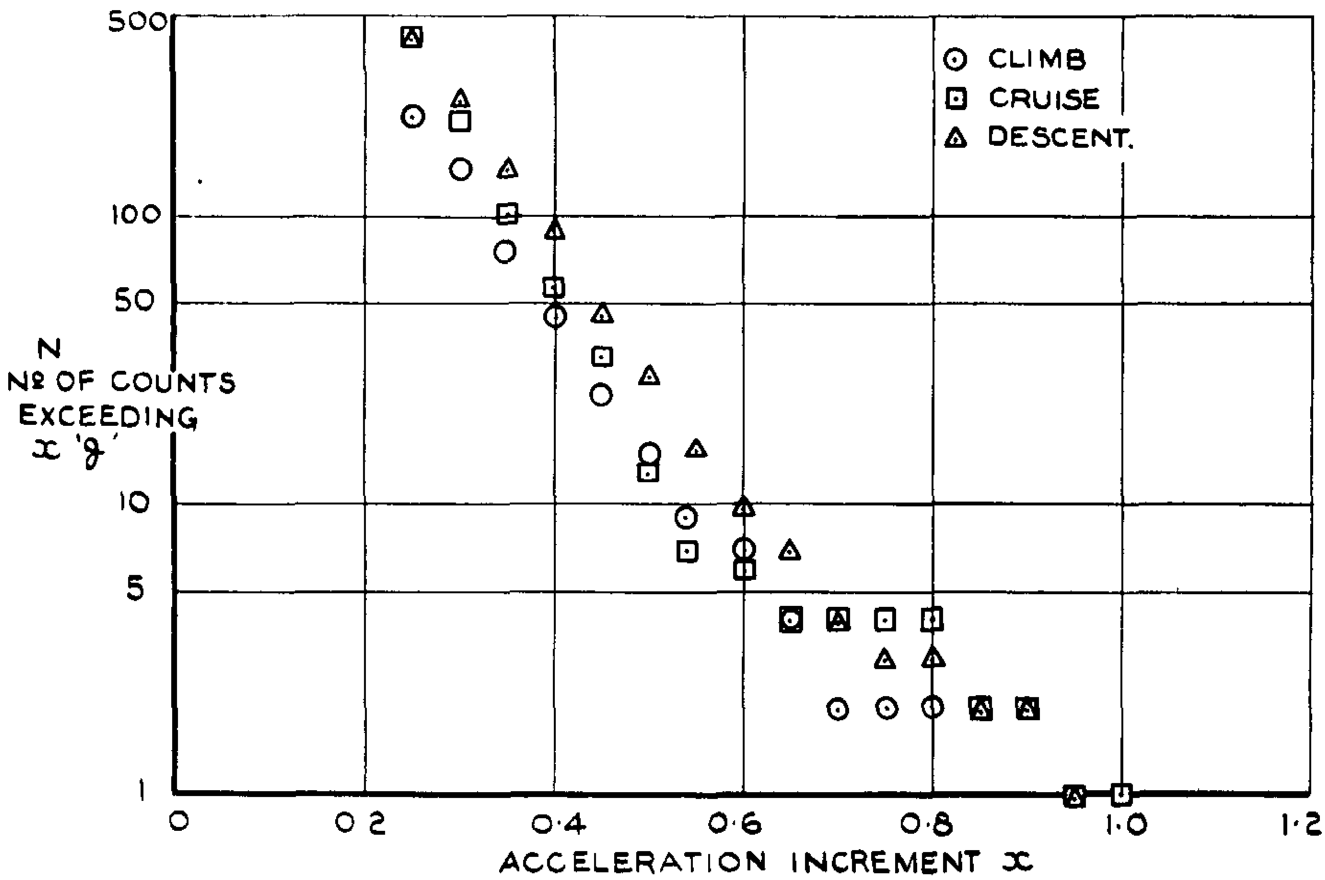


FIG 1 AIRCRAFT TYPE I — TOTAL COUNTS DUE TO TURBULENCE

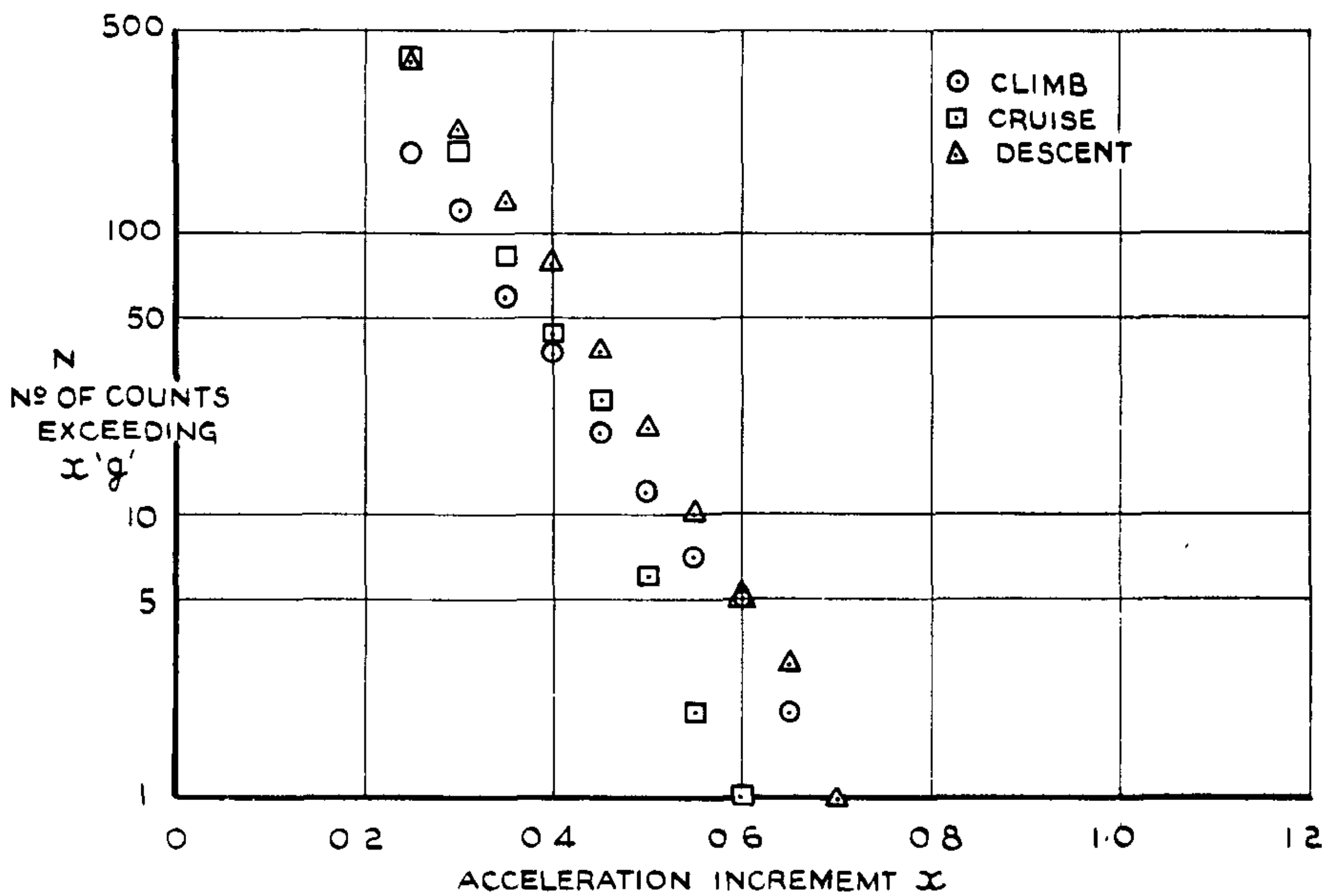


FIG 2 AIRCRAFT TYPE I — TOTAL COUNTS DUE TO TURBULENCE LESS COUNTS OF PATCHES CONTAINING OVER 0 8g

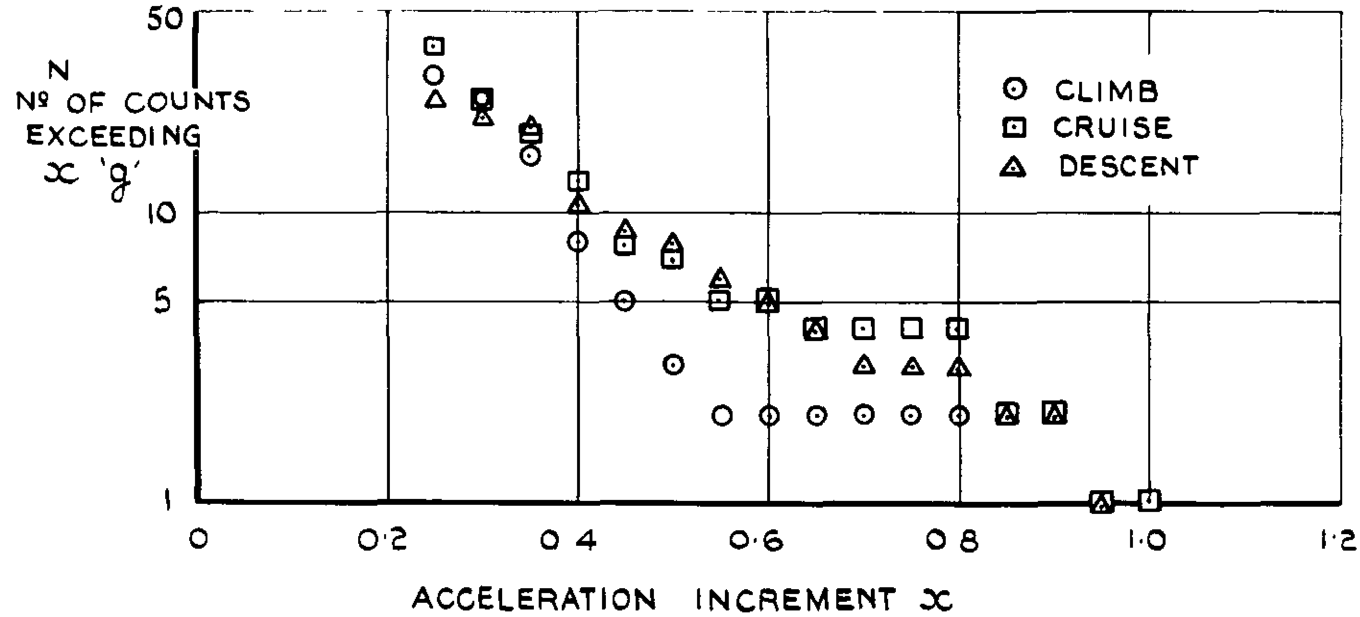


FIG. 3 AIRCRAFT TYPE I — COUNTS OF TURBULENCE PATCHES CONTAINING OVER 0·8g INCREMENT

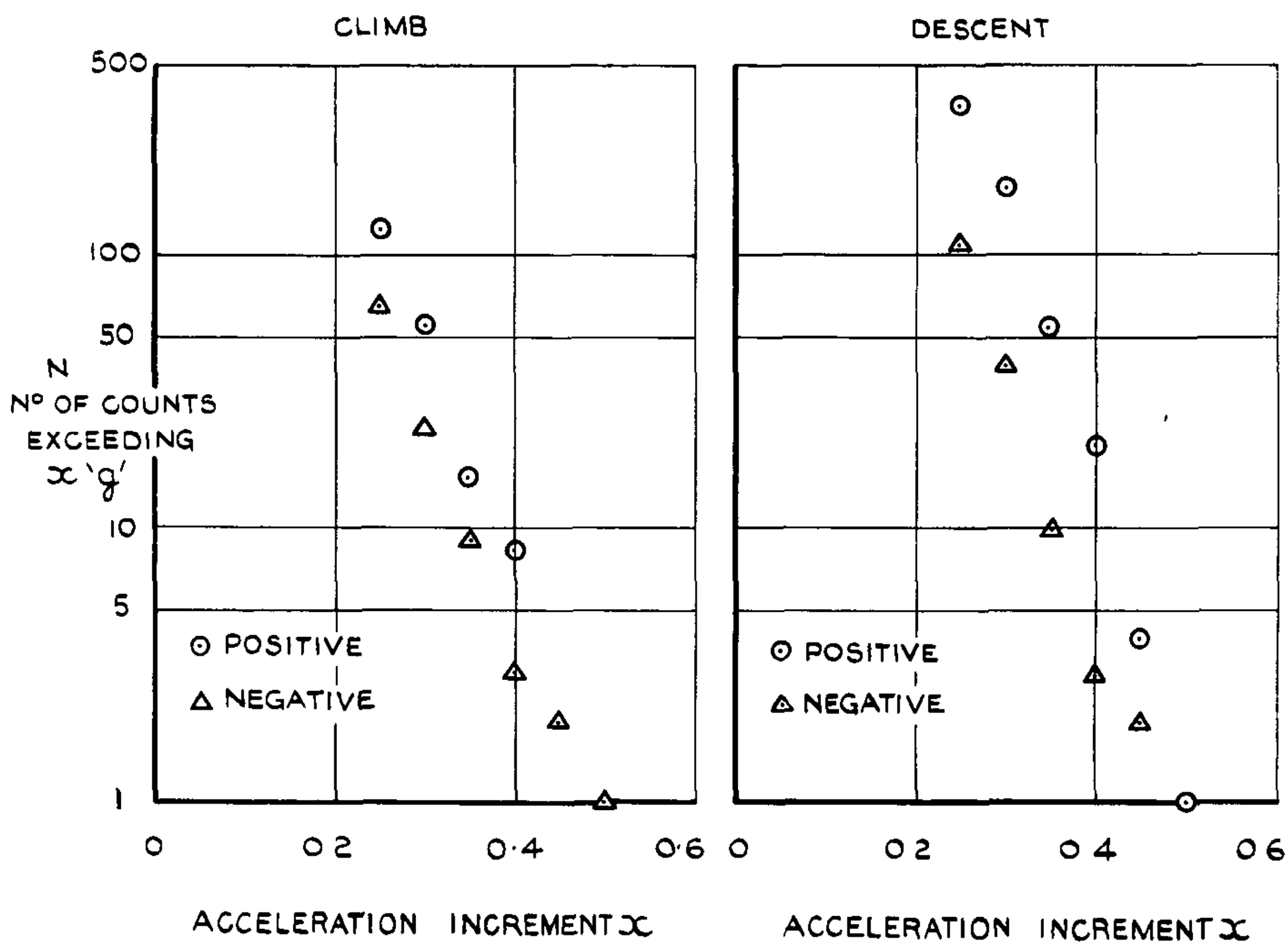


FIG 4 AIRCRAFT TYPE I — MANOEUVRE COUNTS

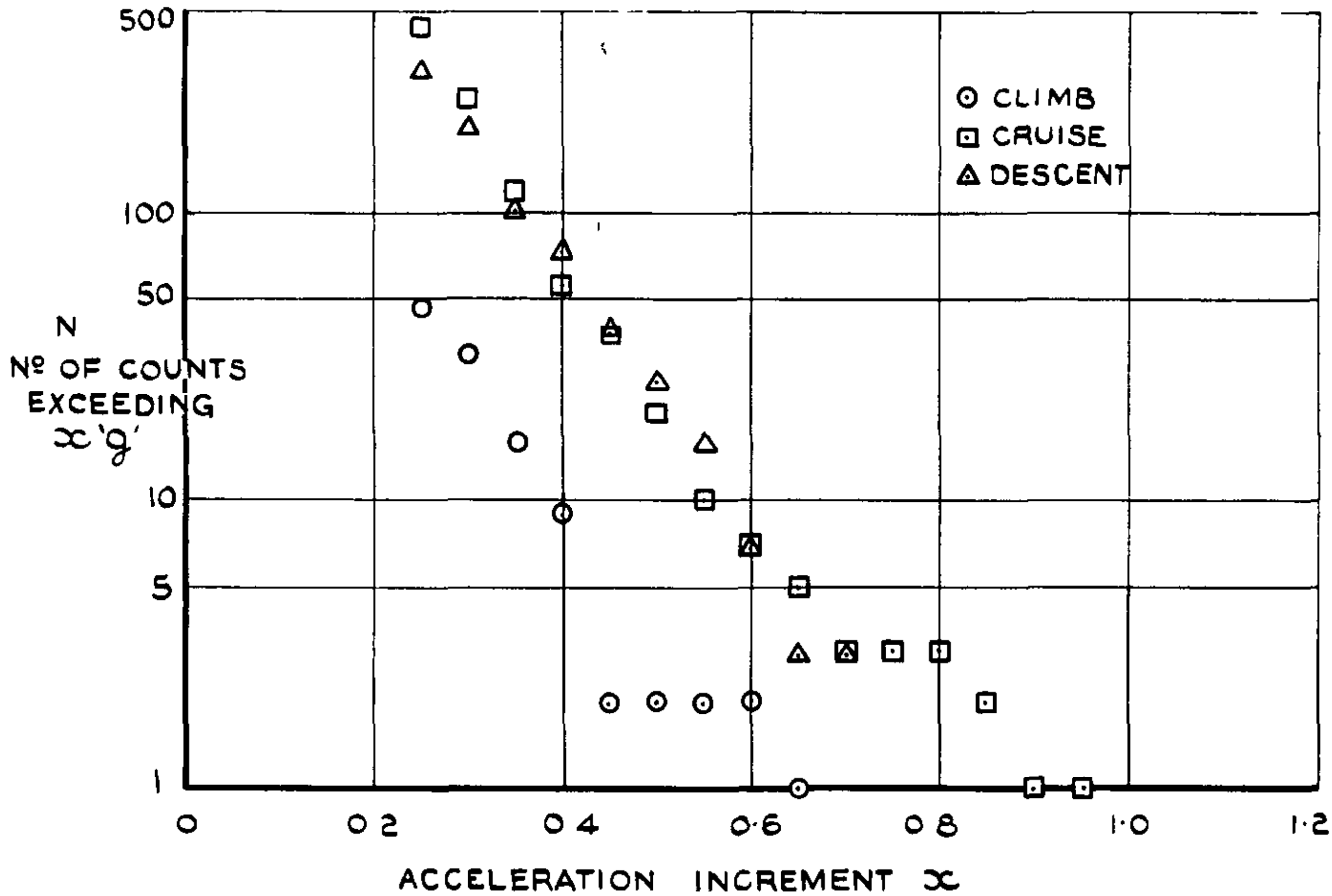


FIG 5 AIRCRAFT TYPE II – TOTAL COUNTS DUE TO TURBULENCE

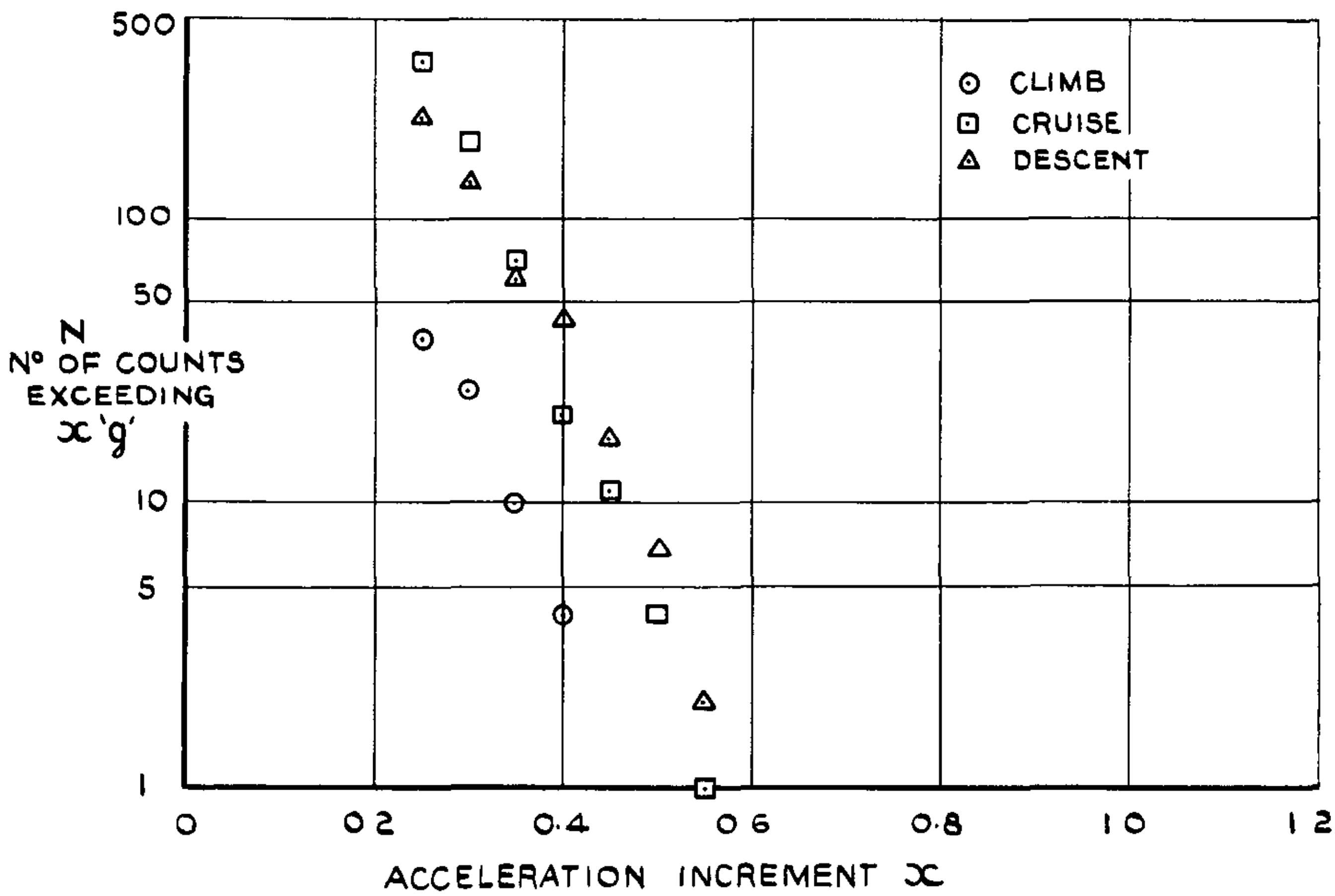


FIG. 6 AIRCRAFT TYPE II – TOTAL COUNTS DUE TO TURBULENCE LESS COUNTS OF PATCHES CONTAINING OVER 0 6g

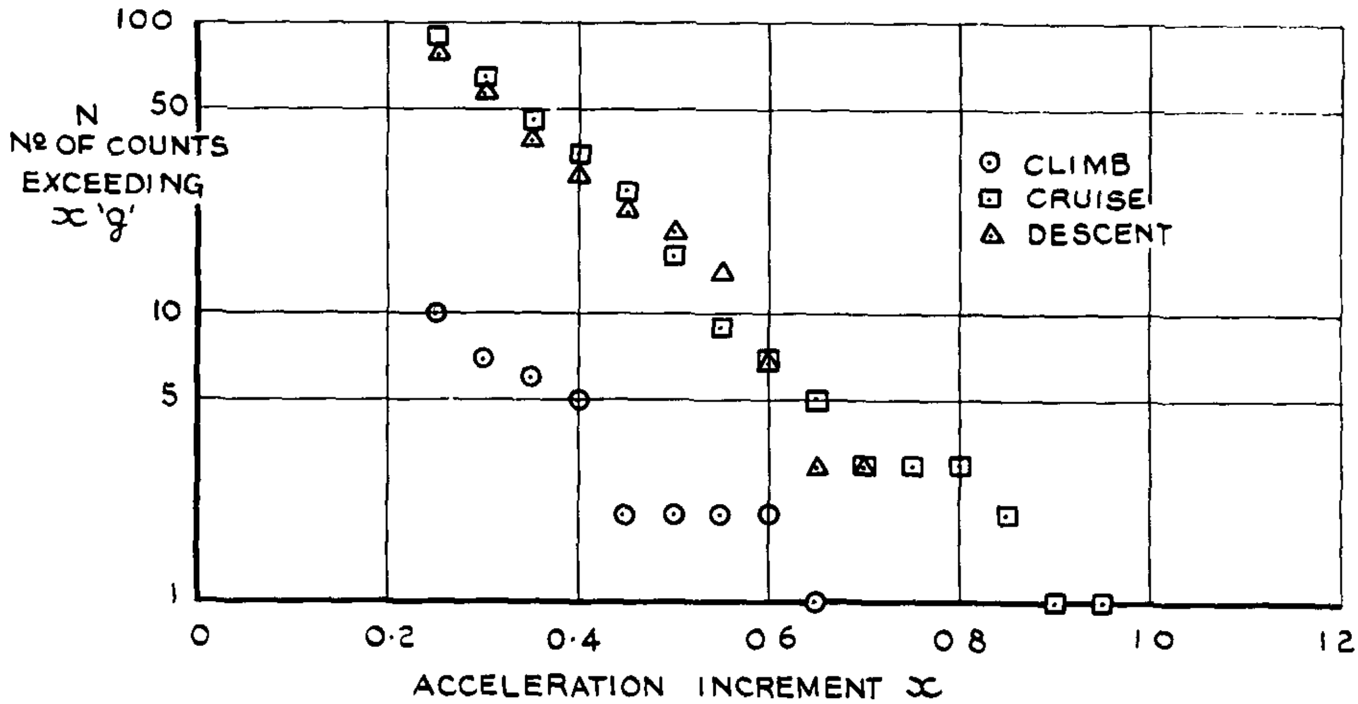


FIG 7 AIRCRAFT TYPE II — COUNTS OF TURBULENCE PATCHES CONTAINING OVER 0·6g INCREMENT

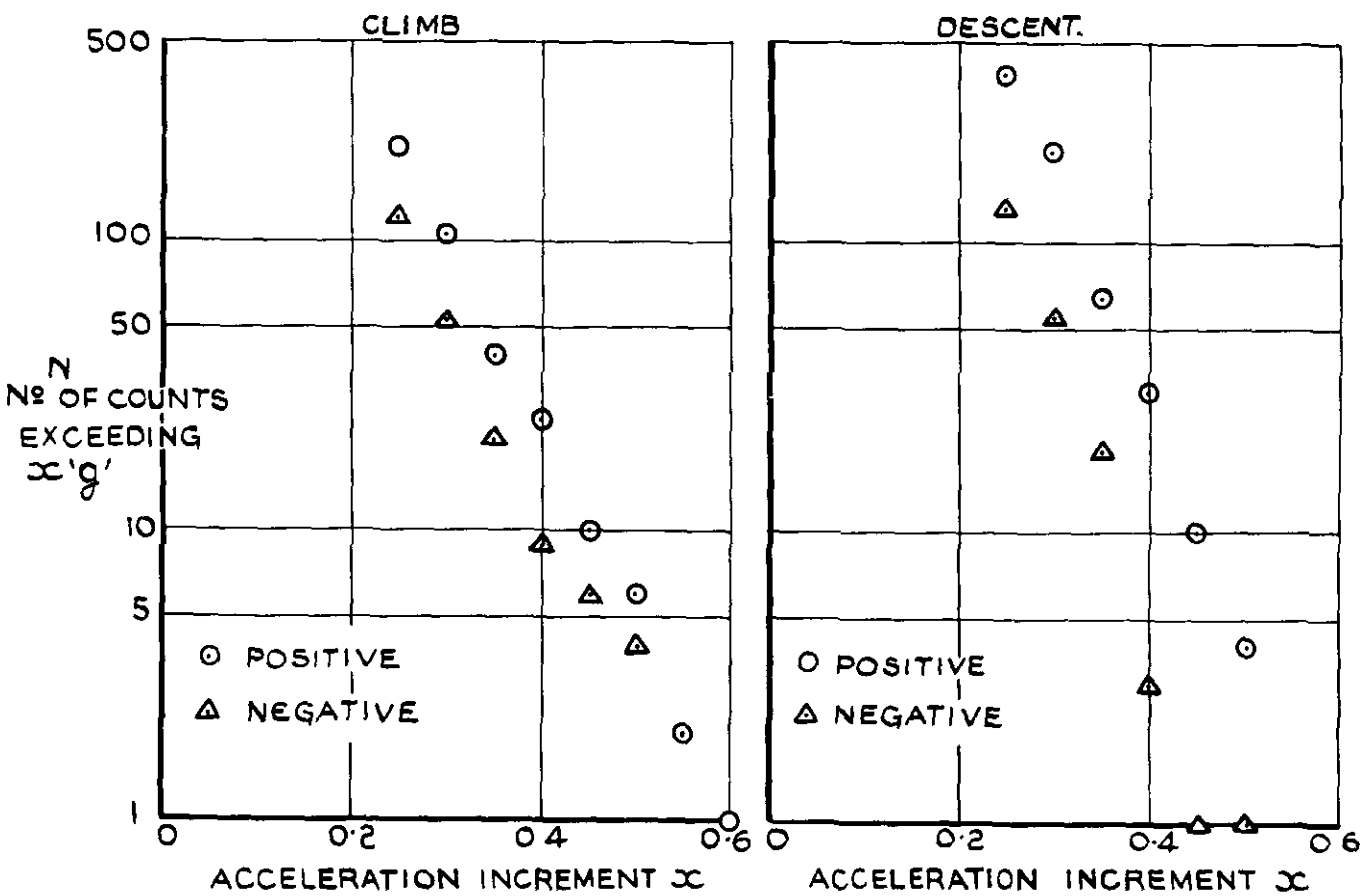


FIG. 8 AIRCRAFT TYPE II - MANOEUVRE COUNTS

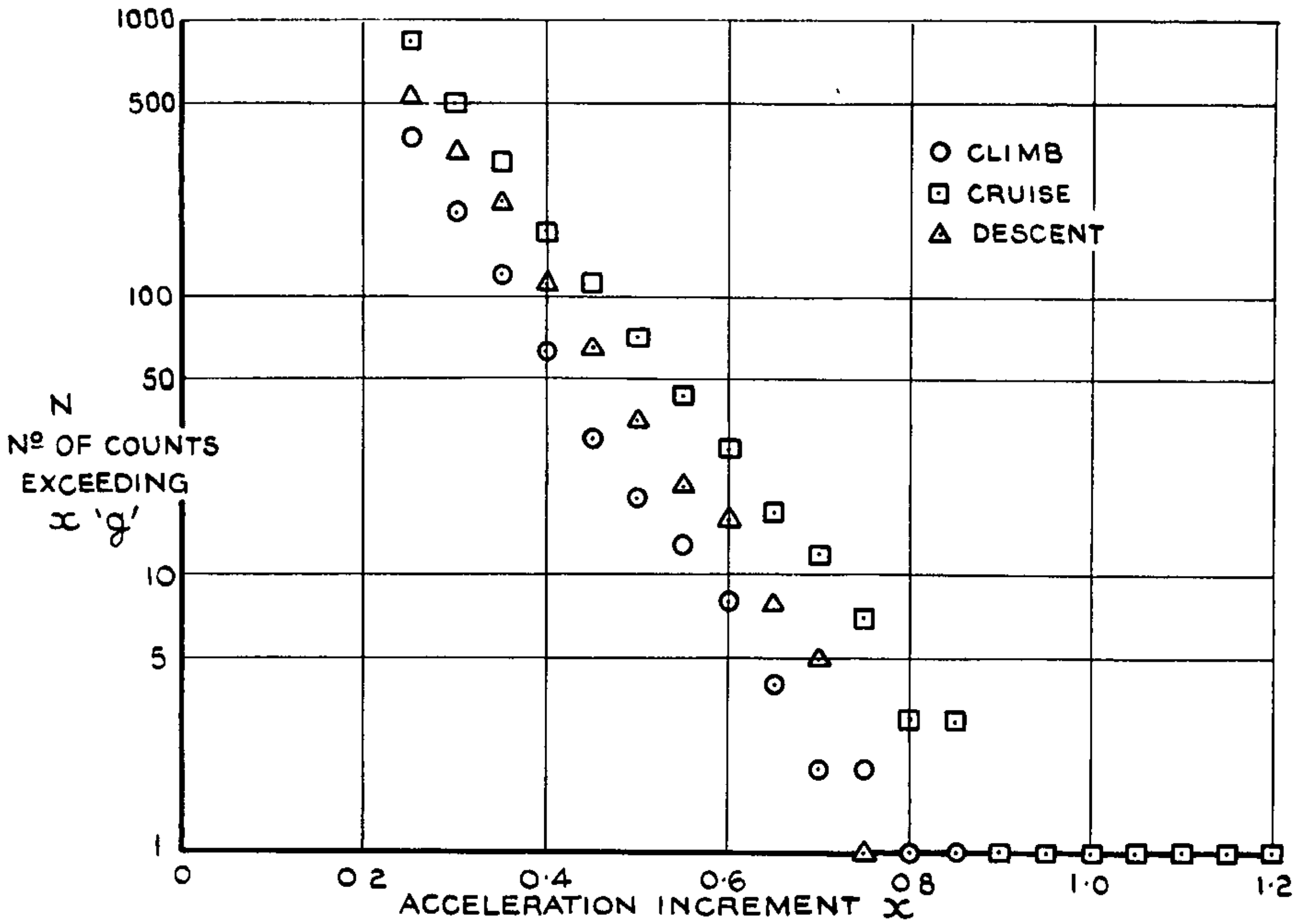


FIG. 9 AIRCRAFT TYPE III - TOTAL COUNTS DUE TO TURBULENCE

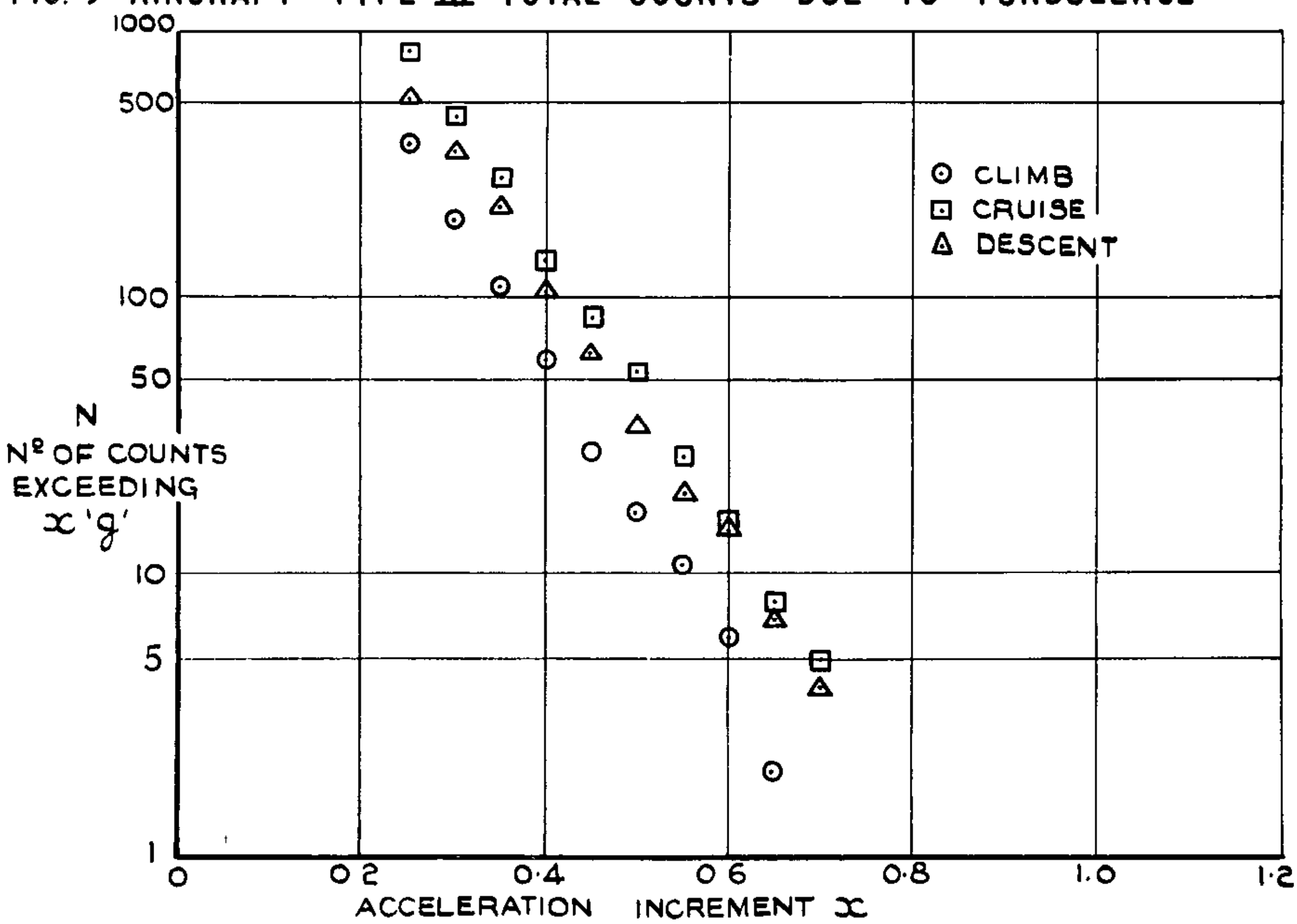


FIG 10 AIRCRAFT TYPE III - TOTAL COUNTS DUE TO TURBULENCE LESS COUNTS OF PATCHES CONTAINING OVER 0·75g

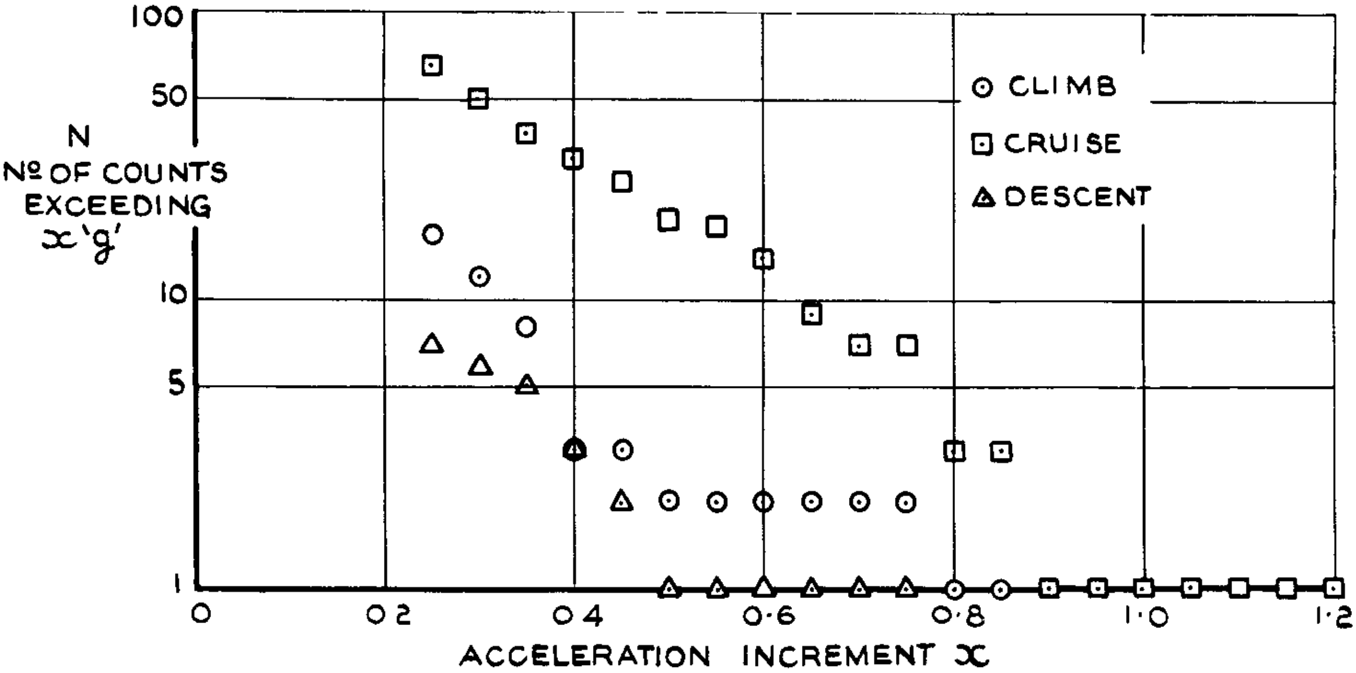


FIG 11 AIRCRAFT III - COUNTS OF TURBULENCE PATCHES CONTAINING OVER 0·75g INCREMENT

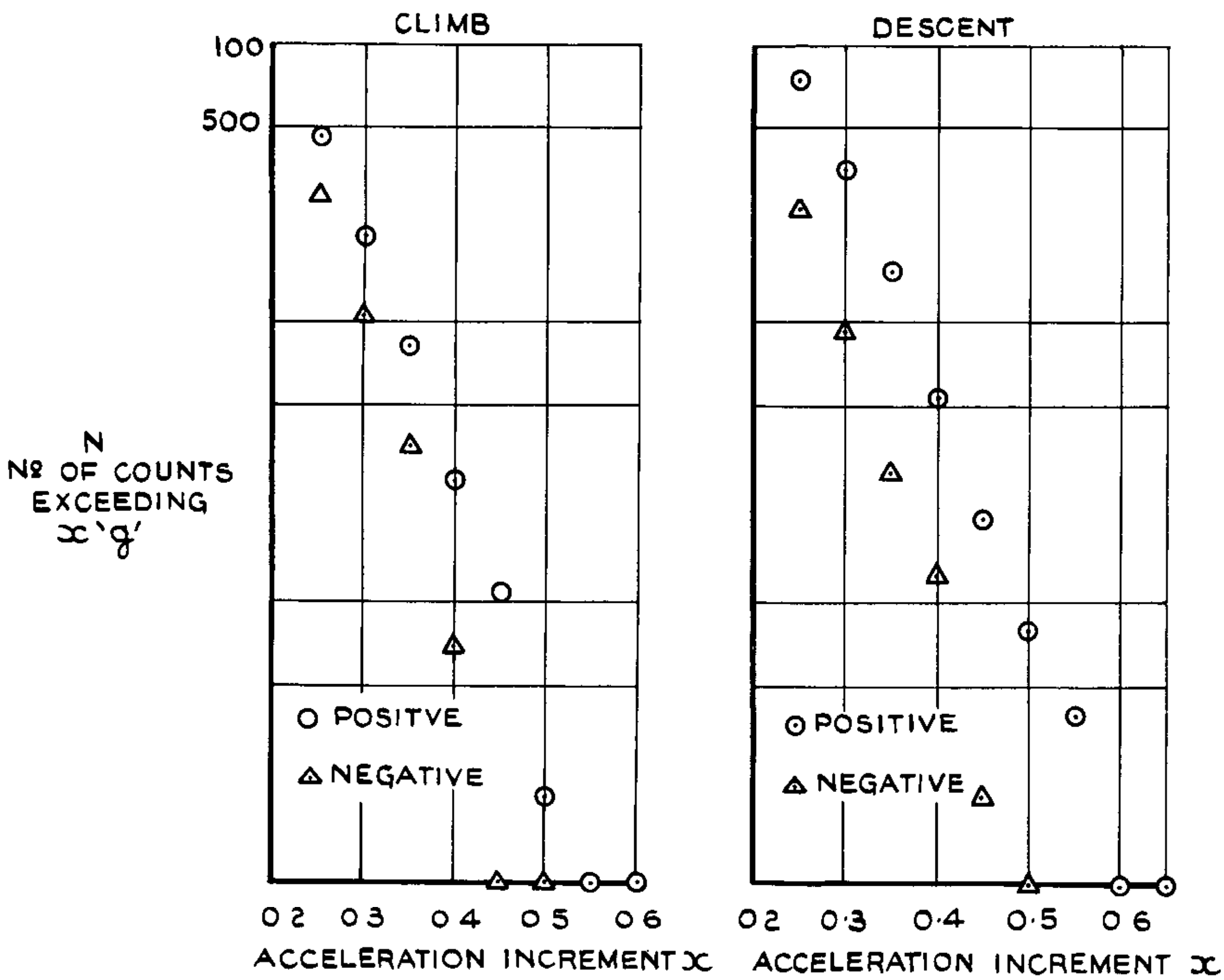


FIG. 12 AIRCRAFT TYPE III - MANOEUVRE COUNTS

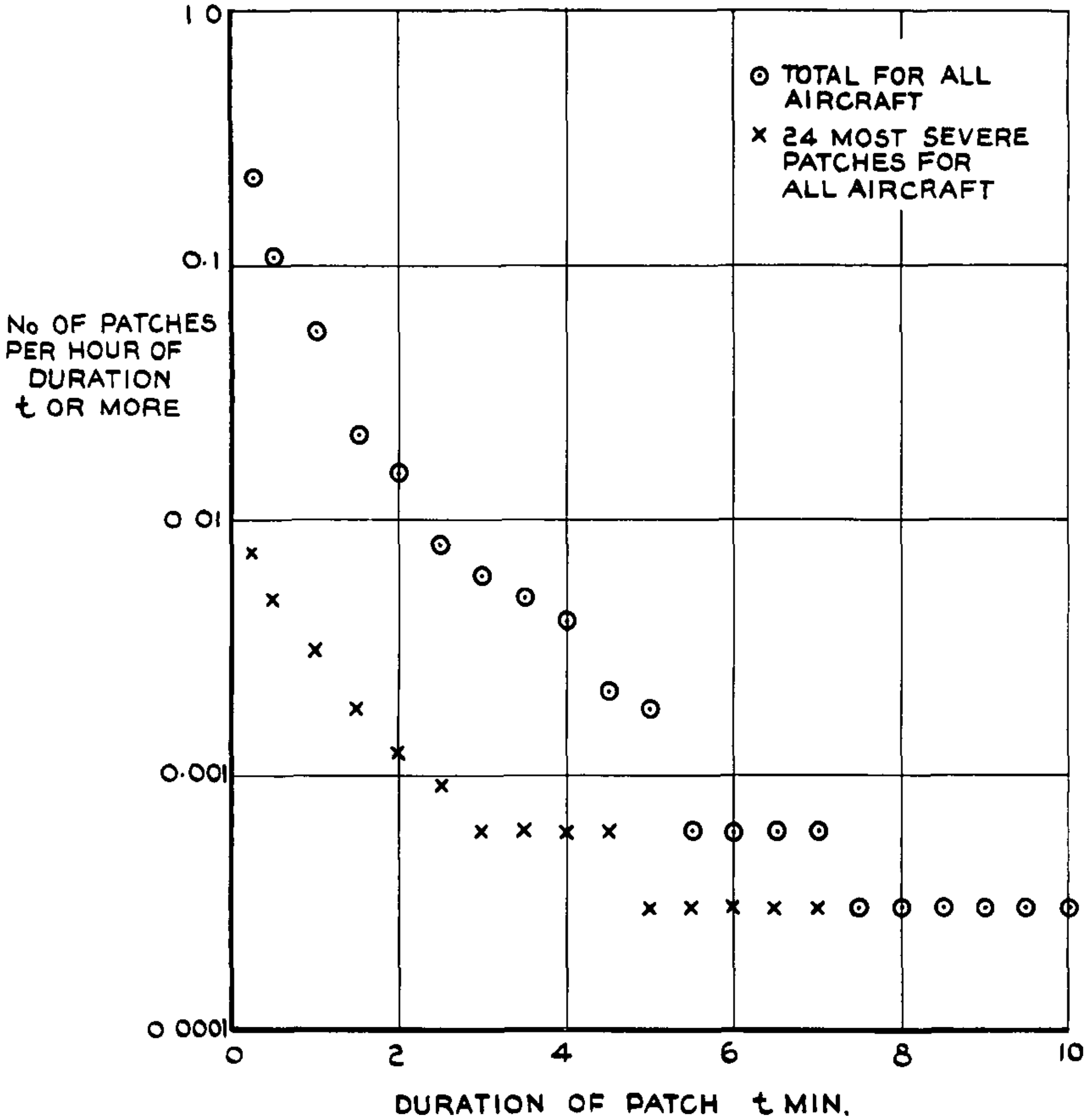


FIG 13 DISTRIBUTION OF DURATIONS OF TURBULENCE.

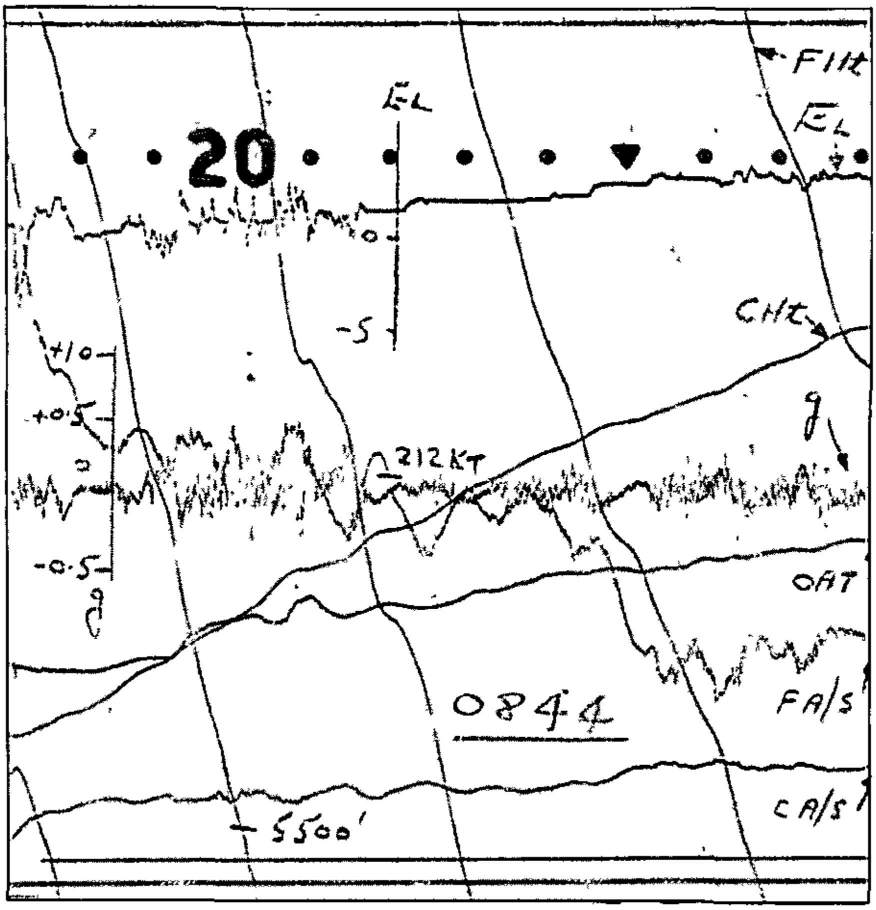


Fig.14 Patch 1a

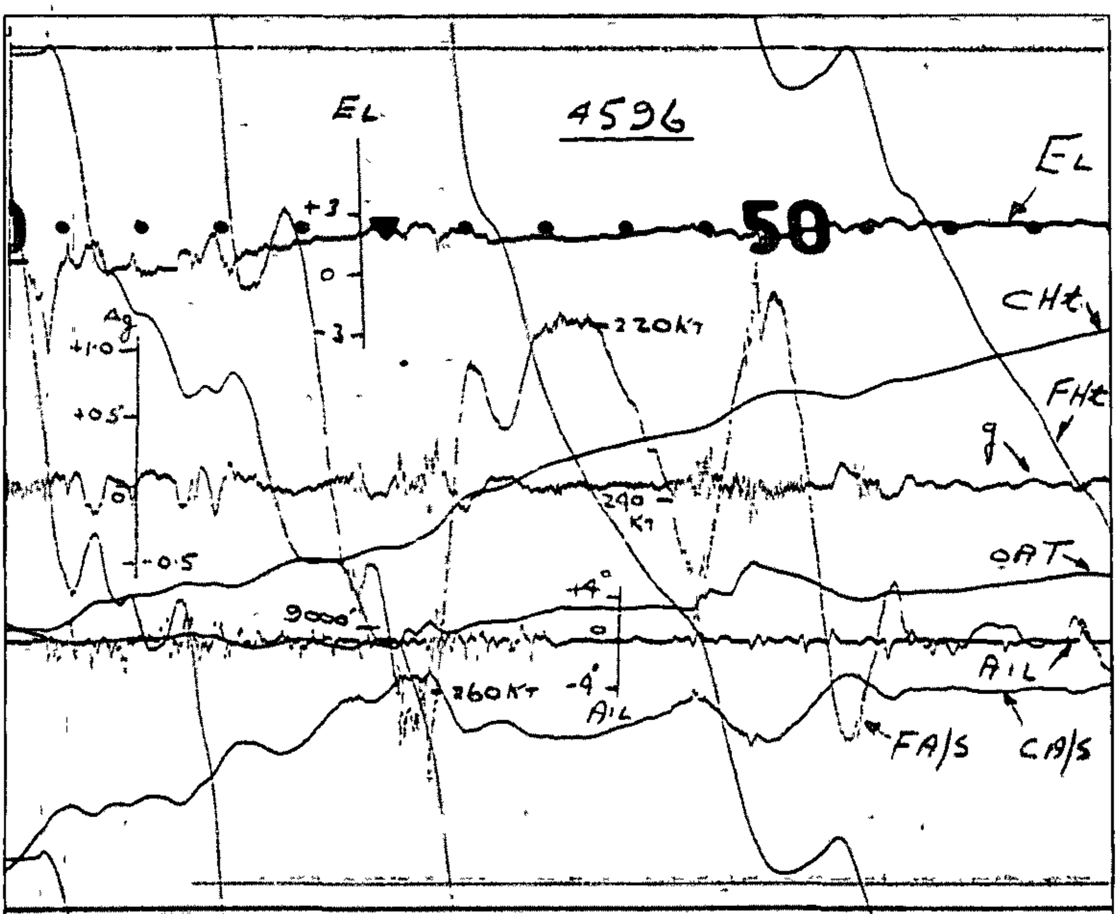


Fig.15 Patch 1b

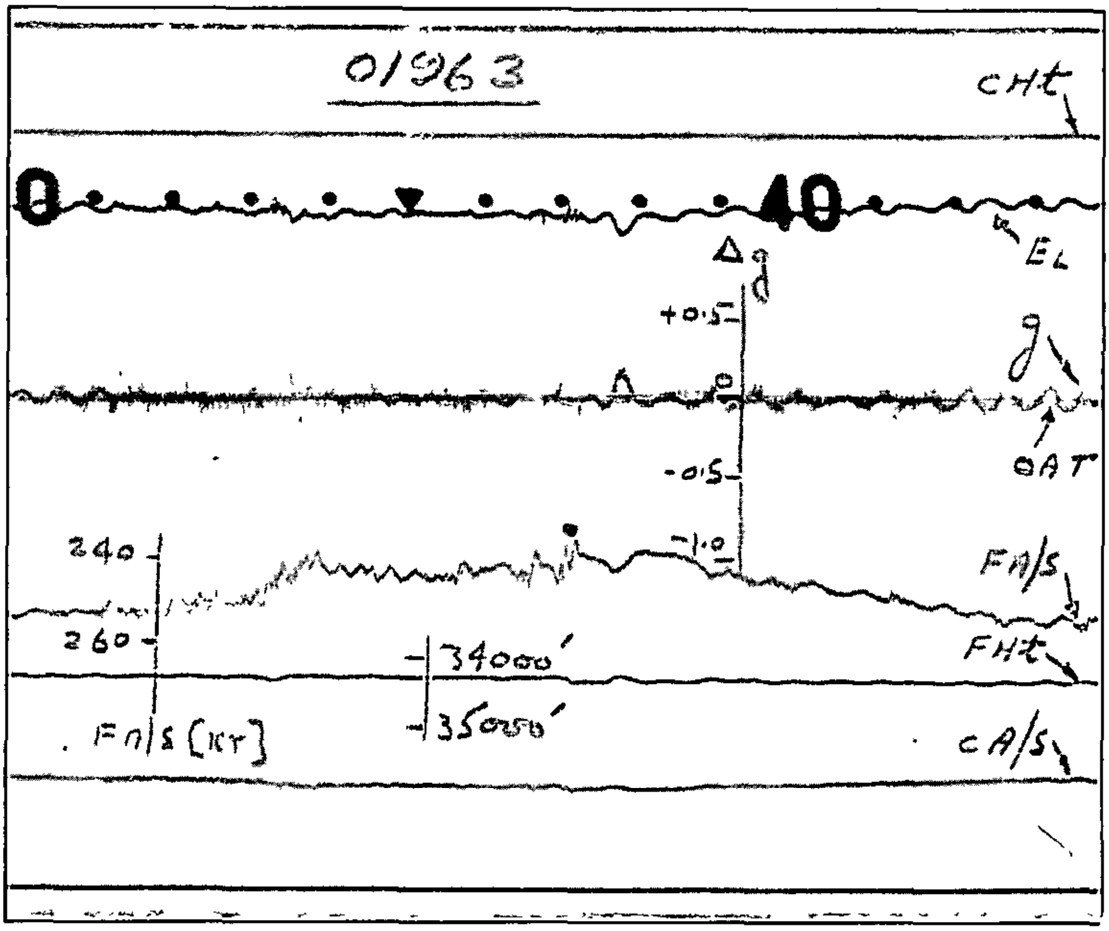


Fig.16 Patch 1c

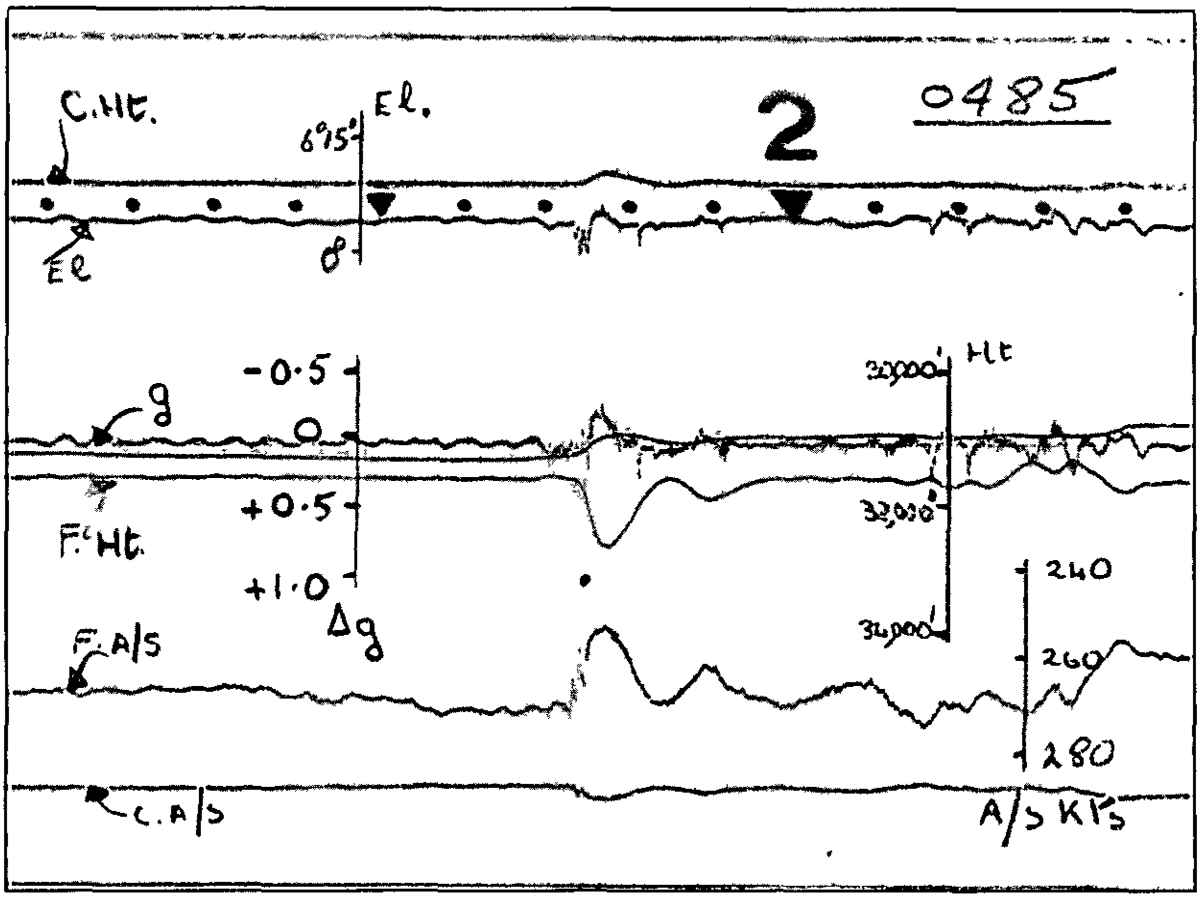


Fig.17 Patch 1d

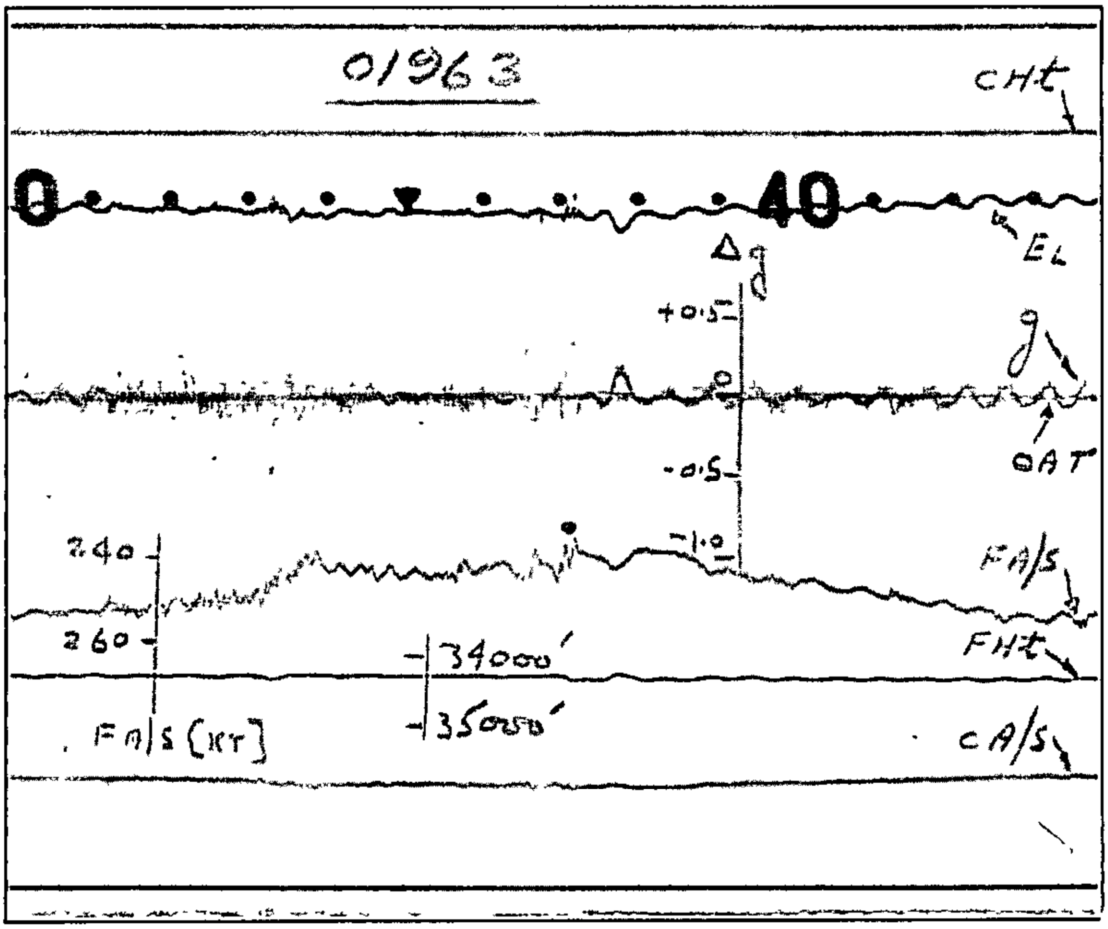


Fig.16 Patch 1c

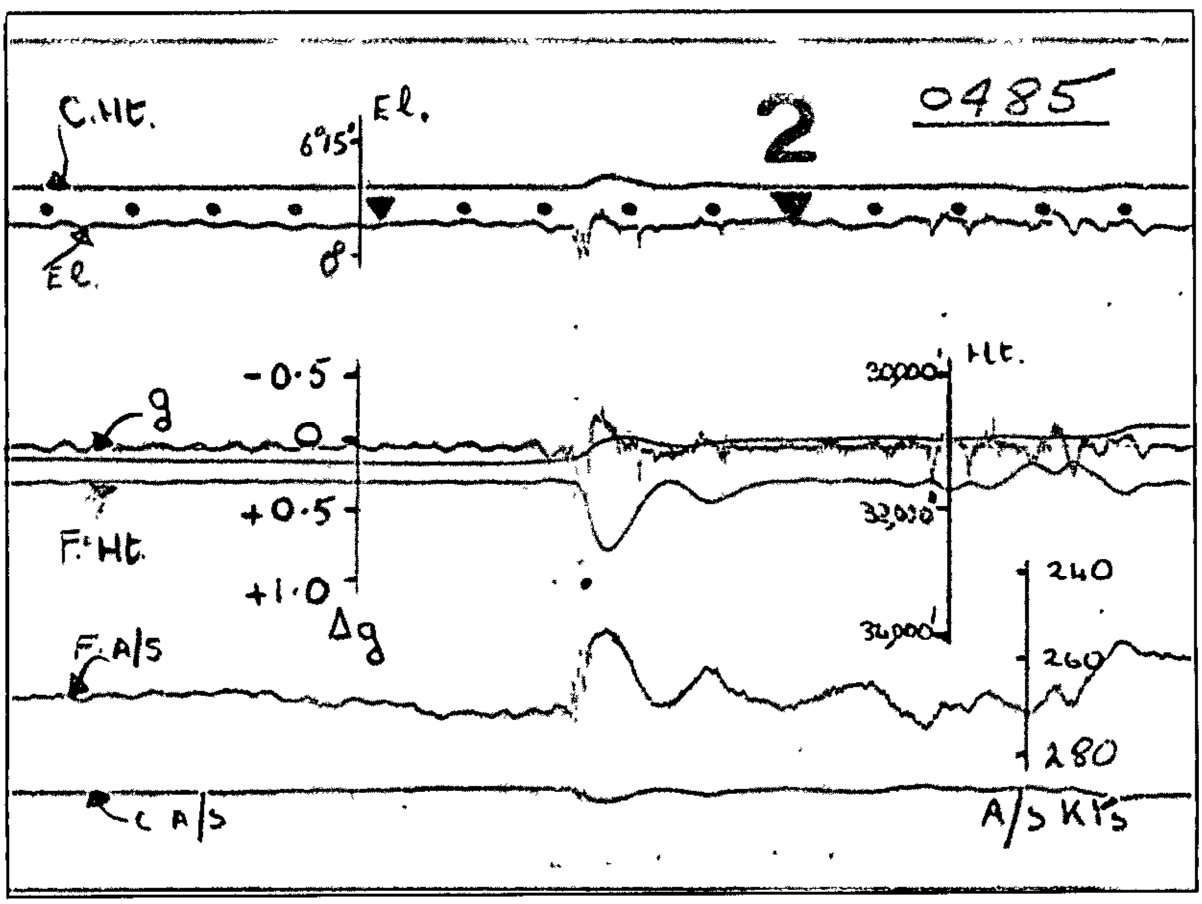


Fig.17 Patch 1d

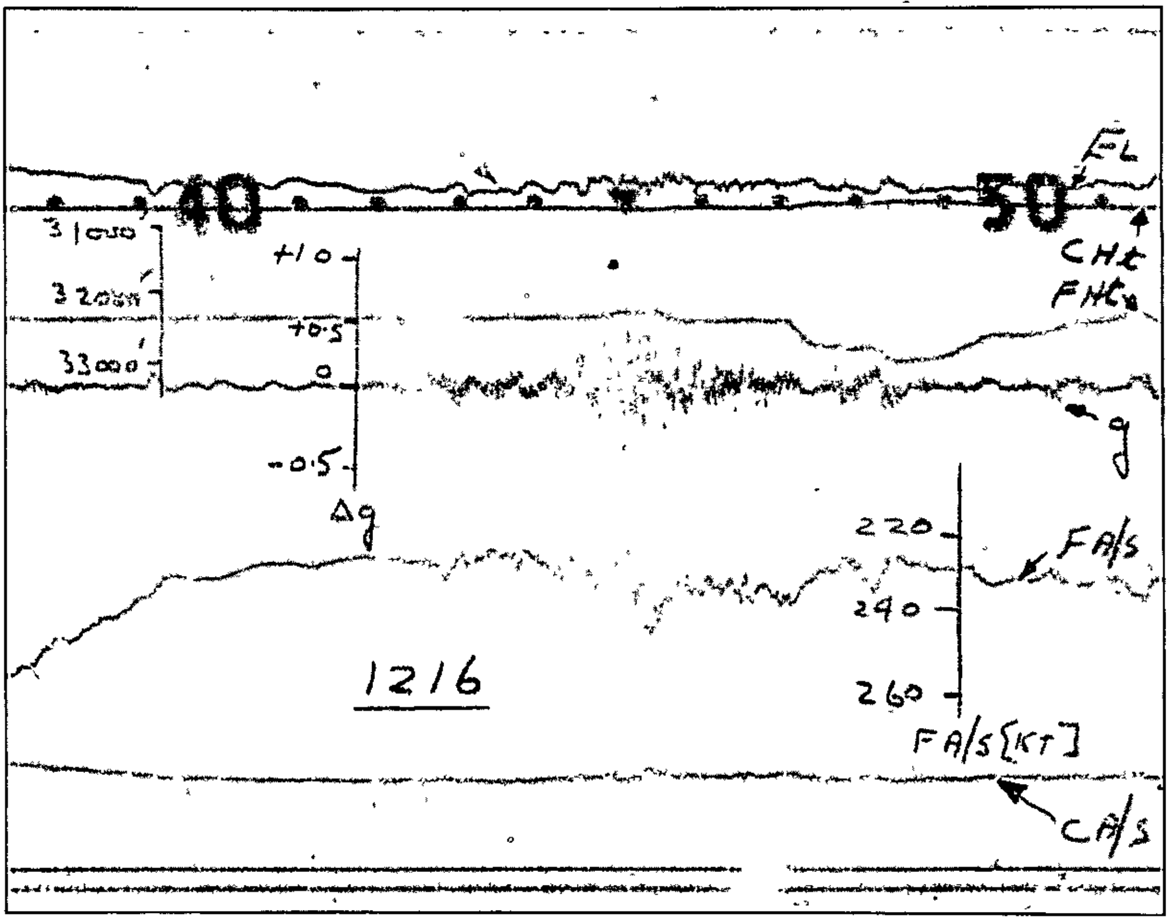


Fig.18 Patch 1e

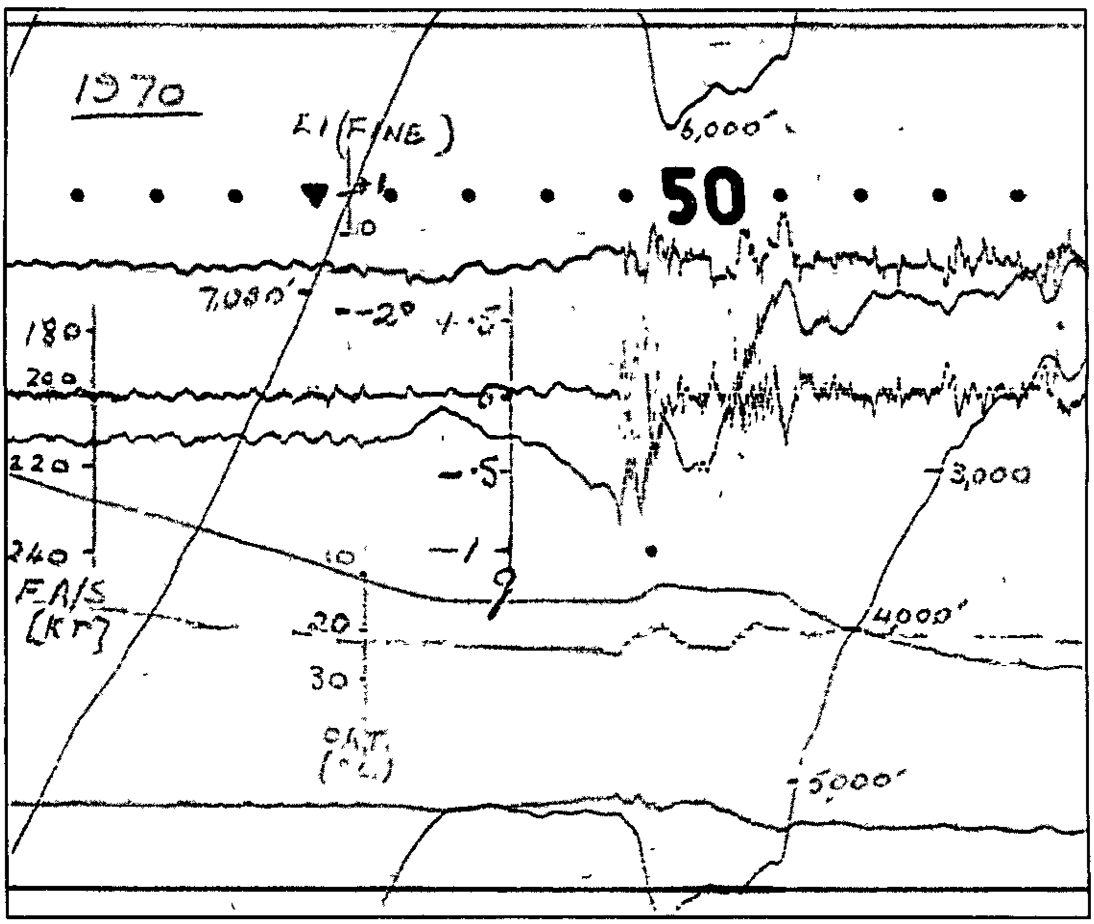


Fig.19 Patch 1f

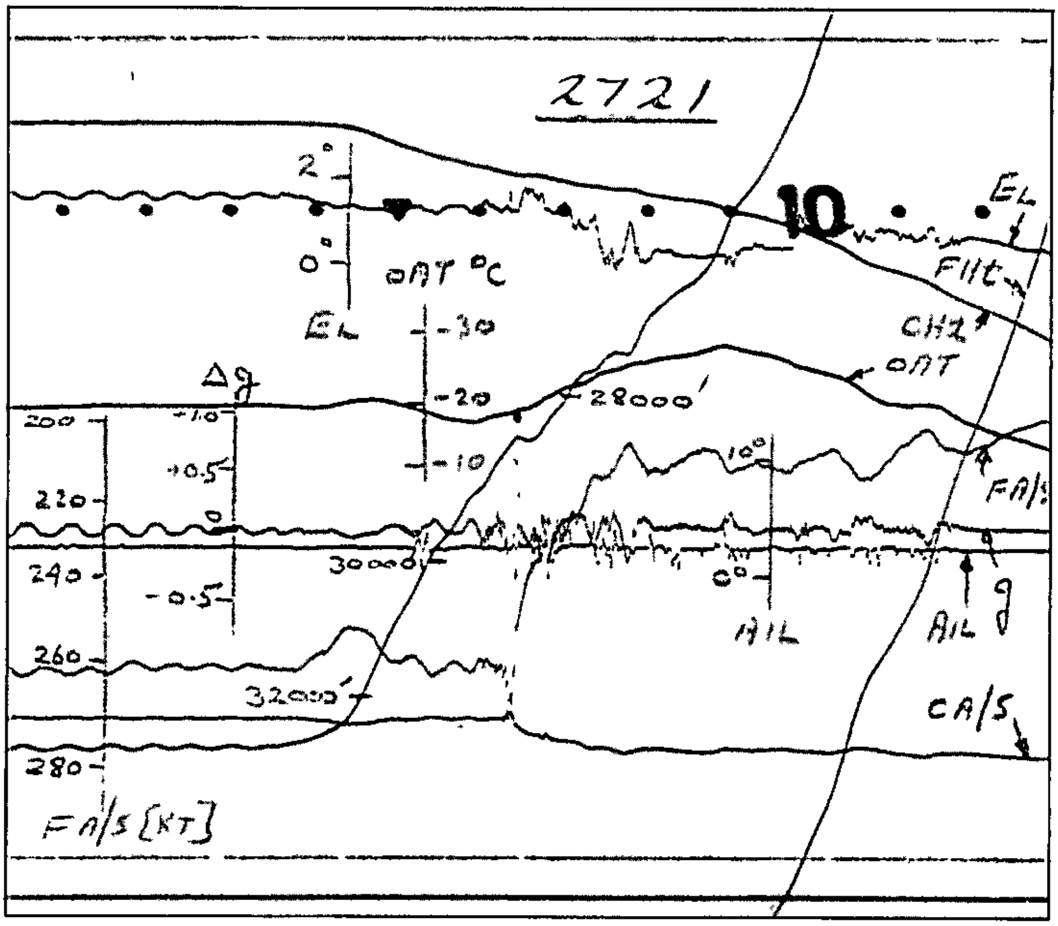


Fig.20 Patch 1g

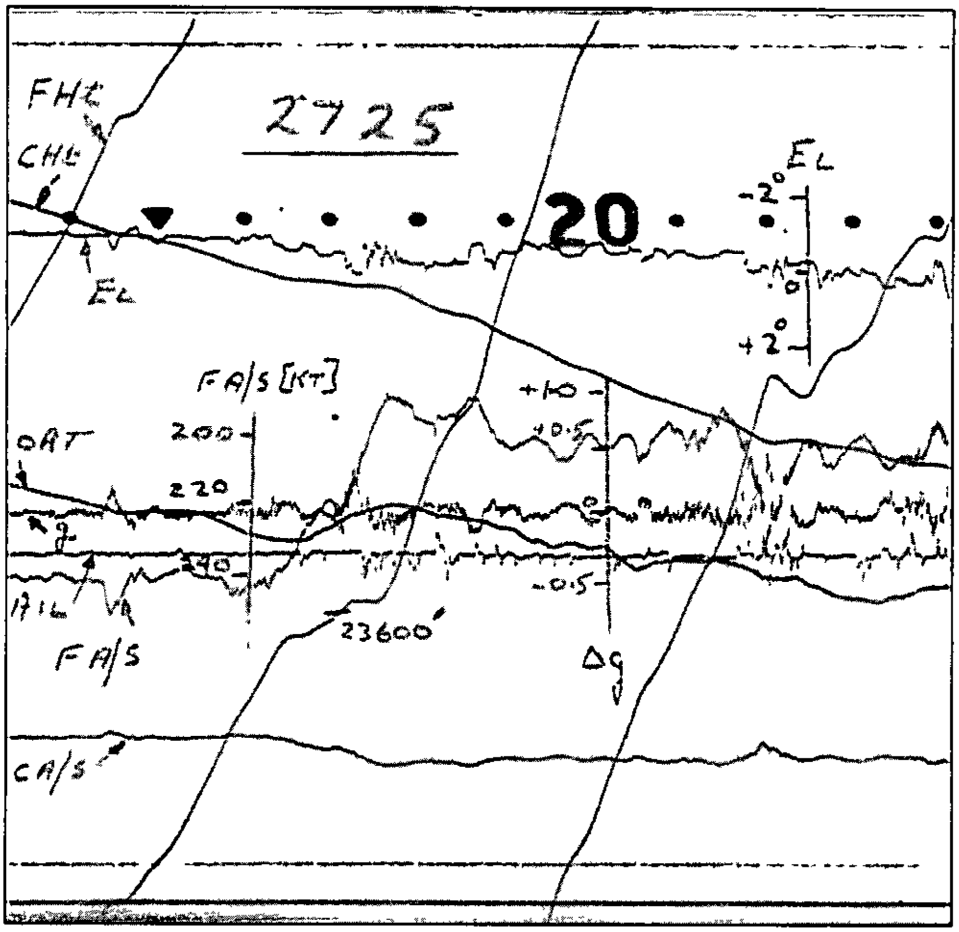


Fig.21 Patch 1h

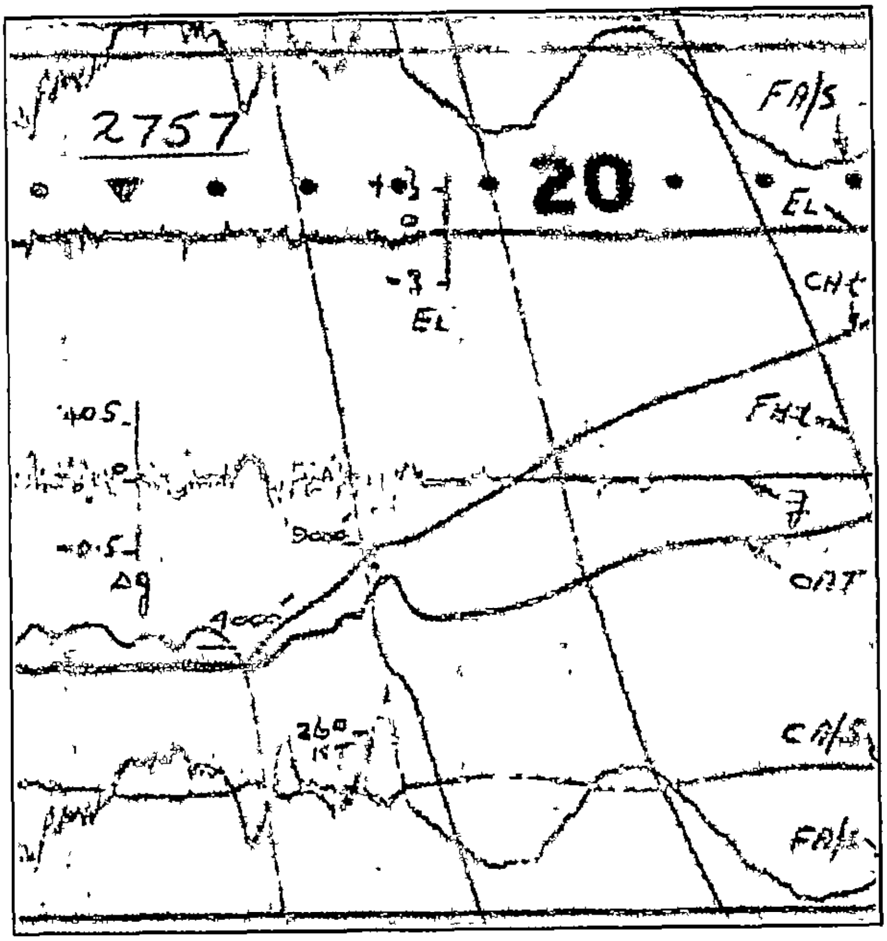


Fig.22 Patch 2a

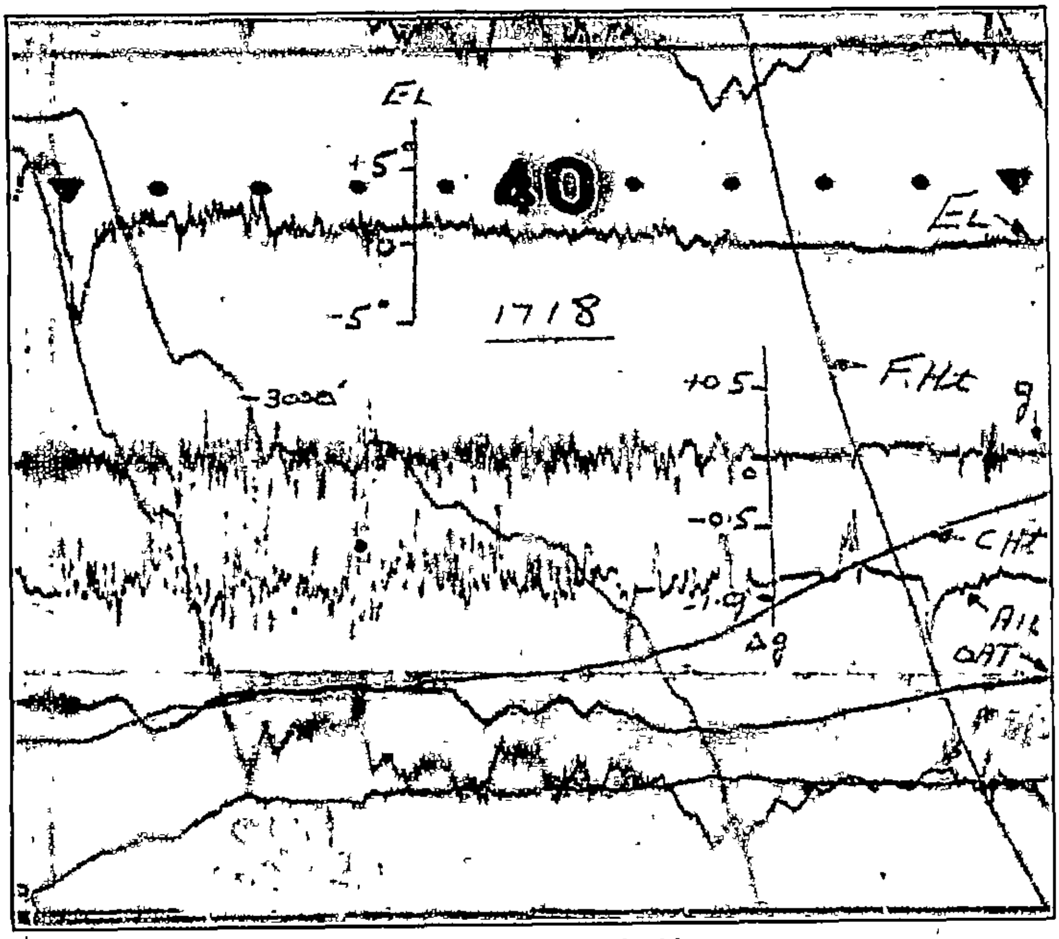


Fig.23 Patch 2b

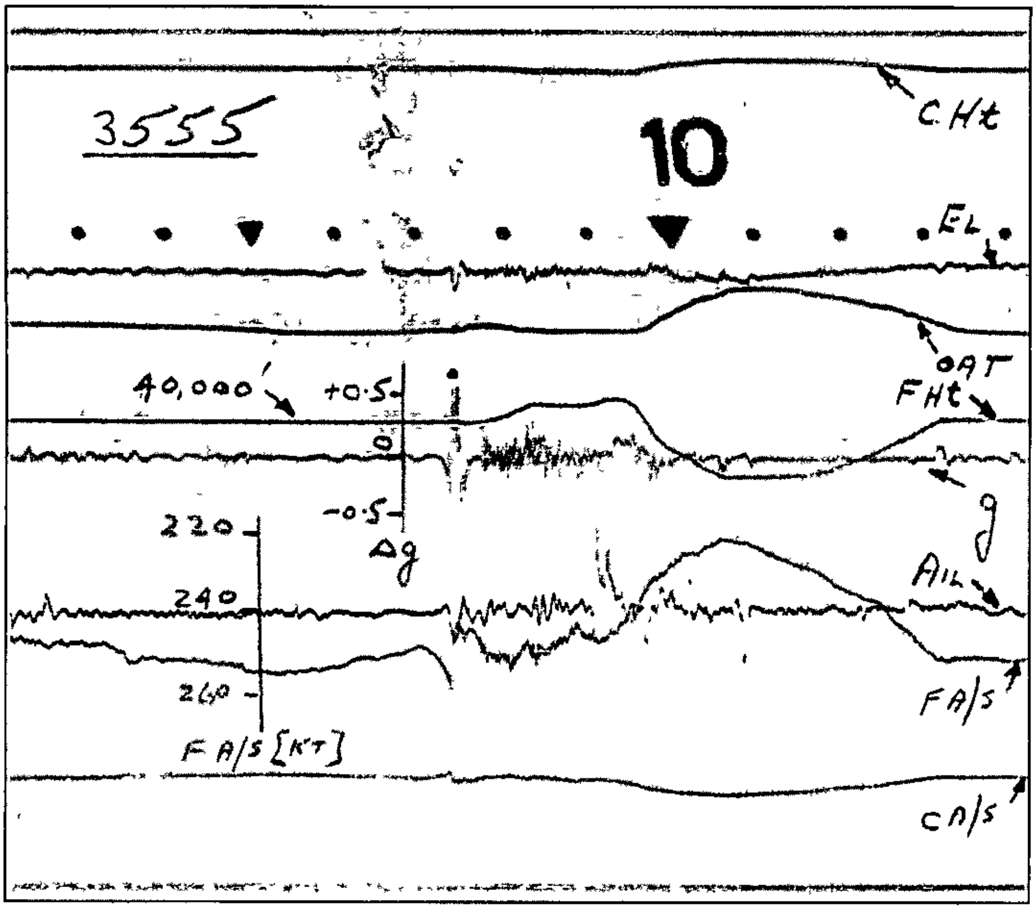


Fig.24 Patch 2c

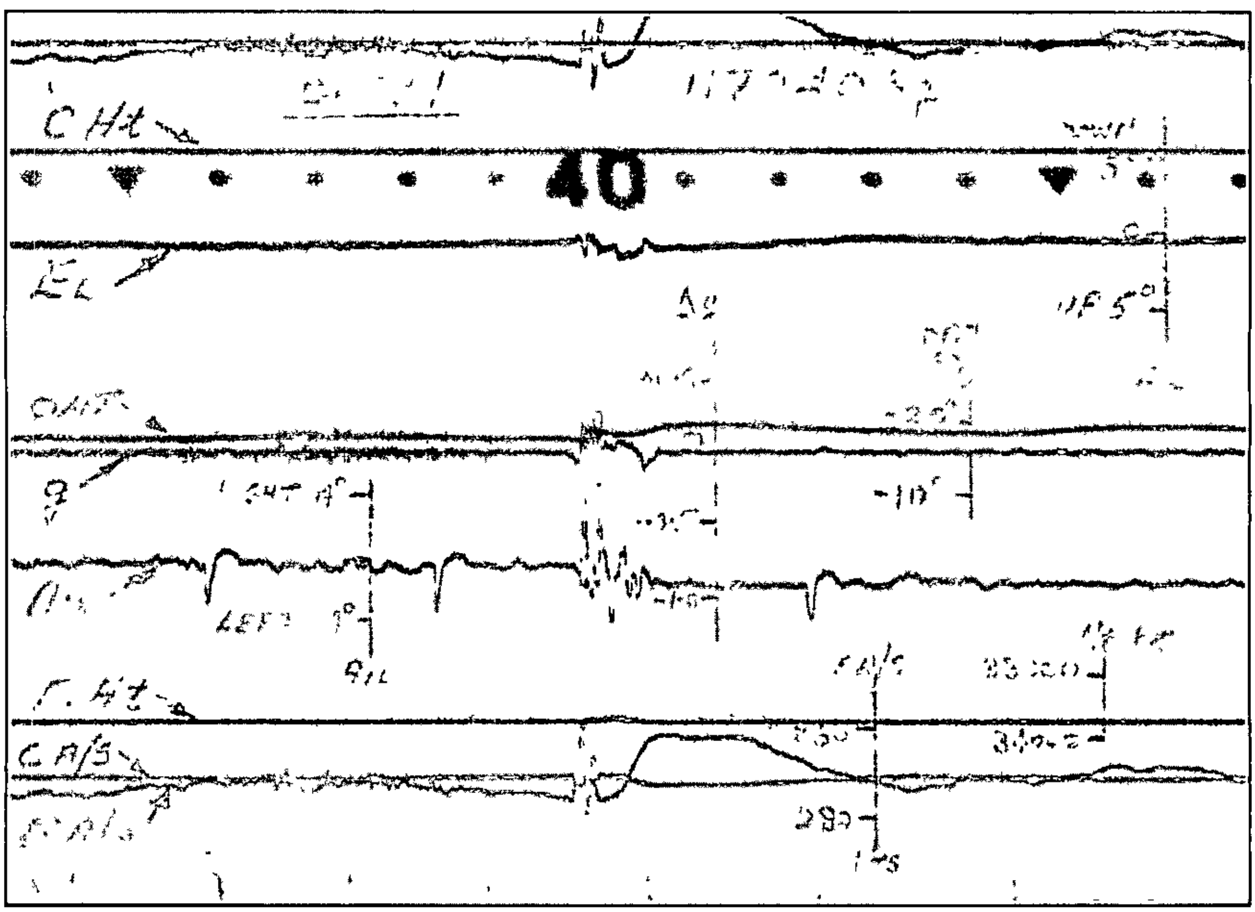


Fig.25 Patch 2d

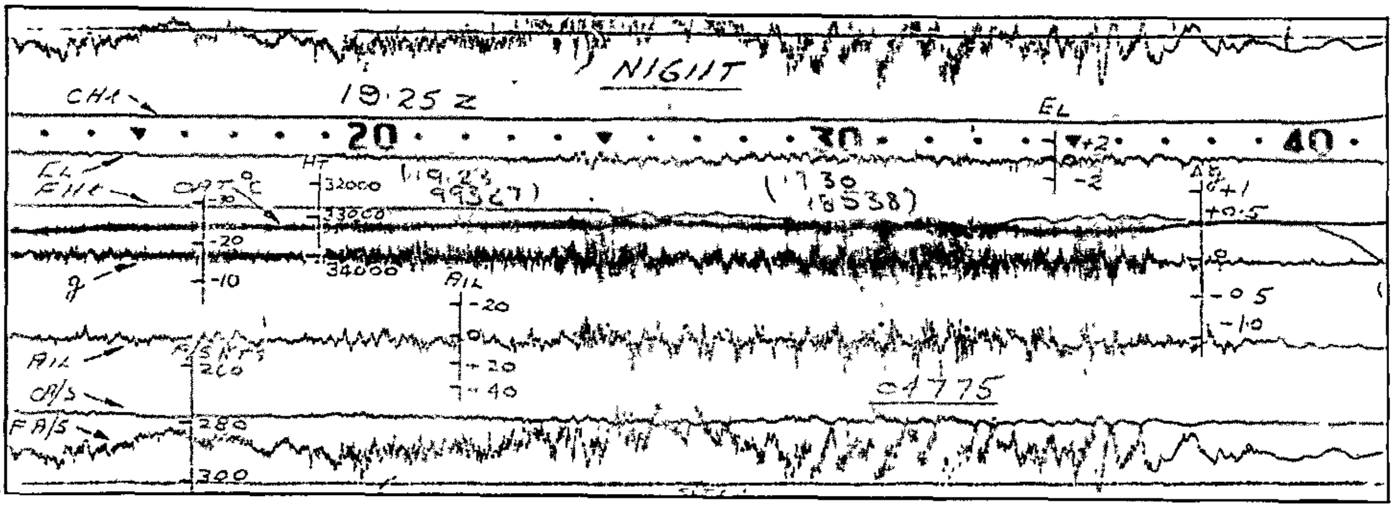


Fig.26 Patch 2e

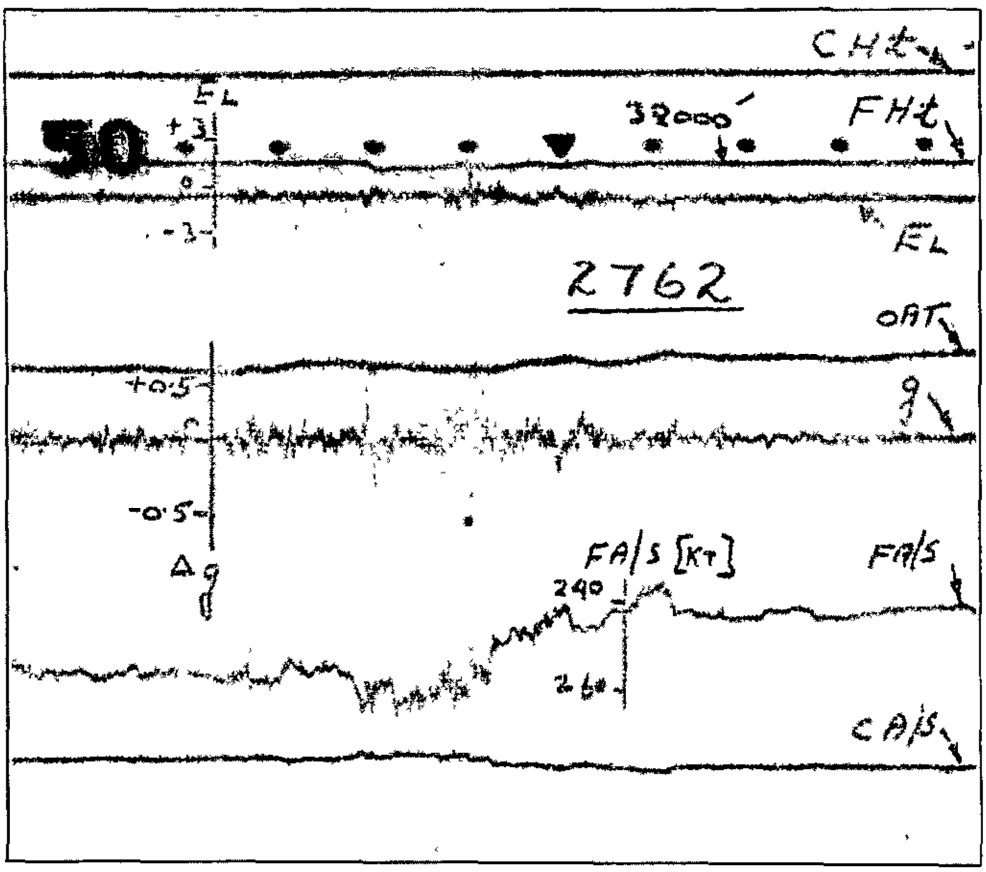


Fig.27 Patch 2f

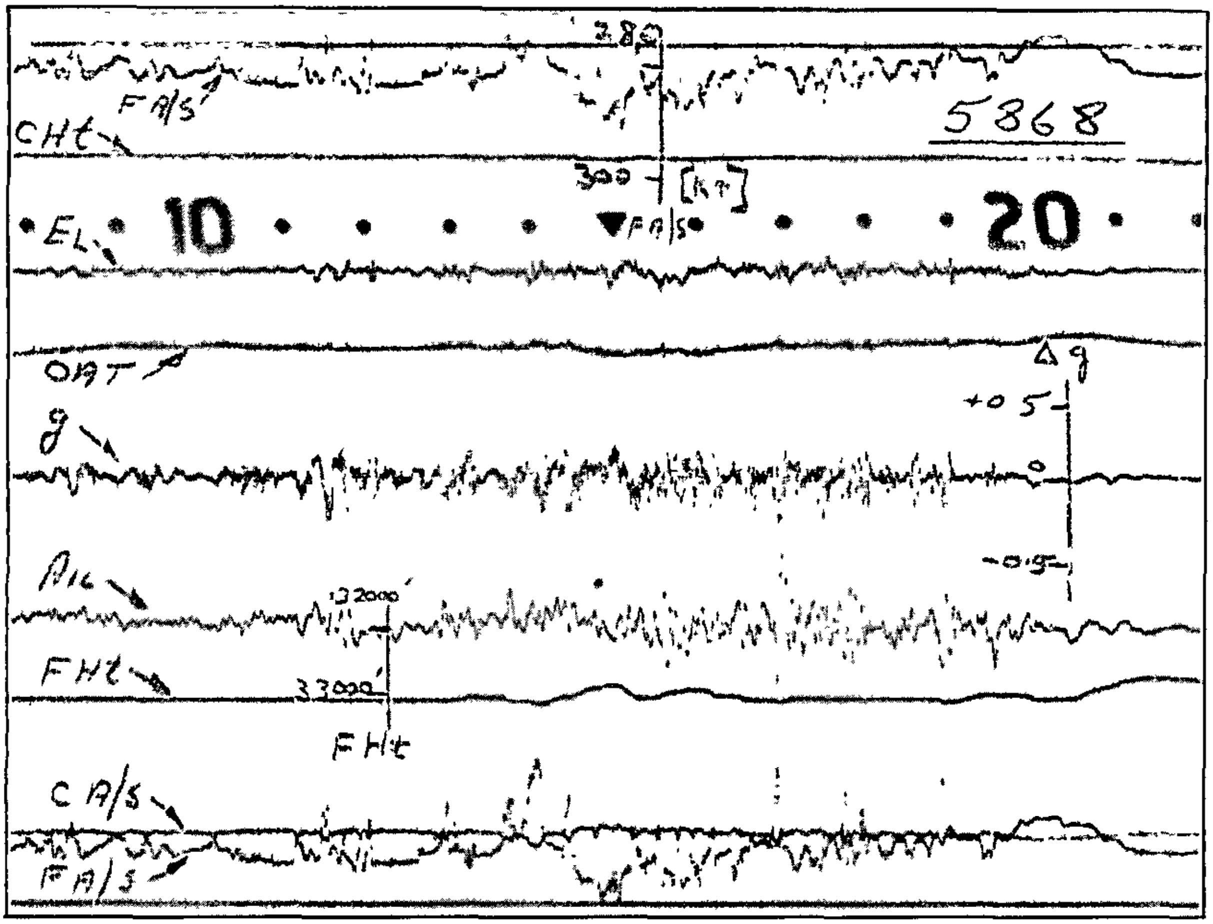


Fig.28 Patch 2g

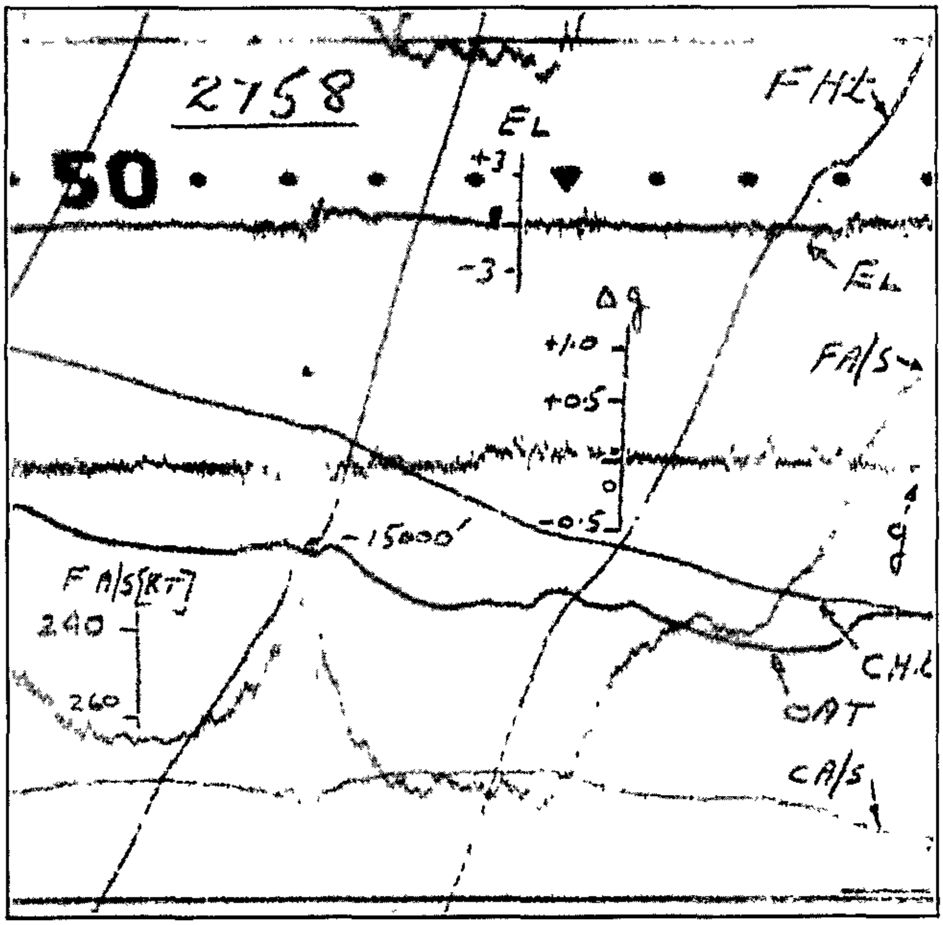


Fig.29 Patch 2h

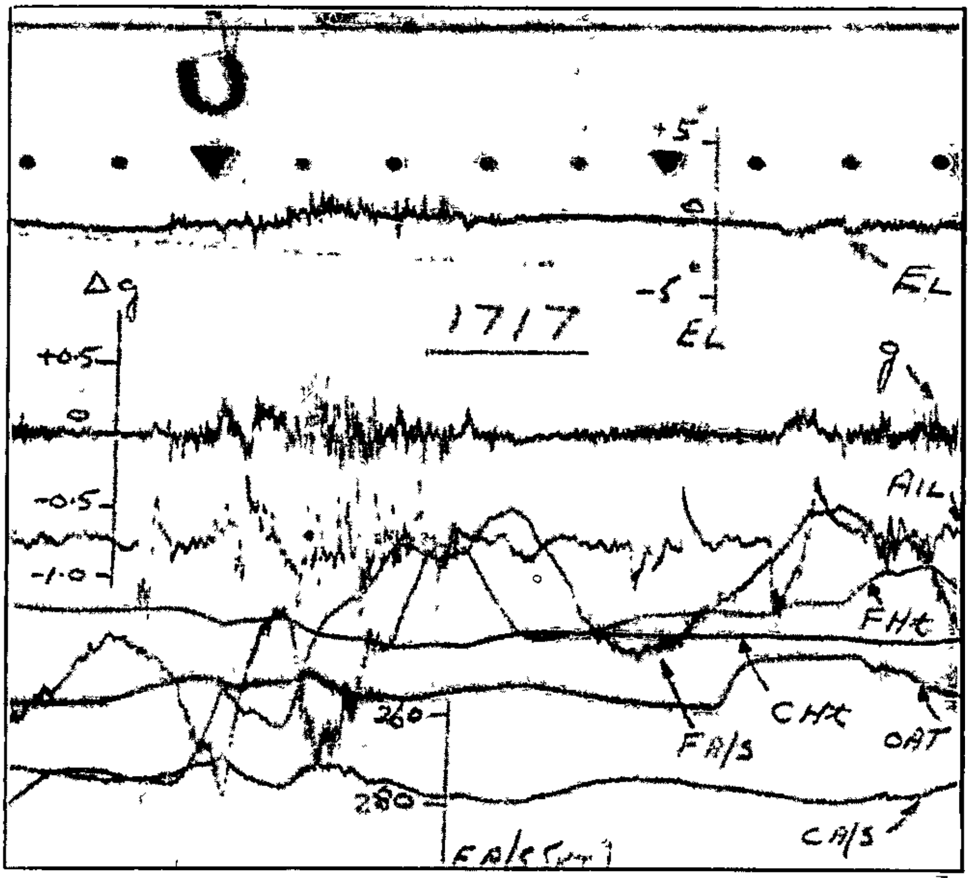


Fig.30 Patch 2i

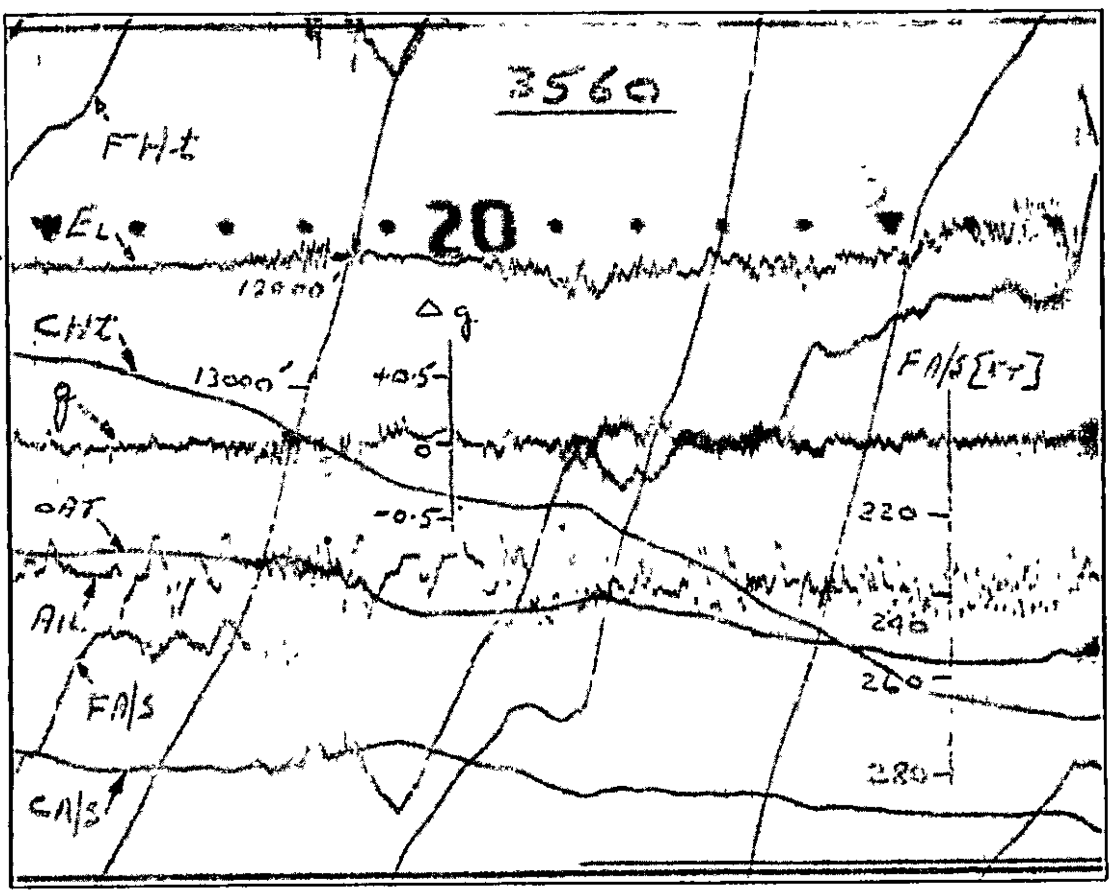


Fig.31 Patch 2j

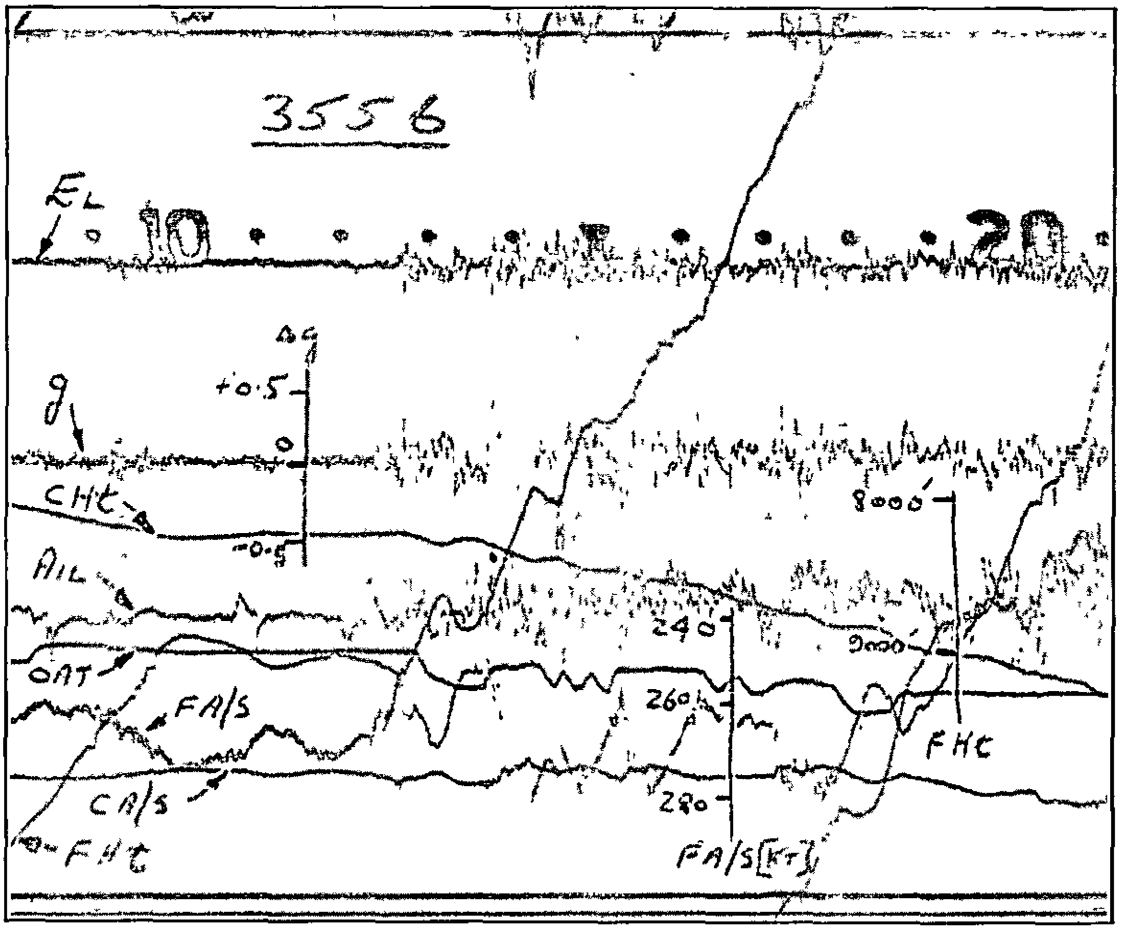


Fig.32 Patch 2k

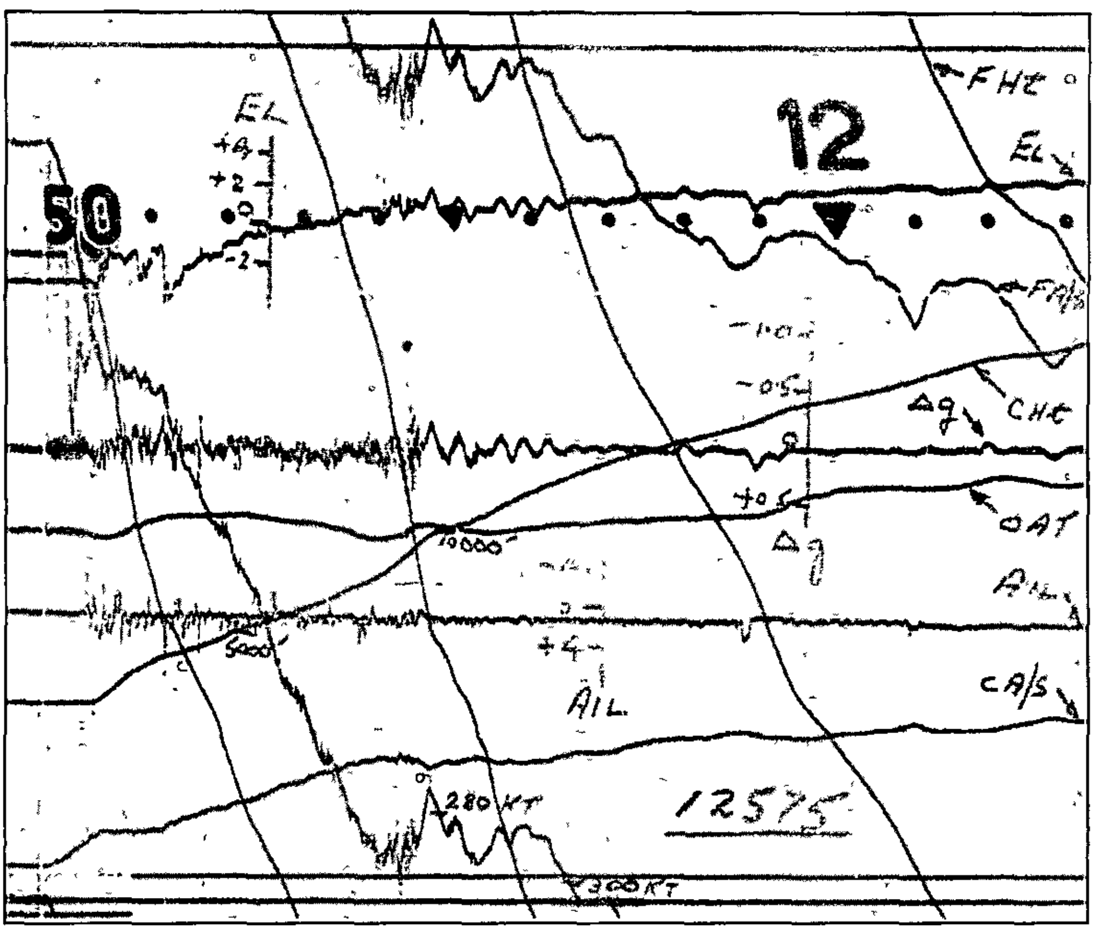


Fig.33 Patch 3a

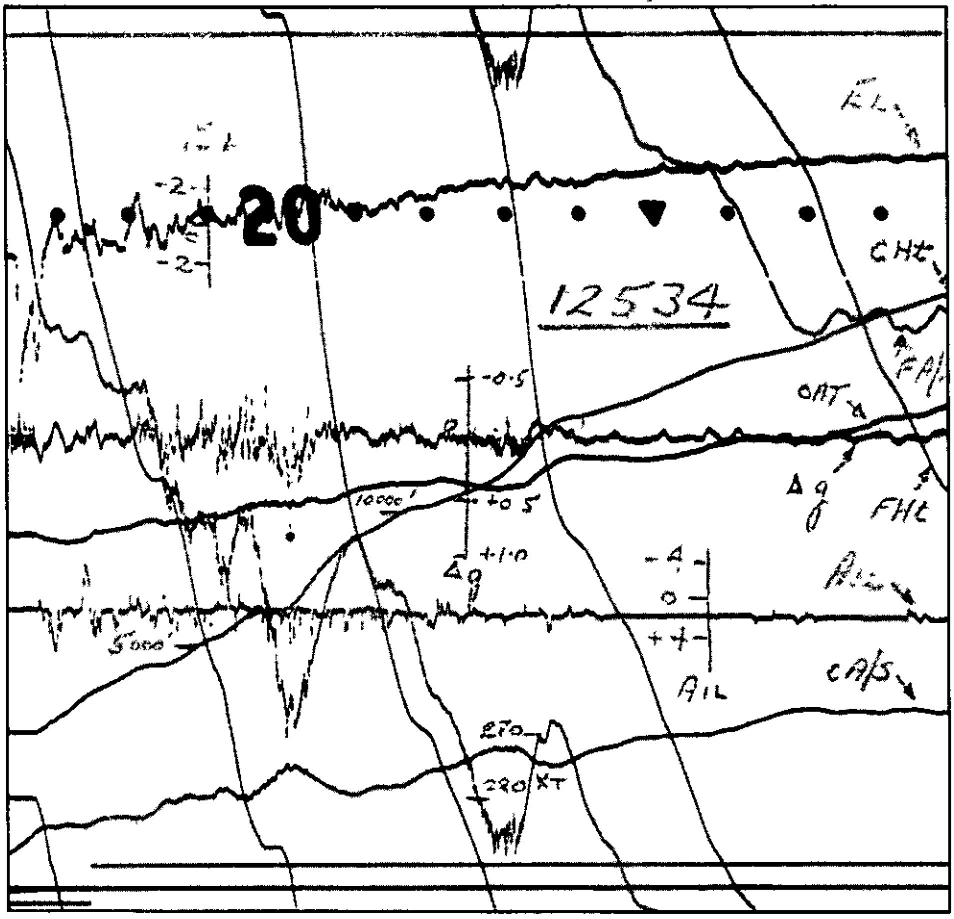


Fig.34 Patch 3b

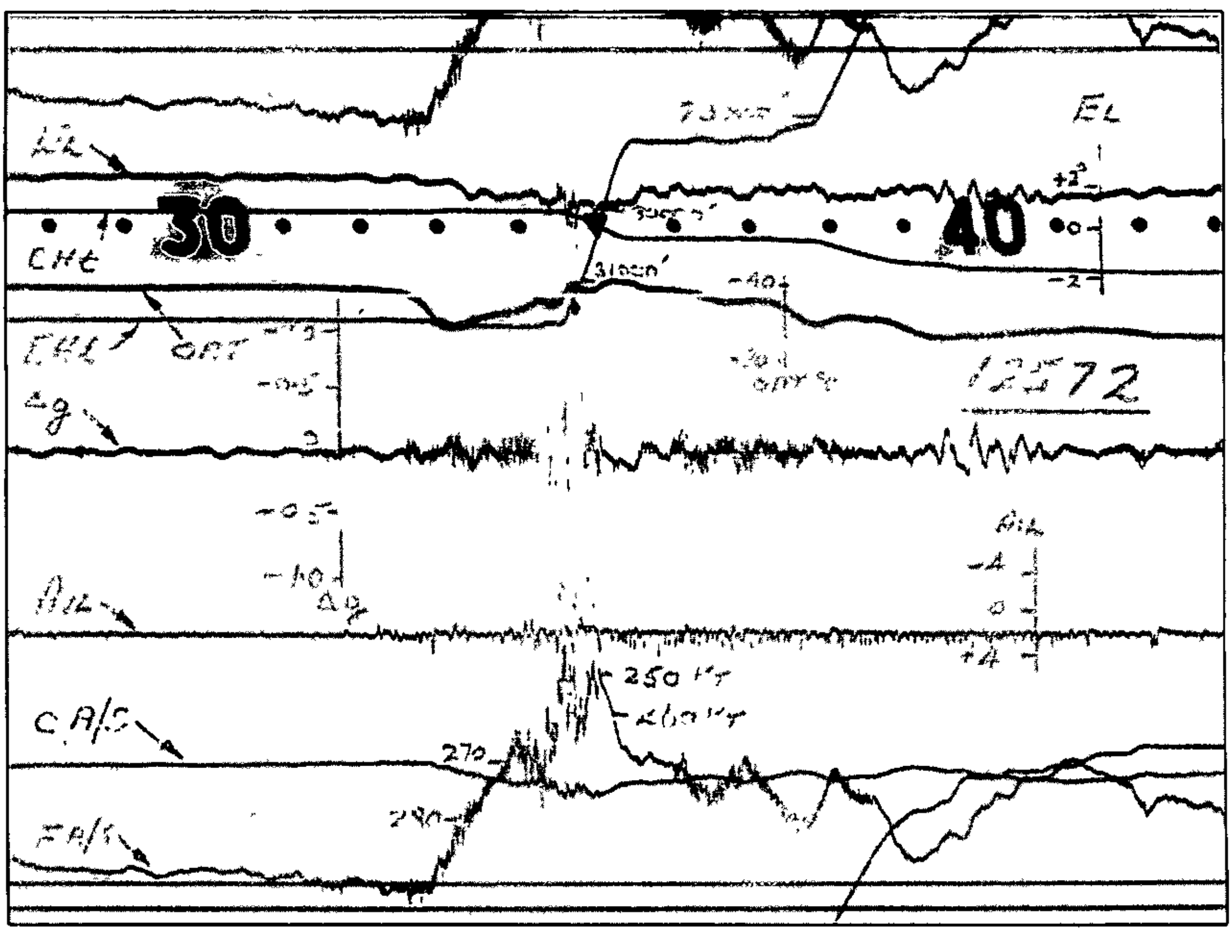


Fig.35 Patch 3c

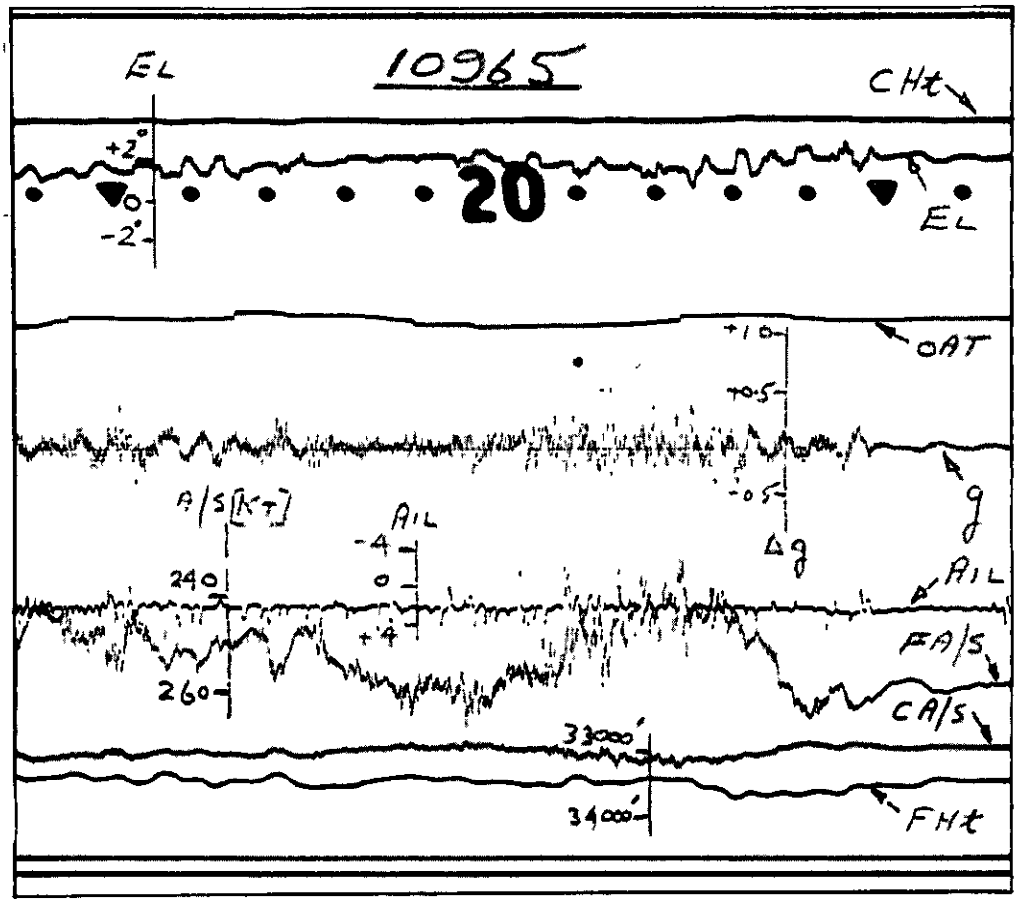


Fig.36 Patch 3d

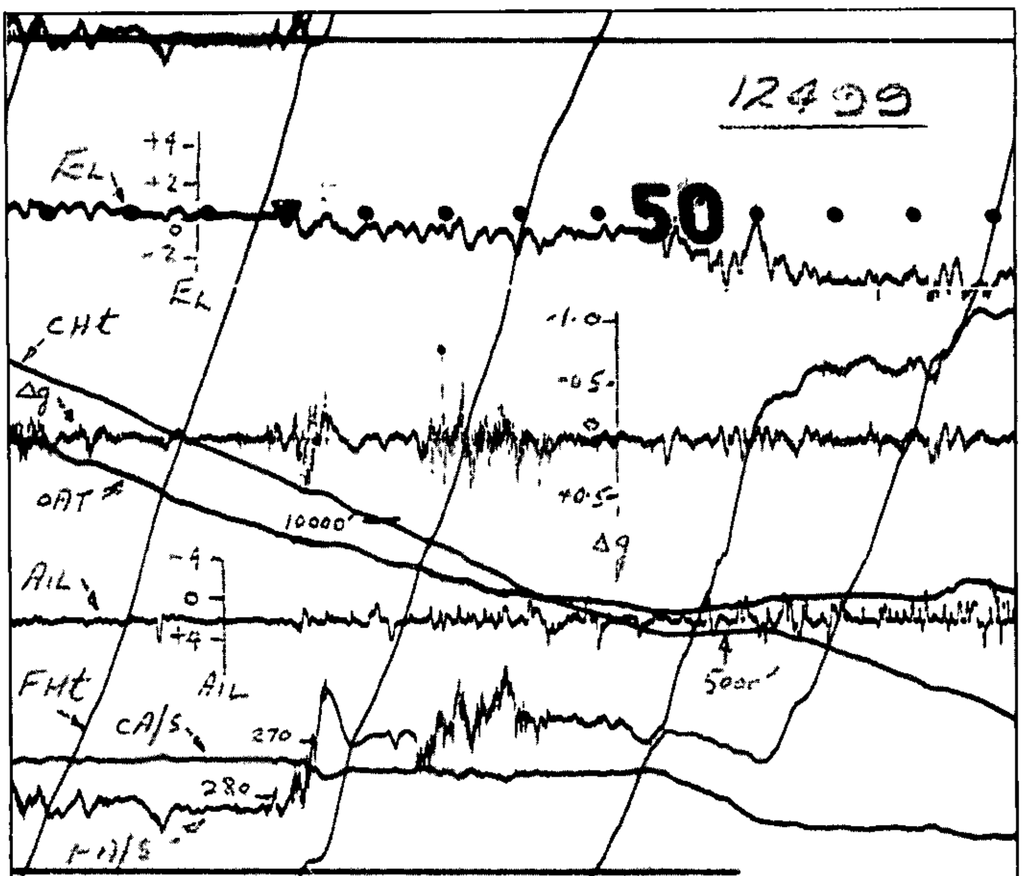


Fig.37 Patch 3e

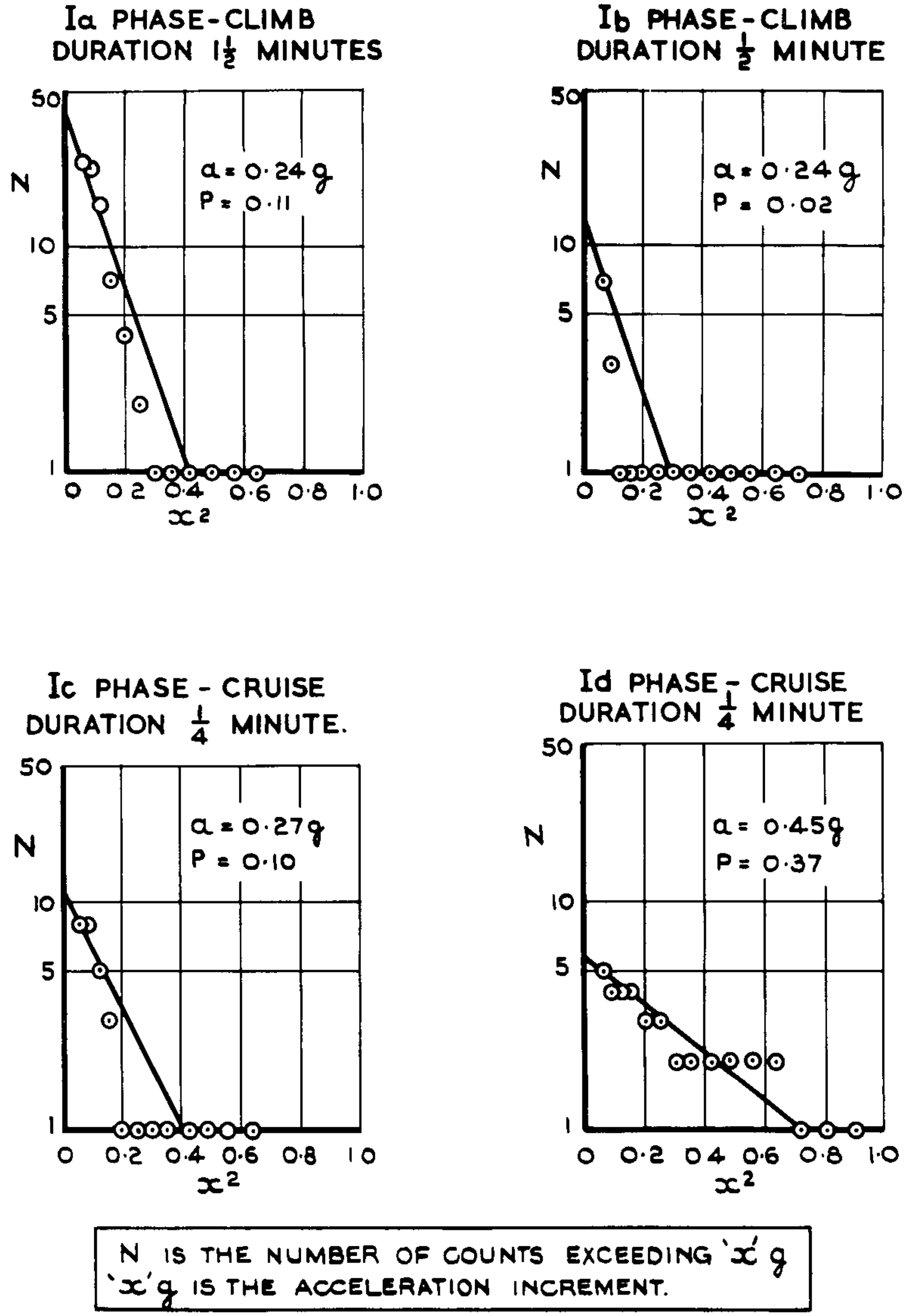


FIG. 38 AIRCRAFT TYPE I - PATCHES OF TURBULENCE CONTAINING OVER 0·8g INCREMENT

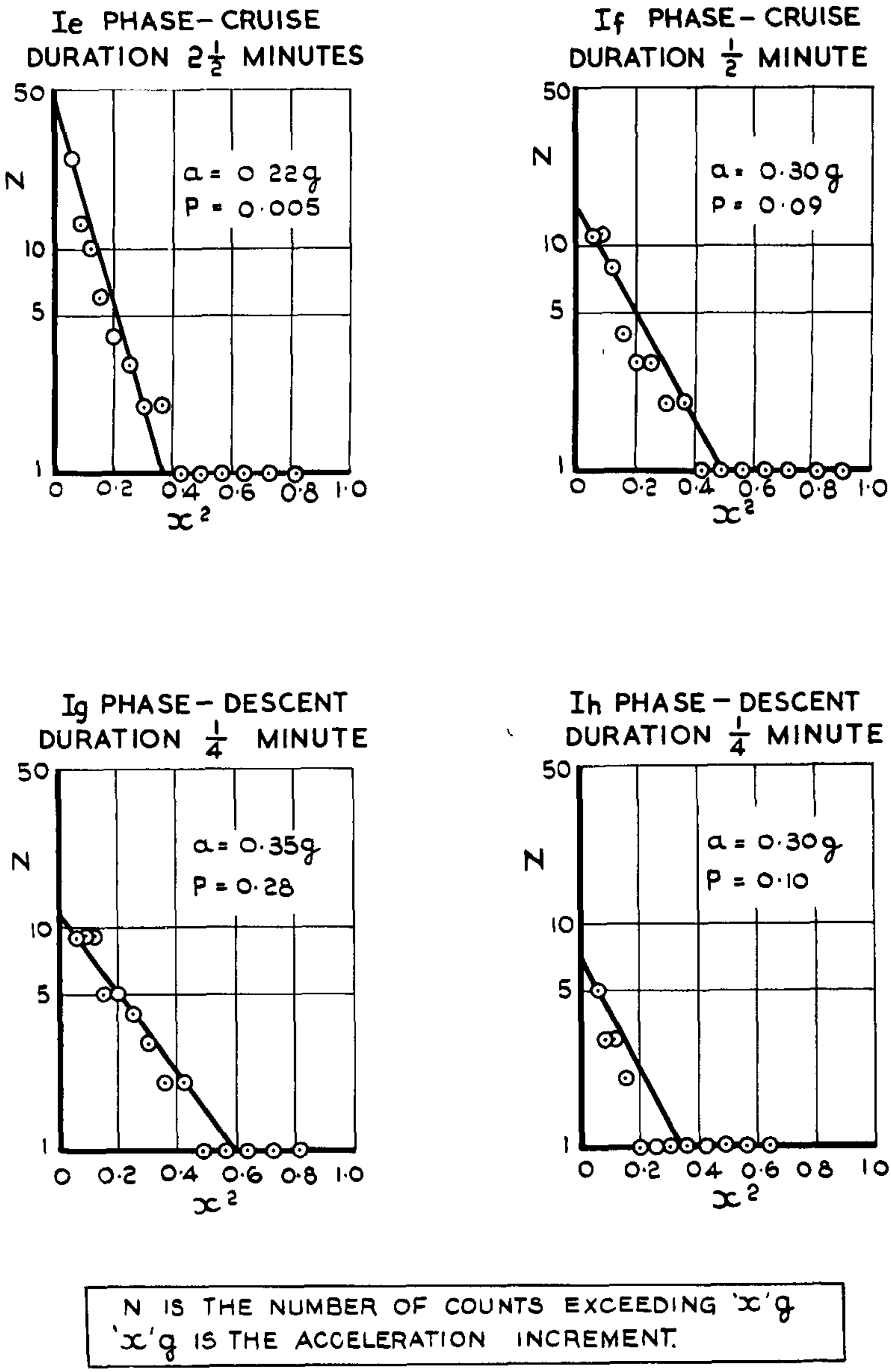
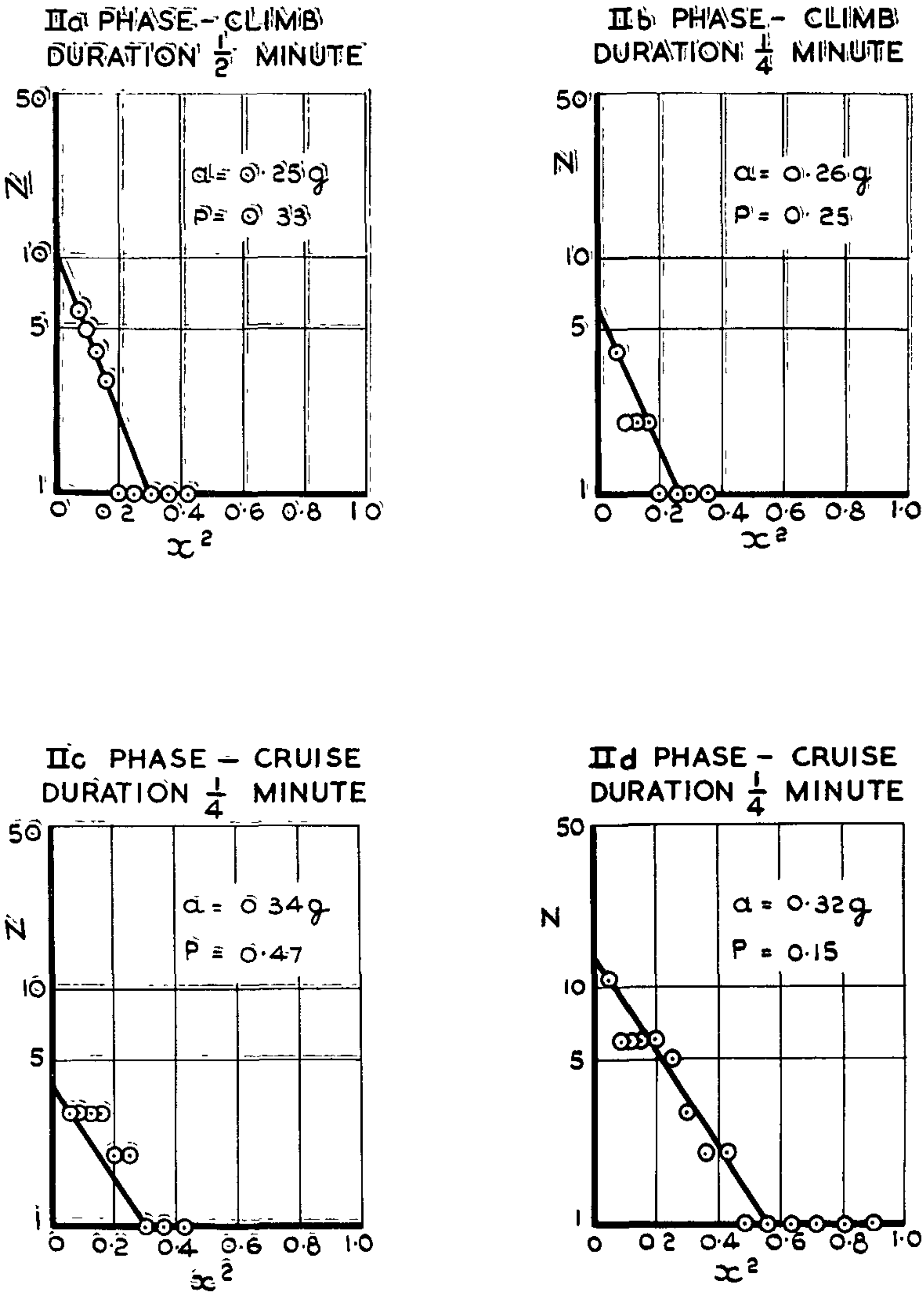


FIG 39 AIRCRAFT TYPE I — PATCHES OF TURBULENCE CONTAINING OVER 0.8 g INCREMENT



N IS THE NUMBER OF COUNTS EXCEEDING 'x' g
'x' g IS THE ACCELERATION INCREMENT

FIG. 40 AIRCRAFT TYPE II – PATCHES OF TURBULENCE CONTAINING OVER 0·6 g INCREMENT

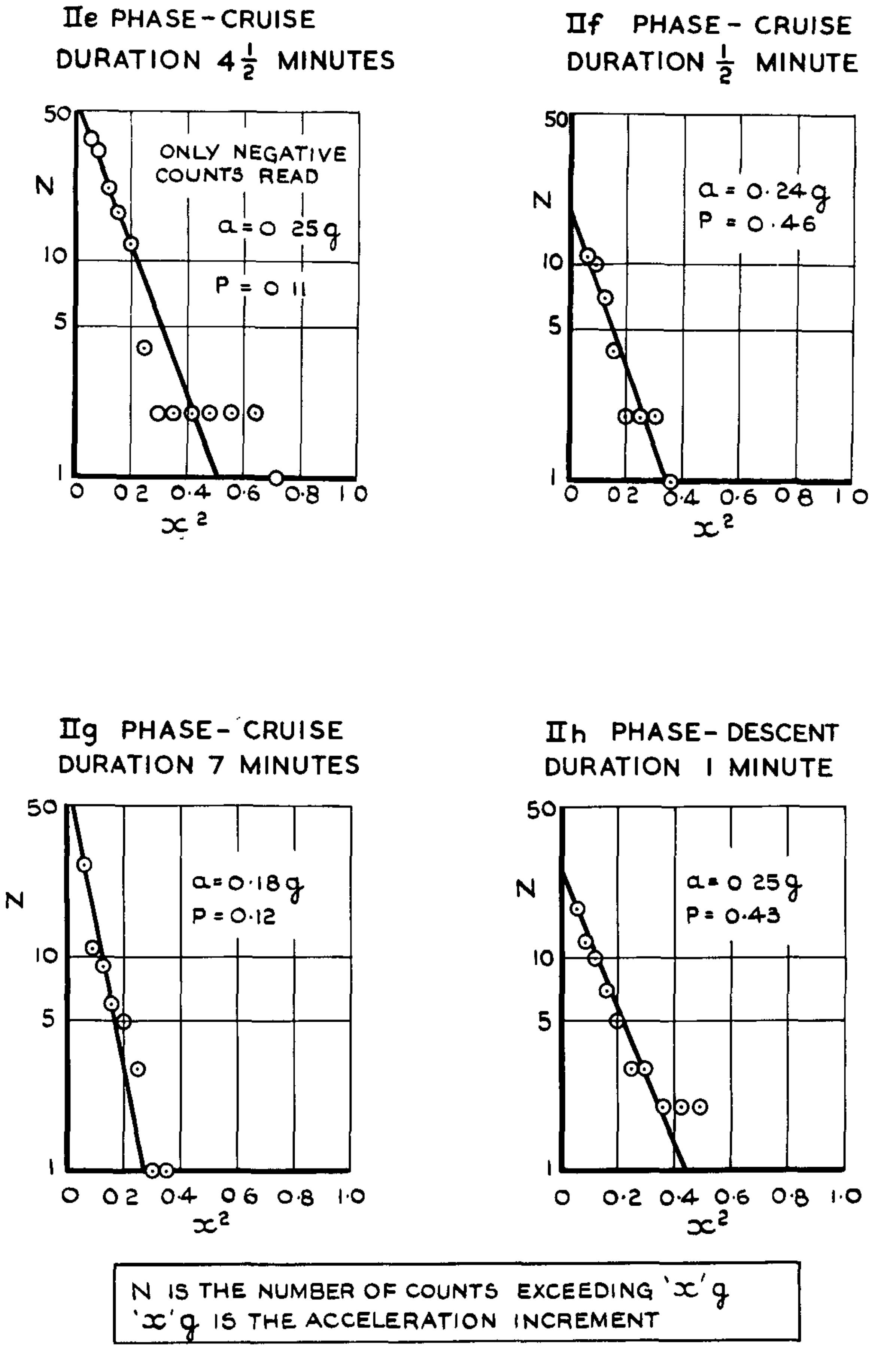
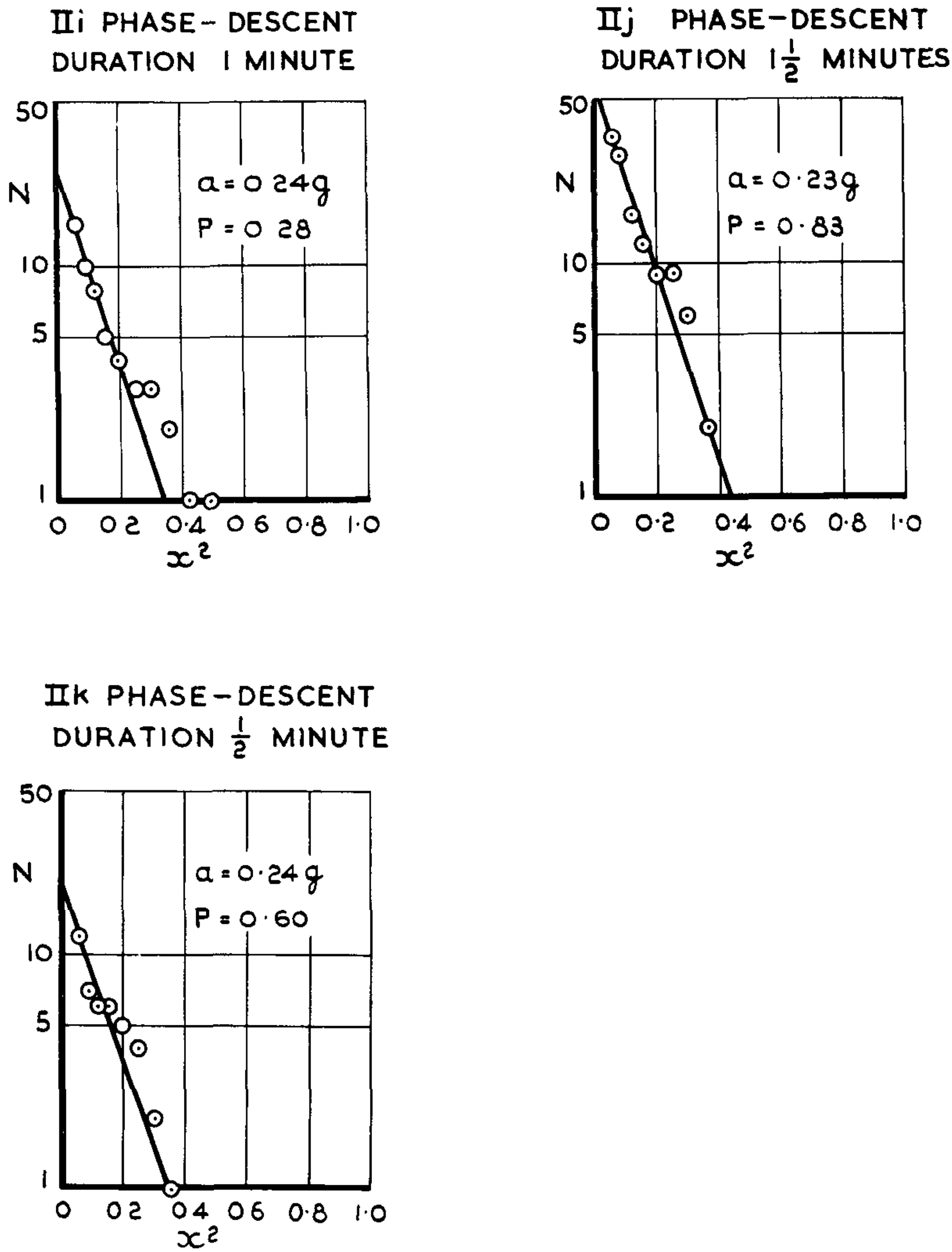
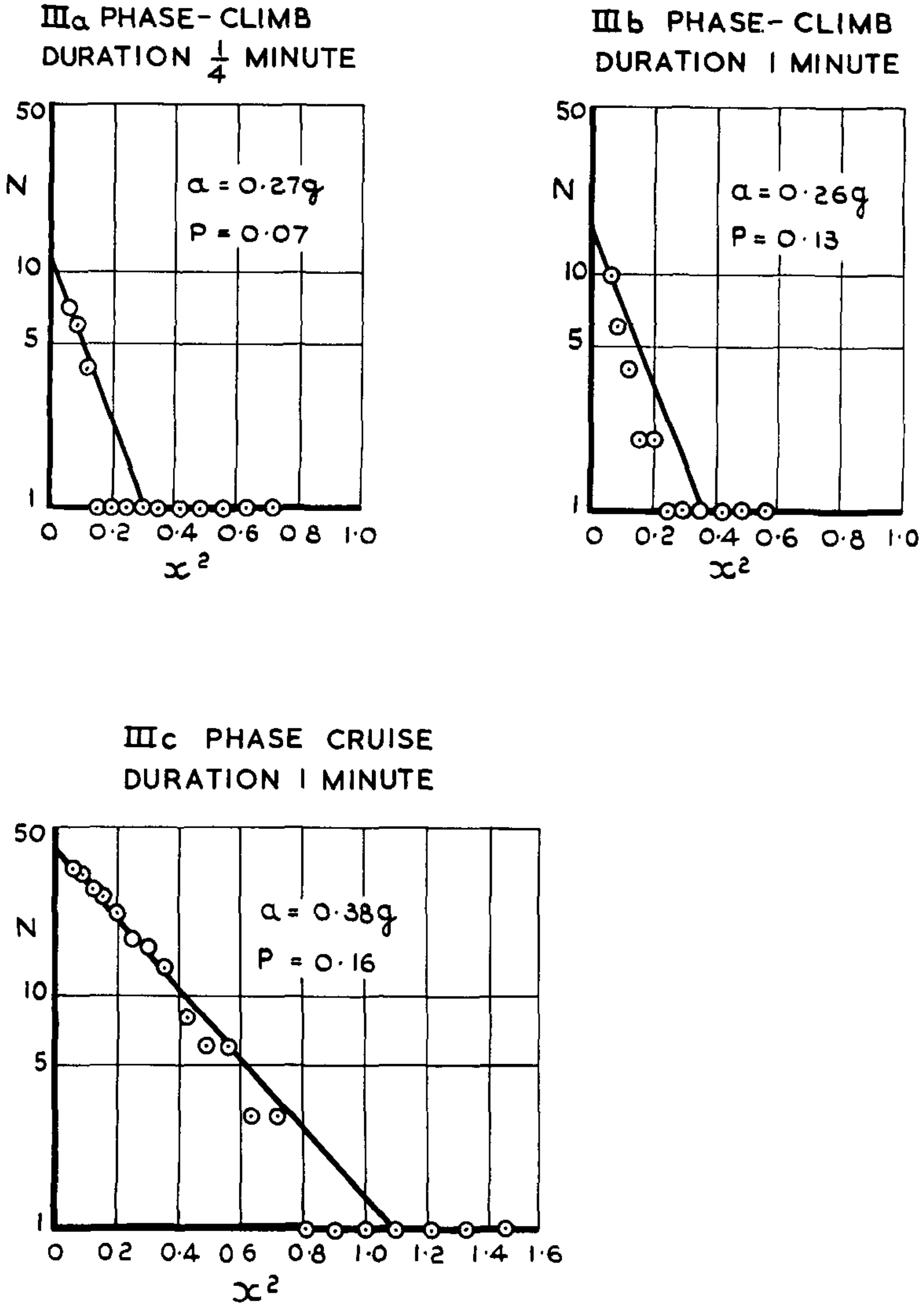


FIG. 41 AIRCRAFT TYPE II — PATCHES OF TURBULENCE CONTAINING OVER 0·6 g INCREMENT



N IS THE NUMBER OF COUNTS EXCEEDING 'x'g
'x'g IS THE ACCELERATION INCREMENT

FIG. 42 AIRCRAFT TYPE II — PATCHES OF TURBULENCE CONTAINING OVER 0·6 g INCREMENT



N IS THE NUMBER OF COUNTS EXCEEDING 'x'g
'x'g IS THE ACCELERATION INCREMENT

FIG 43 AIRCRAFT TYPE III - PATCHES OF TURBULENCE CONTAINING OVER 0·75g INCREMENT

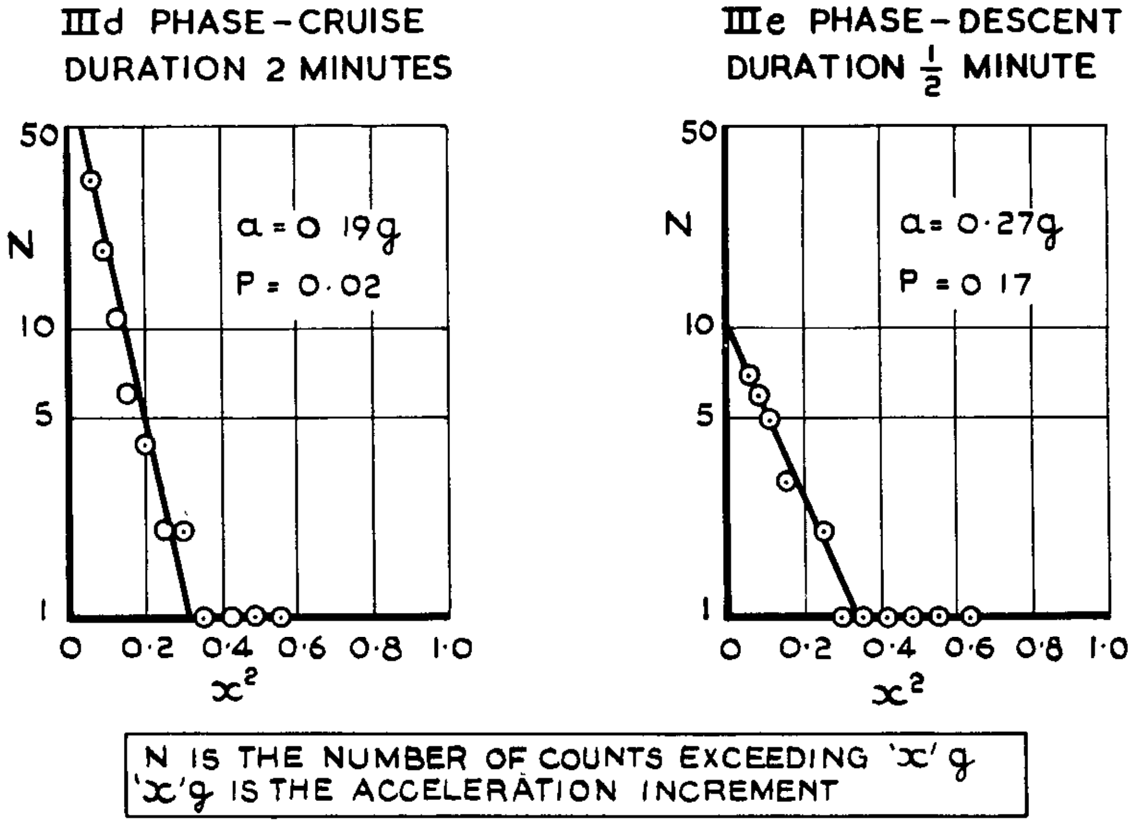


FIG 44 AIRCRAFT TYPE III - PATCHES OF TURBULENCE CONTAINING OVER 0·75g INCREMENT

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A.R.C. C.P. No.974
June 1967

G.E. King

629.135.2:
656.7.091.26:
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629.13.097

CIVIL AIRCRAFT AIRWORTHINESS DATA RECORDING PROGRAMME
STUDY OF SEVERE TURBULENCE ENCOUNTERED BY CIVIL AIRCRAFT

Continuous trace records of airworthiness data have been taken from a small number of aircraft in normal airline service since October 1962.

The acceleration trace on a sample of records covering 3284 flying hours has been read to give peak values. The durations of the patches of turbulence have been estimated and an attempt has been made to distinguish between gust and manoeuvre loads.

The most severe of these patches of turbulence have been studied in detail; it is found that the largest acceleration in a patch is often larger than would be predicted from a Rayleigh distribution of peaks, which is the distribution normally used in spectral analysis of turbulence.

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DETACHABLE ABSTRACT CARDS

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