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The Case for Factors of Safety of 1.5 instead of 2.0, with Special Reference to the Flight Envelope

By

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1.—*Introduction.*—The purpose of this note is to show the desirability of using a factor of safety of 1·5 throughout all design strength requirements, in particular in the first instance for all requirements directly connected with the symmetric flight envelope. Alongside this is shown the desirability of changing the flight envelope to agree more nearly with results obtained in practice (from *V–g* records).

2. *Present Position.*—The use of a factor of safety of 2·0 in determining ultimate loads for design of aircraft structures has been, with the notable exceptions of undercarriage loads, gust loads, and fin and rudder loads, almost universally required in the past.

Recently, however, it has been found convenient to consider the stressing of high-speed fighter aircraft to a speed estimated to be the terminal velocity, *i.e.* the physical limit of speed of the aircraft concerned. A certain arbitrariness has naturally been included to cover the effects of compressibility at these high speeds, but apart from this the major reason for imposing a factor of safety of 2·0 disappeared. By adjusting the normal acceleration which was specified it was an easy matter to recast the flight envelope and its associated stressing cases in terms of a factor of safety of 1·5, thus relieving the high-speed condition of excess strength that could not possibly be required.

This has led to some confusion—in wording rather than in ideas—because the standard stressing requirements are couched in terms of factors of 2·0 in most cases. Thus there have arisen stressing conditions involving mixture of factors.

3. *Design Loads.*—All that the aircraft designer eventually needs in order to stress an aircraft structure is the value of the ultimate failing load to be carried by any given member. Even the proof load requirements are covered by this since, at present, they are specified in terms of the ultimate load.[1]

Whether this ultimate load is expressed in terms of a basic load with a factor of 2·0 or a higher basic load with a factor of 1·5 cannot in the end make any difference whatever. Thus, provided that, where the total load arising in a member is made up from two independent sources (*e.g.*, forward speed and normal acceleration), suitable relative adjustments of the basic conditions are made, it is just as easy to express design requirements in terms of a factor of 1·5 or of 2·0 without altering the ultimate strength. This idea is developed more fully in Ref. 2.

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* R.A E. Technical Note No. S.M.E. 211.

Thus the essential duty of design requirements is to provide adequate ultimate and proof load conditions, the choice of factor being entirely a matter of convenience.

4. *The Choice of Factor.*—In deciding what value to give to ultimate loads it is natural to turn to the expected operational conditions of the aircraft and where possible to make use of experimental data. The natural process is to decide on the limits of operational severity expected and to put a factor on the resulting loads. The obvious choice is to make the factor such that under these limiting operational conditions the structure is not quite proof loaded. Allowing a small margin, this leads at once to a factor of 1·5 on the operational limit. This idea is conveyed in the American term ' limit load '.

Thus as stressing loads are gradually more and more related to actual experimental data, it will be natural to think in terms of a factor of 1·5 rather than of 2·0, thus making the basic condition a flight condition which is considered to be the severest likely to be achieved.

In thinking of realistic load conditions attention has naturally been focussed on the main flight envelope, both by reason of the desire to cover unrestricted dives for fighters and by reason of the increasing number of *V–g* records obtained on all types. It is clear that as instrumentation work proceeds (strain gauges, etc.) it will become increasingly possible to think of all stressing cases in a similar realistic fashion. In the meantime, since as stated above the factor chosen is only a matter of convenience, it seems reasonable to prepare the way by a wholesale change over to a factor of 1·5, which will at any rate have to be partially effected to avoid confusion of mixed factors.

This choice of a factor of safety of 1·5 on a realistic basic design condition will also have the natural advantage of making the basic condition suitable for structural testing, giving an immediate answer not only to the question whether a component has adequate ultimate strength but also showing at once whether the chosen limit load can be withstood without proof loading the structure.

5. *V–g Records.*—Although a factor of 1·5 can be conveniently used for any stressing case, it is only when a rational basic loading has been chosen that its full value is apparent. For the flight envelope, help in choice of this basic loading comes from *V–g* record analysis.

V–g records[3] give a good guide to actual conditions of operation, but leave many details unknown when attempts are made to correlate results with frequency of loading. The main difficulty is that records show only peak values, and hence indicate only how often a given value may be expected as a peak, and not how often any value may occur. An improved instrument to provide this fuller data is under development. However, it is the peak values which are most important, and by plotting these on an *n*—*V* basis, a picture of the operational flight envelope attained in a given time can be built up. Fig. 1 (from Ref. 3) shows such results for the Lancaster, covering typical flying (operational and non-operational) over a period of 500 flying hours. Fig. 2 (also from Ref. 3) shows the results in a slightly different form, peak accelerations being shown in the speed ranges in which they occur.

The results given in Figs. 1 and 2 show up two important results. Firstly the speeds achieved are low in relation to the stressing speed for the type (the maximum level speed being only rarely exceeded), and secondly there is no indication of high acceleration occuring in conjunction with high speed.

Thus it appears that in searching for a flight envelope giving suitable basic load conditions the present form of rationalised diagram is not adequate. In fact the old centre of pressure forward, centre of pressure backward stressing conditions lead in this particular instance more nearly to an envelope covering experimental results. (The achieved C.P.F. and C.P.B. strength (2/3 ultimate) of the Lancaster is superimposed on Fig. 1).

6. *The Ideal Flight Envelope.*—The object is thus to find from *V–g* records of peak loads (or ideally from records from a more suitable instrument) a flight envelope on which all points are equally likely to be reached in a given number of flying hours. Furthermore, since the proof load is the limit for airworthy flight, it is desirable to choose the envelope so that the

average flying time taken to reach the boundary is acceptable as an average time between one proof load occurrence and the next. An ultimate factor of 1·5 on such a flight envelope in effect provides for proof loading at this rate with a small margin.

This determined the ultimate loads which, of course, could easily be put in the form of a factor of 2·0 on a lower basic flight envelope ; but the factoring of loads occurring on a given flight envelope increases strength uniformly along constant incidence lines, and it is not at all necessary that frequency of occurrence of load varies uniformly along incidence lines. Thus this lower basic flight envelope would suffer from the disadvantage of probably not being a uniform occurrence boundary, thus confusing the picture. In fact, in order to find this lower basic flight envelope in a rational system, a start must be made with a " uniform occurrence " boundary.

This same argument leads to the further interesting point that on the basis of a factor on proof load conditions the boundary representing ultimate loads will probably not be a uniform occurrence boundary. This, however, is of little consequence, since loads only just exceeding the proof loading may well be the cause of an accident and since deliberate flight in the region of an ultimate loading boundary is impracticable.

7. *A Practical Case.*—There is not yet enough evidence to enable the ideal of section 6 (which is theoretically applicable to any stressing case) to be achieved, but a step towards it has been taken in one case.

By plotting from V–g records the average number of flying hours needed to reach a given acceleration against the acceleration, it is possible to read off the greatest acceleration which will occur in a given flying time. If this flying time is taken to be the acceptable average time interval between successive proof loads, then the corresponding acceleration will be the design value for the unfactored flight envelope of section 6.

If the same is done for speeds, the design value of the speed for the unfactored flight envelope can also be found in the same way.

This process gives at any rate an idea of the size of the required flight envelope, but not its shape, since speed and acceleration are treated quite independently.

For the case in point the shape of the curves for frequency of speed and acceleration are shown (plotted logarithmically) in Figs. 4 (*a*) and 4 (*b*) (both from Ref. 3). Considerable extrapolation of results is necessary, and so only the order of the results can be taken as accurate.

The ultimate normal acceleration at take-off weight was chosen at $4 \cdot 2g$ ($= 1 \cdot 5 \times 2 \cdot 8g$). Now Fig. 4 (*a*) indicates an occurrence of $2 \cdot 8g$ (or greater) once every 4×10^2 hours. Actual rates of proof loading could be expected to be lower than this, as the aircraft was hardly likely to be at maximum weight when the high load occurred. From the curve of Fig. 4 (*b*) it was found that the speed which occurred just about as often as $2 \cdot 8g$ (*i.e.* every 4×10^2 hours) was 300 m.p.h. (E.A.S.). This speed was far below that which would be specified as a diving speed on the old basis of a multiple of maximum level speed.

Turning to the alternative idea of equal frequency of ultimate loading it was found by considerable extrapolation that $4 \cdot 2g$ occurred once every 10^5 hours, and the speed which occurred at just about the same rate was 500 m.p.h. (E.A.S.) which is $\sqrt{1 \cdot 5} \times 400$ m.p.h. (This bears out the point made in section 6 that factoring a boundary chosen for uniform occurrence does not lead of necessity to another boundary of uniform occurrence.) The aircraft under consideration was expected to be faster and to have a lower drag/weight ratio than that from which the V–g records were taken. Hence 400 m.p.h. (E.A.S.) was chosen as the stressing speed. Now 400 m.p.h. was clearly far below the terminal velocity (at reasonable heights), and so to emphasise its nature a speed limit of 360 m.p.h. (E.A.S.) was proposed for this new design as a service limitation. This choice was made because

(*a*) it is unlikely that pilots would want to exceed this speed,

(*b*) torsion loads have a factor of at least 2·0 at this speed and hence it can be exceeded to the same degree as previous diving speeds before proof loading.

Having thus chosen the maximum values of acceleration and speed the flight envelope was sketched in to follow the lines indicated by the results of Fig. 1. In particular the " case B " and " case C " corners were cut off as being not achieved in practice and demanding extra strength.

Fig. 3 shows the final envelope arrived at on these lines. It is seen that at the placard speed (360 m.p.h. E.A.S.) unrestricted flight up to $2\frac{1}{2}g$ is possible, but at the stressing speed all that is catered for is $2g$ pull-out from a dive assumed so shallow as to be effectively level ($1g$).

The negative side of the envelope was based on the strength necessary to cover automatic controls up to cruising speed, fading away to meet the positive side of the envelope at the placard speed.

8. *Impact on Other Requirements.*—The above outlines a method of introducing experimental measured values of loads with a factor of 1·5, and it has been shown that it is convenient to apply the factor of 1·5 to all stressing cases. In attempting to do this certain anomalies are brought to light. These have cropped up in the case of high-speed fighters where the diving speed chosen in relation to a factor of 1·5 has been used in conjunction with other stressing cases without appropriate alteration, thus making these cases more severe than would have been the case if a lower diving speed and a factor of 2·0 had been specified for the flight envelope

There may, however, be reason for this, since it may be that the terminal velocity for fighters differs from the " 1·5 speed " for other aircraft in that the former may be a blank wall effect—fairly frequently reached and impossible to exceed—while the latter is not a " blank wall " but merely a speed rarely approached in operation. There are as yet insufficient V–g records on high-speed fighter aircraft to settle this point.

Pending a wholesale changeover to factors of 1·5 throughout all stressing cases, it was agreed for the case considered in section 7 above to work with the placard speed of 360 m.p.h. (E.A.S.) for all stressing cases apart from those not directly connected to the symmetric flight envelope.

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No.	*Author*	*Title, etc.*
1	.. ..	A.P. 970, Appendix 1.
2	Montagnon	The Avoidance of Mixed Factors. R.A.E. Tech. Note No. S.M.E. 162.
3	Taylor	A First Summary of V–g Recorder Results for Bombers in Operations. A.R.C. 7266.

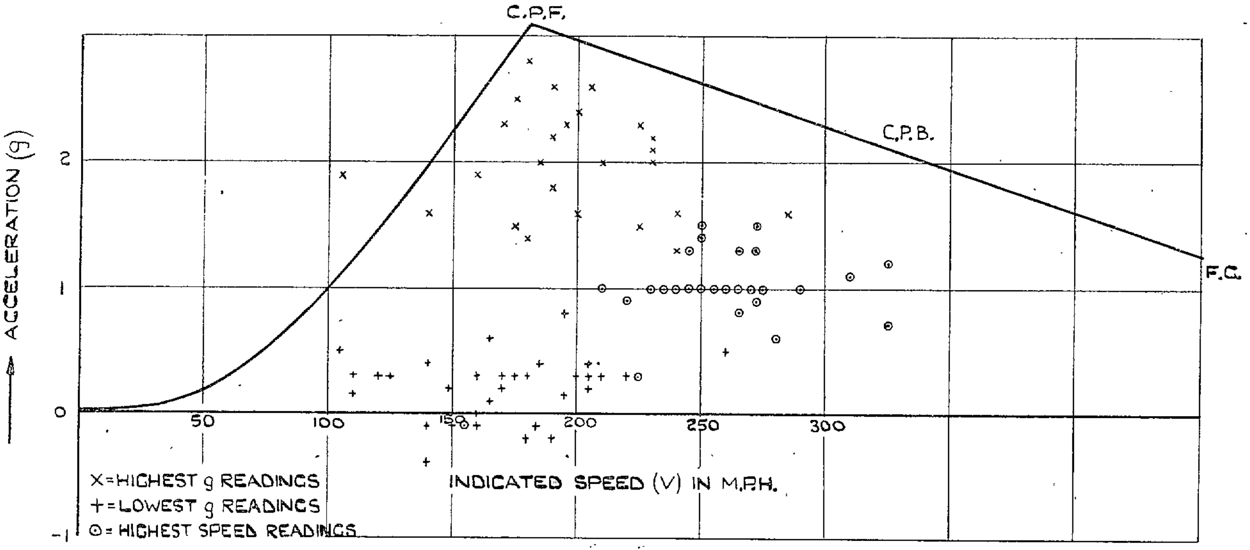


FIG. 1. *V–g* Recorder Results for Lancaster.

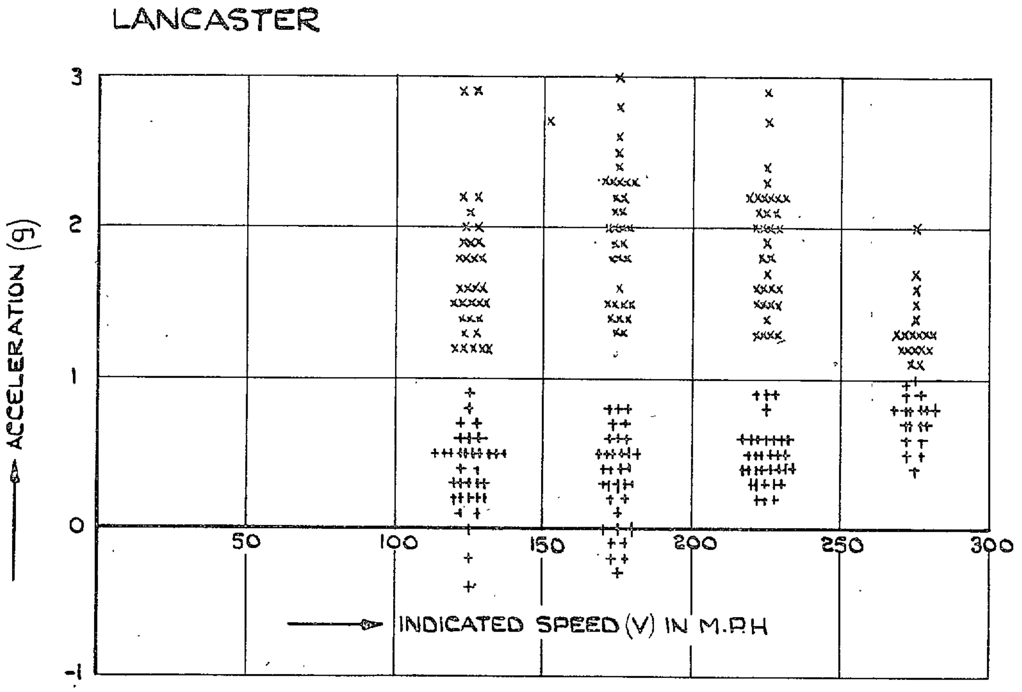


FIG. 2.

(94986) Wt. 14/806 K.5 1/51 H.W.

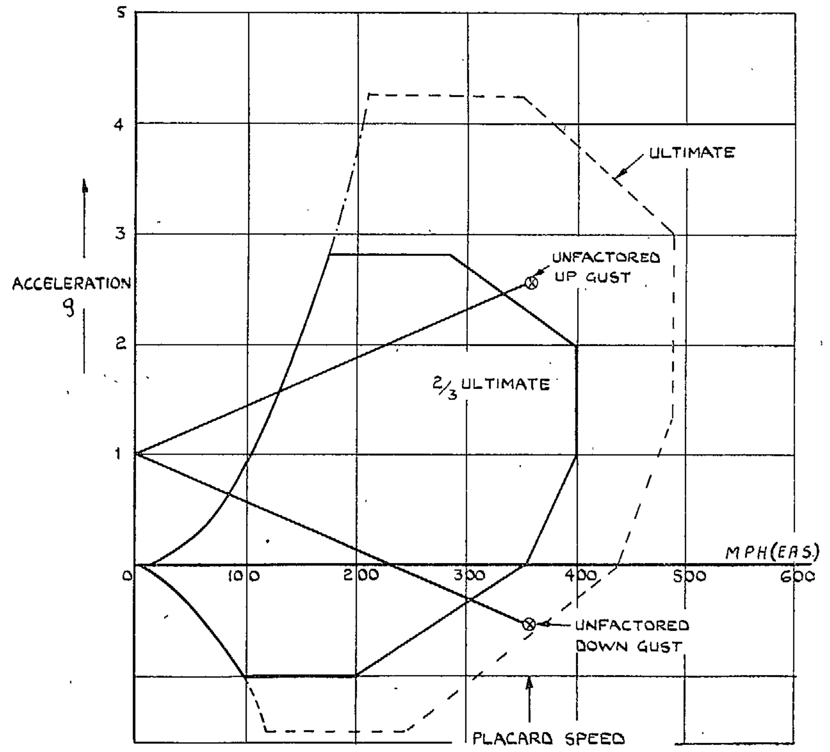
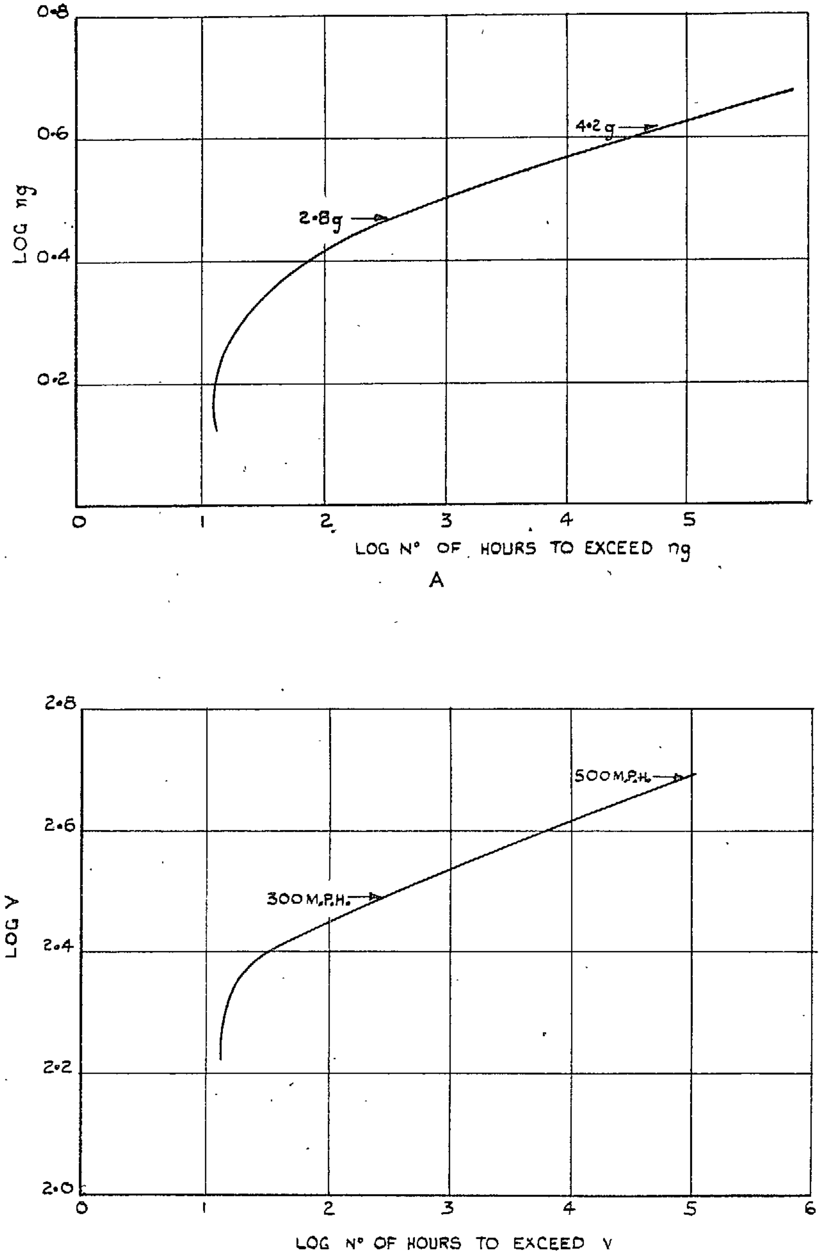


FIG. 3. Flight Envelope.



A

B

FIG. 4.

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