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The Effect on Weather Minima of Approach Speed, Cockpit cut-off Angle and type of Approach Coupler for a given landing success rate and level of safety

By

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ADDENDUM

Fig. 1 shows the angular distance below the horizon of the furthermost point which the pilot would require to see in order to obtain visual guidance from a given height. This information enables the reader to obtain an impression of what the pilot is looking at, but for purposes of calculation, what is more often wanted is the range required for guidance from a given height. These ranges are given in Fig. 5.

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ROYAL AIRCRAFT ESTABLISHMENT

The effect on weather minima of approach speed, cockpit cut-off angle and type of approach coupler for a given landing success rate and level of safety

by

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SUMMARY

The performance of instrument approach aids, as for instance I.L.S. and G.C.A., has hitherto been assessed in two ways. The first way is to determine the mean and maximum deviations from an ideal path. This is of little use to the aircraft operator, since his fundamental interests are weather minima and safety. The second way is to determine the lowest height down to which the approach aid can be used and still allow sufficient time for the pilot to transfer to visual ground references and make any corrective manoeuvres which may be necessary. This is more useful to the operator, but to apply it, assumptions have to be made as to the final corrective manoeuvres which the pilot is willing and able to make under visual guidance in bad visibility. In the past the assumptions made have been arbitrary, and have been related mainly to the manoeuvring characteristics of the aircraft.

During 1955/56, full scale flight tests have determined the times actually taken to correct azimuth displacements of various magnitudes, and it now seems that these final manoeuvres are closely related to the human characteristics of the pilot. During the same period, operational research and simulated tests have determined the minimum visual stimulus which must exist if the pilot is to make these manoeuvres with an acceptable level of safety. This note utilises these results to show the effect on visual range and cloud base of approach speed, accuracy of instrument aid, cockpit cut-off angle, width of runway, and length of approach lighting pattern, for a given landing success rate.

It is pointed out that with a ground pattern which includes crossbars the visual information becomes adequate in the horizontal plane at a greater height than it does in the vertical plane. There are theoretical reasons for thinking that in marginal weather conditions, no improvements in the ground pattern will ever raise the quality of the guidance in the vertical plane to that which exists in the horizontal plane. The implications of this are widespread, and have a bearing on factors such as the flying controls of the aircraft, the cockpit procedures used at landing, the G.C.A. patter, the provision of sighting devices in the cockpit, and the use of simulators for training in visual landings. These factors are discussed, particularly in relation to future aircraft, and some suggestions for improving safety are made.

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1 Introduction

1.1 At present when an aircraft lands in bad visibility two systems of guidance are used, an instrument system for the initial approach, and a visual system for the final stage of the approach and landing. The performance of each system influences the performance of the combination, and it is therefore difficult to disentangle the various factors, and assess their effects on the landing success rate at any given level of safety and in any given visibility and type of aircraft. Some recent work has, however, made it possible to devise a simple method which could eventually be made to give quantitative answers to some at least of the questions which the operator has been asking for many years. It is the object of this note to describe the general method, and draw attention to some of its implications.

1.2 To obtain exact quantitative answers in the case of a particular operation involving a given set of parameters, it is necessary that the values assigned to these should correctly represent the particular case. The values used in this report are intended to represent civil operations at the present time, but it may well be that they will need to be amended in the light of future experience. It is believed, however, that they are already sufficiently representative to enable a realistic picture to be obtained of the effect of changes in parameters such as approach speed, cockpit cut-off angle, accuracy of approach coupler, width of runway, length of approach lighting pattern etc. The implications should therefore be taken into account in designing aircraft, instrument approach systems, and airfields. They also suggest a review of the procedures used in the cockpit and by the G.C.A. controller. Indeed the implications are so widespread and important, both for safety and landing success, that it is suggested that this note should be regarded in the first place as putting forward a basis for discussions out of which a more realistic way of looking at the landing problem may emerge. If accepted, it can then be regarded as providing a simple theoretical framework into which the results of future operational research can be fitted.

2 The various forms of approach coupler

2.1 In the instrument system used for the initial (non-visual) portion of the approach, information obtained from a radio or radar beam is fed into a "coupler" which operates the aircraft controls. There are two classes of coupler, "manual", in which the human pilot operates the controls, and "automatic", in which an automatic pilot operates them.

2.2 In the coupler known as "conventional manual ILS", information obtained from two radio beams is displayed on a meter with two crossed pointers, the "vertical" one indicating angular displacement right and left from the runway centre line, and the "horizontal" one indicating angular displacement up and down from the glide path. The pilot combines the displacement information obtained from this meter with the rate information given by other flight instruments i.e. heading and rate of descent respectively, and mentally computes what control movements are required to change the rate terms so that zero displacement is obtained in each plane. In other words, the pilot is continually matching rate and displacement indications in order to achieve zero displacement and zero rate of change of displacement as the end condition. This matching process, which the pilot has to perform in two planes at the same time, is a difficult and uncertain operation, needing much skill and constant practice before the amplitude of the oscillations of the flight track about the defined path can be kept within acceptable limits. In the presence of disturbing factors such as cross-wind, turbulence or beam bends, this task is so difficult that it is a question whether it is not beyond what a human being can safely be asked to do as a regular operation as approach speeds increase.

2.3 In the coupler known as "manual ILS with flight director", this matching process is done in an automatic computer, and the instrument display incorporates four moving elements. Two of these elements give the displacements, and the other two tell the pilot what to do with the flying controls in order to obtain and hold zero displacements in the two planes. This makes the matching process easy, and greatly reduces the mental load on the pilot. He is able to follow the defined path more closely, and the chance of a visual misjudgment at the moment of transition from instrument to visual flight is reduced.

2.4 An automatic coupler reduces the work load on the pilot a stage further. Signals from the computer are fed into an automatic pilot, and the human pilot merely monitors the approach, using either a cross pointer meter or a flight director.

2.5 In the coupler known as "manual G.C.A.", radar scanning devices are used to display the aircraft situation in plan and in elevation to a ground controller who is in radio communication with the pilot. In azimuth, the pilot is given rate information in the form of headings to fly but is given little displacement information. In elevation, the G.C.A. controller gives the pilot displacement information in the form of actual distance above and below glide path, but gives little instruction with regard to rate of descent. There is, however, a time lag in obtaining and passing the information, and this can be dangerous, particularly at high speeds, if for any reason the pilot is unable to maintain a stable track in elevation. No extra equipment is required on the aircraft, but on the other hand, the pilot has to rely on the skill and foresight of a ground controller. In civil operations, there may also be a language difficulty which increases the time lag.

3 The concepts of approach success and landing success

3.1 These different couplers have their advantages and disadvantages, and it is important to assess their performance correctly, so as to be able to judge which one will give the best combination of safety, overall landing success rate and general reliability. One way of assessing these couplers is to make a large number of approaches with a representative group of pilots in various weather conditions, and obtain a figure for the standard deviation of displacement from the defined path at various positions on the approach. This puts the couplers in an order of merit, but gives no answer to the practical question of what weather a particular combination of aircraft and coupler will defeat in actual operations.

3.2 In 1950 the Sperry Gyroscope Company of America suggested[1] that the performance of a coupler at any height on the approach should be assessed by giving the percentage of approaches in which it brought the aircraft into a situation such that a landing could then be made with a standardised final manoeuvre. This manoeuvre was based on what they thought to be an acceptable maximum rate of roll and maximum bank angle for a particular aircraft. This percentage was called the "approach success" of the coupler-aircraft combination at that height. This gives a better picture of the relative performances of the various couplers, but it is more useful to the coupler designer than to the aircraft operator. What the operator wants to know is not the approach success at a given height, but the landing success in given meteorological conditions for an aircraft with a given cockpit cut-off angle when this aircraft is landing at an airport with a given pattern of visual aids and a given width of runway. To obtain this it is necessary to set up a "standard visual pilot" for each cut-off angle and pattern, i.e. to set up a family of curves giving the amount of the pattern which the average operational pilot would require to see at any height in order to be able to make his final manoeuvre. Such a family of curves is shown in Fig.1 for three different ground patterns, all with crossbars. These curves have been arrived at by a study of the records of many thousands of instrument approaches at civil airports, by a consideration of the weather minima which have been found to give acceptable levels of safety in civil operations, by questioning large numbers of pilots over a period of years, and by watching the behaviour of representative practising pilots on a landing simulator. By using curves of this kind, and assuming a final manoeuvre which correctly represents what the average practising pilot is willing and able to do, the operator can, as explained below, obtain a realistic picture of how the various factors which control the landing success rate are inter-related.

3.3 A given set of curves represents a certain standard of pilot training and experience, and a certain level of safety, and it is open to any operator to prepare a different set is he thinks that these will fit his particular type of operation more closely. However this may be, it is suggested that the curves in Fig.(1) are representative enough to be used as a basis for comparing the relative performance of the different couplers over a wide range of operating conditions.

3.4 A detailed description of how these curves were derived is outside the scope of this note, because, as stated above, the object is merely to present a general picture of the landing problem based on assumptions about the nature and limitations of visual guidance which are believed to be more realistic than those previously used. A partial explanation is, however, given in the notes on Fig.1, and an example of how to use the diagram is given in Fig.1A. In Fig.1A the full line curve, XYZ, is the guidance curve for a nominal cut-off angle of 10° and an approach lighting system 3000 ft long with crossbars every 500 ft. Because the pattern is 3000 ft long, the particular curves used in Fig.1A are those marked (c) and (3) in Fig.1. If the pattern had been 1500 ft long, the curves marked (2) and (b) would have been used, and if there had been no approach pattern at all, the curves (1) and (a) would have been used.

3.5 The part of the pattern which the pilot requires to see in order to obtain visual guidance is called the "guidance segment", and this may be expressed either as an angle or a length. Fig.1 gives only the angular segments, but from these the lengths, and also the visual ranges, can be calculated, as shown in the table on Fig.1A. When the aircraft is manoeuvring in the vertical plane, the size of the visual segment varies for any given range, because of the changes in pitch attitude of the aircraft. These changes are taken as being $1\frac{1}{2}°$ above and below the pitch attitude for a steady descent on glide path at the correct speed, and the part of the visual segment which is regarded as being effective is that which <u>always</u> remains in view during these changes. The guidance curve for any angle of cut-off has a discontinuity at the height at which the outermost end of the ground pattern comes under the effective cut-off line of the cockpit. For a nominal cut-off angle of 10°, the effective cut-off is $8\frac{1}{2}°$, and the discontinuity occurs at a height on glide path of 300 feet. At this point the length of the guidance segment is minimum. Below this point the length increases until the height is reached at which the flare-out begins. If the downward view is good, i.e. the cut-off angle is 12° or more, then the increase in pitch attitude during the flare-out has little effect, and the length at touchdown is only a little less than the runway visual range. If, however the angle of cut-off is less than 9°, the effect of a change in pitch attitude is large, and with cut-off angles less than 7°, visual guidance for a few seconds before touchdown may cease to exist, due to the nose-up attitude of the aircraft. It is for this reason that the curves for angles of 9° and below are shown dotted for heights below 50 ft.

4 <u>The final manoeuvres under visual guidance</u>

4.1 The assessment of the various couplers depends greatly on the manoeuvres which it is assumed the pilot is prepared to make under visual guidance. If it is assumed that these depend mainly on the lateral manoeuvrability characteristics of the aircraft, and that substantial alterations to the flight path will be made simultaneously in both the horizontal and vertical planes right down to runway level, then the coupler will be assessed as being successful down to a low height, which will be lower the more manoeuvrable the aircraft. If, on the other hand, it is assumed that these final manoeuvres depend mainly on the psychological capabilities of the pilot in interpreting the visual indications in bad visibility, and that the manoeuvres he is able and willing to make are within the capabilities of the aircraft, then the height down to which the coupler is assessed as successful will be higher, and will not depend much on the lateral manoeuvrability characteristics of the aircraft. The assumptions made by the Sperry Company, and later by Mercer[2], were based largely on the capabilities of the aircraft, and as a result, automatic couplers were assessed as giving an approach success of 100% at heights of the order of 100 feet[3]. This result was known to be about 100 feet lower than the heights which had been found to be acceptable in actual operations. It was realised that there must be some error in the assumptions, but there was at that time no data on which more realistic ones could be based.

4.2 In 1955-56 flight tests were made at R.A.E. with two groups of pilots, one a group of civil pilots flying the aircraft to which they were accustomed, and the other an experienced group of military test pilots[4]. The task was to correct lateral displacements of given magnitudes, this being the manoeuvre which in general controls the success rate of the combined approach and landing operation. The civil pilots were asked to make the manoeuvre as they would do it in actual operations, and the test pilots to make it as quickly as they thought was safe. Most of the aircraft were propeller driven transports. The results showed that the differences between the groups were small, and somewhat surprisingly, that the time taken to correct a given displacement was nearly the same for all the types of aircraft tested, although these had different approach speeds, maximum rates of roll, maximum accelerations in roll etc. The explanation of this would seem to be that the violence of the final manoeuvre is limited by what the pilot is prepared to do, rather than by the manoeuvring capabilities of the aircraft.

4.3 This is an elegant result, because it means, firstly, that standard manoeuvres can be set up which are closely representative of all existing types of transport aircraft, and secondly, that it becomes a simple matter to show the effect of changing the approach speed. The time-distance relationship used in this note is the average of those found in the above tests for the civil group. This is as follows:-

Side-stepping distance	Time taken to correct
0 feet	0 seconds
40 "	10 "
100 "	12.5 "
200 "	15.0 "
330 "	17.5 "
500 "	20.0 "

Same track heading at end of manoeuvre as at beginning.
Wings level at beginning and end of manoeuvre.

5 Visual guidance in elevation and its effects on the final manoeuvre

5.1 In 1955 a bad weather landing simulator was completed at R.A.E. which enabled a subject "pilot" to make an instrument approach, and then "go visual" at some height determined by the particular visual range and particular angle of cockpit cut-off for which the simulator was set up. Many pilots with varying degrees of experience in instrument flying made approaches on this simulator using the I.L.S. cross pointer meter or G.C.A. and their behaviour was carefully observed particularly during and after the transition from instrument to visual flight. Without telling the subject, various disturbing factors such as altimeter errors, radio beam distortions, crosswind changes with altitude, visibility changes with altitude, were introduced, either singly or in combination. It was found that the subject frequently deviated from the nominal glidepath during and after the transition, but there was a tendency to go below glidepath rather than above. (This tendency has also been noticed by G.C.A. controllers.) It was also noticed that the magnitude of the deviation from glidepath was correlated with the difficulty of the azimuth manoeuvre which faced the subject. In some cases the deviation was sufficient to cause an undershoot. When this happened the subject invariably stated that he had a sudden impression of being too low some seconds before striking the ground, but there was not sufficient time to pull up. These tests made it quite clear that the quality of the visual guidance was nearly perfect in azimuth, provided that crossbars were used in the ground pattern, but was very imperfect in elevation at all heights above about 100 feet. This is in accordance with the streamer theory of visual judgments in motion, but it had not been realised that the situation was as potentially dangerous as these tests showed it to be. An account of the streamer theory will be found in Reference (5).

5.2 For the above tests the pitch control on the simulator gave a positive stability in that the "aircraft" could be trimmed to have a desired <u>rate of descent</u>. This remained constant unless the pilot exerted and maintained pressure on the elevator control. If the elevator control was disturbed and then released, the "aircraft" changed pitch, and in consequence, rate of descent, but returned to its original pitch attitude and rate of descent several seconds after the control was released, the actual time depending upon the magnitude and duration of the control displacement. Further tests were made in which this positive stability was removed, and the pitch control made neutrally stable. In this second case the aircraft took up a <u>different</u> pitch attitude and rate of descent after the elevator control had been moved and then released. In the first case there was a connection between stick force and both rate of change of pitch attitude (or "g"), and to a lesser extent, rate of descent. In the second case there was a connection between stick force and rate of change of pitch attitude only. This change in the pitch control tended to increase the magnitude of the deviations above and below glidepath, particularly when the pilot was flying visually. If disturbing factors were introduced, undershoots were more frequent than with the original control system.

5.3 It was concluded from these tests that a high level of safety in manual approaches can only be ensured if two requirements are met. The first is that the pilot must be skilful enough in instrument flying to be able to establish and hold a plane of descent close to or coincident with the instrumental glide path. (In an I.L.S. approach this means holding the horizontal needle of the cross-pointer meter steady on a small or zero deflection.) The second requirement is that the aircraft control system must be such as to enable the pilot, when he "goes visual", to know by the feel of the elevator control that he is continuing to follow the plane of descent previously established. These two requirements arise from the fact that, in the absence of the real horizon, there is an interval between the time when the pilot makes visual contact with the ground pattern and begins the side-stepping manoeuvre, and the time when he becomes able to see accurately where the aircraft is going in the vertical plane. Since the critical heights used in civil operations are usually between 200 and 300 feet, and the height at which visual guidance in the vertical plane becomes adequate may be as low as 100 feet, this time interval in marginal conditions is unlikely to be less than 10 seconds, and may well be as long as 20 seconds. If the aircraft control system is such that the pilot cannot, by means of elevator feel, continue along the plane of descent established on instruments, then during this interval the flight path will, in a number of cases, depart from the glide path to such an extent that the tangent will intersect the ground short of the threshold. The pilot will have warning of this at a height, which, as mentioned above, may, in marginal conditions, be as low as 100 feet. Whether this height will be sufficient to prevent an undershoot will depend largely on the rate of descent, the speed, and the characteristics of the aircraft.

5.4 If the pilot is making a correction in azimuth the warning indications are less definite, because additional motions, one sideways and the other rotational, first in one direction and then in the other, are superimposed on the streamer pattern. Experience seems to show that with the crossbar pattern the warning time is in fact just sufficient for the present generation of propeller driven aircraft, because in 5 years or so no serious undershoot accident due to a visual misjudgment has been reported on this pattern, although on a few occasions, aircraft have been known to strike the approach lights with their undercarriages. The margin of safety, therefore, is very small, and may not be sufficient for future aircraft. There are three reasons for this:-

(a) approach speeds, are tending to rise, and this for a given glidepath angle means increased sinking speeds. For a given vertical deceleration the height required to stop the aircraft sinking is proportional to the square of the speed.

(b) at speeds near the stall, the jet propelled aircraft has less potential lift increase immediately available, because of the absence of slipstream effect over the wing.

(c) the introduction of certain plan forms, particularly the "pure delta", results in an increase in the time taken to achieve a given increase in lift by means of elevator control, even at normal instrument approach speeds.

If the guidance in elevation is not improved, and present procedures remain unchanged, then the undershoot rate will probably go up. What is needed to prevent this is to "quicken" the indications by improving both the displacement and the rate information. It would seem that there are only two ways of doing this visually. The first is to produce a line which the pilot sees when he looks through his windscreen and which always remains coincident with the true horizon. This would restore his datum for estimating pitch attitude and his displacement from glidepath in bad visibility, and would enable him to carry out the matching process in the vertical plane. The practical difficulties of such an installation are, however, very considerable since it would involve a projection device like a large optical gunsight and gyroscopic stabilization. The second method is to use an improved form of angle of approach indicator on the ground, and combine this with stub bars. This greatly improves the displacement information in moderate and good visibility, and the installation is simple and cheap. The best solution would be, of course, to use both methods together.

5.5 Since the process of correcting errors in the horizontal plane impairs the pilot's capacity to judge the situation and make adjustments in the vertical plane, it would seem that in bad visibility the side-stepping manoeuvre should be completed some seconds before the flare begins. It is assumed in this note that this manoeuvre should be completed at a height such that the aircraft is 6 seconds from the ground at the normal sinking speed for the approach. If the height of the pilot's head above the wheels is taken as 15 feet, and the glidepath is 1 in 20, this height is 78 feet for an approach speed of 125 knots, and 103 feet for an approach speed of 175 knots. This agrees closely with the views expressed at various meetings of the Flight Study Group of the Technical Committee of the International Air Transport Association[6].

5.6 Two more assumptions are necessary to relate the final manoeuvre to the dimensions of the runway. It is assumed in this note that the pilot, when he reaches the height defined above, will accept the situation if the aircraft is not less than 50 feet from the runway edge, and is tracking substantially parallel to the centre-line with wings level. It is also assumed that the runway is of such length that the pilot is satisfied to touch down near the aiming point, and has no bias to try to touch down either nearer or further away from threshold.

5.7 With these assumptions, and the time-distance relationship given in paragraph 4.3 above, it is possible to draw curves for various speeds giving the loci of the latest points in an approach at which the final manoeuvre under visual guidance must begin if the aircraft is to land within the assumed limits. The curves shown in the full lines in Fig.(2) are for a runway 200 feet wide, and for approach speeds from 100 to 200 knots. In the Sperry report referred to above, these were called "mandatory manoeuvring lines".

6 The effect of approach speed on the height down to which a coupler can be used

6.1 Let us suppose that a large number of approaches have been made by operational pilots with a certain coupler at a certain speed, and that the plan positions of the aircraft in each approach have been continuously recorded together with the bank angles. If we examine these records at a given distance from threshold we find various combinations of displacement error, track heading error, and bank angle. With each combination a certain time will be required for the pilot to be able to achieve the end conditions assumed in the final manoeuvre if he manoeuvres in the same manner as in the tests referred to in para.4.2. Let us imagine that each combination is replaced by another in which the track heading error and bank angle are zero, but in which the displacement is such that the pilot takes the same time to achieve the assumed end conditions, i.e. all the actual combinations are imagined to be replaced by equivalent displacements all with zero heading errors and zero bank angles. If this is done for various distances from threshold, it is then possible to draw lines which represent the equivalent displacements which will be exceeded only on a given percentage of occasions. The dotted line marked 125 kts on Fig.2 approximates to the equivalent displacements which will be exceeded on only 5% of occasions for aircraft using I.L.S. with flight director at typical present day approach speeds. The lines for speeds other than 125 knots have been obtained by assuming that the displacements bear a linear relationship to approach speed. This may not be exactly true, but the discrepancy is unlikely to be large enough to make much difference to the overall picture obtained by making this assumption.

6.2 The intersection of the mandatory manoeuvring line for a given speed with the equivalent displacement line for that speed gives the closest point to touch-down to which the coupler can be used in an aircraft with that approach speed with a success rate of 95%, assuming that the pilot makes the final manoeuvres in accordance with the assumptions given in Sections (4) and (5) above. The intersections (marked with small circles) of the various pairs of lines then form a curve connecting approach speed with the distance from aiming point at which the visually controlled manoeuvre must start for a success rate of 95%. This curve is shown in the full line in Fig.3. Similar curves are shown dotted for runways 150 ft and 300 ft wide. In these curves the distances have been converted into heights on a glidepath of 1 in 20. It will be noticed that the curve for the 300 ft runway bends downwards at a speed of about 95 knots. This means that below this speed a coupler of this accuracy can be used in azimuth right down to the runway without the failure rate rising above 5%.

6.3 If in a particular type of operation, a failure rate of 5% is acceptable, then the curves in Fig.3 may be regarded as approximating to curves connecting cloud base height with approach speed for aircraft using manual I.L.S. with flight director, provided visibility is good beneath the cloud base. A more accurate connection is obtained if the heights given on the diagram are increased by an amount equivalent to the height lost between breaking out of cloud and starting the corrective manoeuvre. This additional height will correspond to a time period of about 2 or 3 seconds, and will vary from about 20 feet to 40 feet over the speed range covered in the diagram. If the visibility is not good, then the downward view of the aircraft has to be taken into account by making use of the curves shown in Fig.1. By using these in conjunction with Fig.3, the family of curves shown in Fig.4 is obtained for a crossbar pattern of approach lighting 3000 feet long, and a runway 200 ft wide. The operator can now see the effect of increased speed and poorer downward views on the slant range required to keep the failure rate below 5% when any aircraft using a flight director lands on a runway with this pattern of visual aids.

Similar sets of curves can be prepared for runways of any width, without approach lighting, or with a crossbar pattern 1500 ft long.

7 Effect of increased accuracy in the approach coupler

7.1 If the equivalent displacements at the various distances from threshold were half those given above, then the curves connecting approach speed with the height at which the final manoeuvre under visual guidance must begin would be as shown in Fig.5. These curves, in conjunction with those given in Fig.3, show that for a given approach speed, the height at which the visual manoeuvre must start is reduced by a comparatively small amount by using the more accurate coupler, but that this amount increases as the approach speed increases. It will also be seen that the speed and height at which the curve representing a given runway width bends over (indicating that on 95% of occasions no visually controlled azimuth manoeuvre is necessary) are both raised. The curves shown in Fig.5 may be regarded as typical of an automatic approach coupler.

7.2 It is also of interest to compare the performance of the two couplers discussed above with that of a third coupler having equivalent displacements twice as large as those given for the typical flight director. (This third coupler may be regarded as representing conventional manual I.L.S. when the pilot is in good instrument flying practice.) Fig.6 shows the connection between approach speed and slant range for a 95% landing success rate for an aircraft with a cockpit cut-off angle of 12°, using the three different couplers in conjunction with a 200' wide runway and a 3000' long crossbar approach lighting system. It will be seen that up to an approach speed of about 130 knots, there is a difference of only about 150 feet in slant range between automatic approach and I.L.S. with flight director, and between I.L.S. with flight director and I.L.S. with cross-pointer meter. In view of the uncertainties of weather forecasting these differences are too small to be operationally significant. It seems, therefore, that if the pilots are highly trained, and keep in good instrument flying practice, then increases in coupler accuracy within quite wide limits will not reduce the operational weather minima, or increase regularity at the approach speeds commonly used in transport aircraft at the present time, when operating on runways with approach lighting systems 3000 ft. long. The arguments for using flight directors and automatic couplers in these conditions must therefore rest on quite other grounds, i.e. those of safety.

7.3 It can be seen from Fig.6 that for speeds above about 130 knots, speed has an increasing effect upon the operating limits attainable with couplers of different accuracy. To illustrate the effect of the length of the approach lighting system on the situation Fig.7 has been drawn. This repeats the curves shown in Fig.6, but assumes an approach lighting system only

1500' long. It can be seen that in this case, even at present day approach speeds of 125 knots, there are appreciable differences in the performances of the couplers. Similar sets of curves can be drawn for runways of different widths, for different lengths of approach lighting, and for aircraft with different cockpit cut-off angles.

8 Discussion of results and suggestions for improving safety

8.1 During an instrument approach a large number of things need to be monitored in a regular sequence. These include, heading, bank angle, I.L.S. displacements, rate of descent, speed and altitude. In a manual approach one of these things will require adjustment from time to time, as for instance, heading, and for a short time the pilot's conscious attention will be given to this. For this short time the monitoring process is interrupted, and if, during this time a second thing requires adjustment, as for instance, rate of descent, the adjustment actually made will probably be inexact, until the pilot can give his conscious attention to it. If the pilot has too much difficulty in making the original adjustment, due perhaps to turbulence or changes in cross-wind, then a number of such inexact adjustments may be made, and a potentially dangerous situation may build up. This seems to be what pilots mean when they say that they have become "mesmerised" by a particular instrument or group of instruments. Although the greater accuracy of the flight director and automatic couplers is advantageous at high speeds and with short approach lighting patterns, the main argument for their use rests on the fact that they enable the two matching processes described in paragraph 2.2 above to be properly carried out without overloading the pilot. This may be of particular importance when the pilot has not had the opportunity to practice instrument landings in poor visibility under operational conditions for some time. The importance of having an aircraft control system such that the feel of the elevator control enables the pilot to ensure that the aircraft proceeds substantially along the previously established plane of descent with little or no visual guidance, lies simply in the fact that it enables him to keep the situation stable in the vertical plane while he deals with the situation in the horizontal. Some future aircraft may have instrument approach speeds near or below minimum drag speed, and in these cases, it would seem that, in view of the poor quality of the visual guidance in the vertical plane, "feel" in this sense is a matter which requires careful investigation.

8.2 With the flight director the added complication, as compared with conventional manual I.L.S., is small, and a large increase in safety is therefore obtained at a small cost in weight. With the automatic coupler the added complication is large, unless an automatic pilot is already installed for other reasons, and it is not certain that the overall safety level is any greater than with the flight director. Indeed there are two reasons for thinking that it might even be a little less. The first is that when the automatic coupler is disconnected, the pilot does not necessarily know what pressure to apply to the elevator control to maintain the established rate of descent, and since visual guidance in elevation is poor, there is a possibility that he will increase it. This danger could probably be obviated by keeping in the pitch control down to a low height, say, 100 feet. If the azimuth displacement is seen to be large, and the particular design of automatic pilot permits it, then it may be advantageous to disconnect the azimuth control before disconnecting the pitch control, because in the azimuth plane the human pilot can make larger corrections in a given time. The second reason is that if the automatic coupler becomes unserviceable, and the pilot has perforce to make a manual approach in bad visibility, he may, for lack of practice, be less able to deal with the situation.

8.3 In a manual I.L.S. approach, the procedure in many airlines is for the co-pilot to make the instrument approach, and for the pilot to look out for the lights, and take over for the final approach and landing when he considers that the visual guidance is adequate. Since the height at which visual guidance becomes better than the instrumental guidance is lower for the vertical plane than for the horizontal, it is suggested that after the pilot takes over, the co-pilot should continue to monitor the position of the aircraft with reference to the instrumental glidepath down to, say, 100 feet. He might even take preventive action on his own initiative if the aircraft deviates too far from the glidepath. This procedure would seem to be particularly desirable in aircraft in which the cut-off line has a pronounced slope.

8.4 It is suggested that in a G.C.A. approach the pilot should give the controller his critical height at the beginning of the talk-down. When the aircraft reaches the range corresponding to this height on the nominal glidepath, the controller should announce the fact, and thereafter give glidepath information only. To continue to give range and azimuth information beyond this point on the approach is simply to add "noise" to the control system, because if the pilot has made contact with the visual system (and he cannot legally continue the descent if he has not) he already has better range and azimuth information than the controller can give him. Beyond this critical point on the approach, glidepath information should be given in a steady rhythm at intervals of about one second, so that the pilot can extract a rate. The one thing which must always be avoided is to give the pilot glidepath information which leads him to increase his rate of descent just as he goes visual, and then stop the flow of information before he has re-established a safe and stable rate of descent. There is good reason for thinking that a stoppage of this kind, or unduly long intervals in the glidepath checks when near the ground, may have contributed to many undershoot accidents. With present procedures, if the pilot, due to some disturbing factor, fails to assimilate a height check, he may be as much as 14 seconds without any height information. This is far too long for high speed aircraft when below break-off height, particularly if the aircraft is at a speed such that the pilot has to use the throttle to control the rate of descent. The proposed procedure has the added advantage that the actual break-off point is not affected by errors in the altimeter. (It is understood that, due to hysteresis in the capsule, these may be as large as 200 feet.) It also eliminates the possibility of the controller making an error through changing back and forwards from one scope to the other.

8.5 It is suggested that pilots should have periodical courses of training on a landing simulator. The function of such a trainer is not for practicing instrument approaches, but to demonstrate the pitfalls in the transition process and in the subsequent period of visual flight, particularly when disturbing factors are introduced. It is hard to see how a pilot can keep in practice for bad weather landings when it is considered that some long haul airline pilots make on the average only one per year.

8.6 If approach speeds increase, and/or downward views decrease, then the weather minima for the less accurate couplers will rise. This means that an improved angle of approach indicator would be increasingly effective. In a proposed new indicator the indications are obtained by the use of stub bars, a method which has the important advantage of increasing the undershoot warning time as well. In the installation now being flight tested[7] two paths are indicated, a "desired" path at about 3° to the horizontal, originating from a point near the aiming point, and a "lowest safe" path originating from a point near the threshold. This indicator has a further important advantage in that it can be used right down to the concrete.

8.7 It is understood that in both civil and military operations a pilot may have an instrument rating check on one type of aircraft, and may then be regarded as covered for some other type with substantially different characteristics. If the views put forward in this note are accepted, then the pilots rating should apply only to aircraft with characteristics closely resembling those of the aircraft used for the rating test.

9 Concluding remarks

9.1 If the arguments set out above are correct, then certain penalties have to be paid for increased approach speeds and poor downward views. To some extent these penalties can be offset by better couplers and better visual aids. It is hoped that this note will stimulate discussion of these problems, and that the various curves will be of some immediate assistance in enabling operators to decide what compromise will best meet their particular operational requirements. It should be realised, however, that these curves are in the nature of a worked example, and do not exactly represent any particular type of operation. It should also be remembered that the ranges are those which the pilot must have when he observes the ground pattern from the cockpit. When flying in rain there may be a considerable difference in the maximum distance from which the ground pattern can be seen from the cockpit compared with the distance it can be seen by a static observer.

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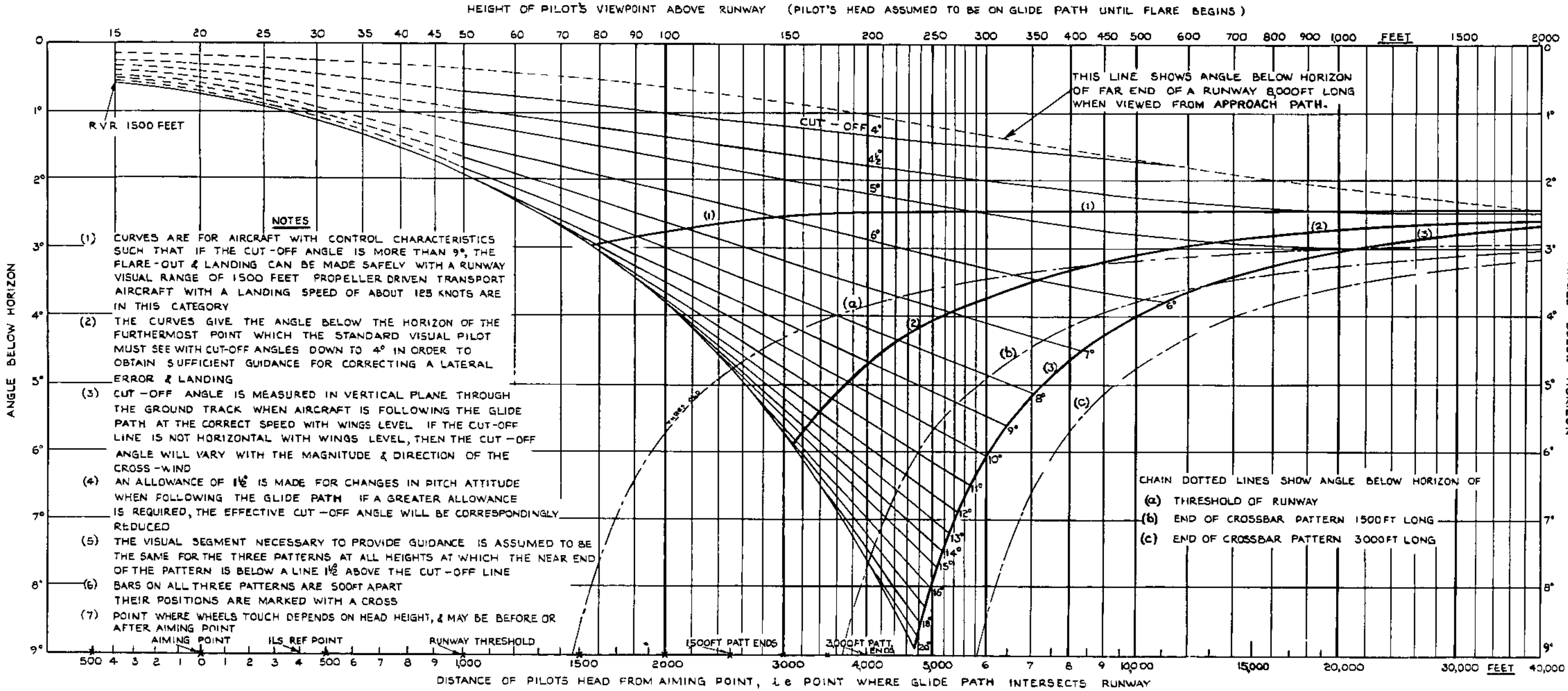
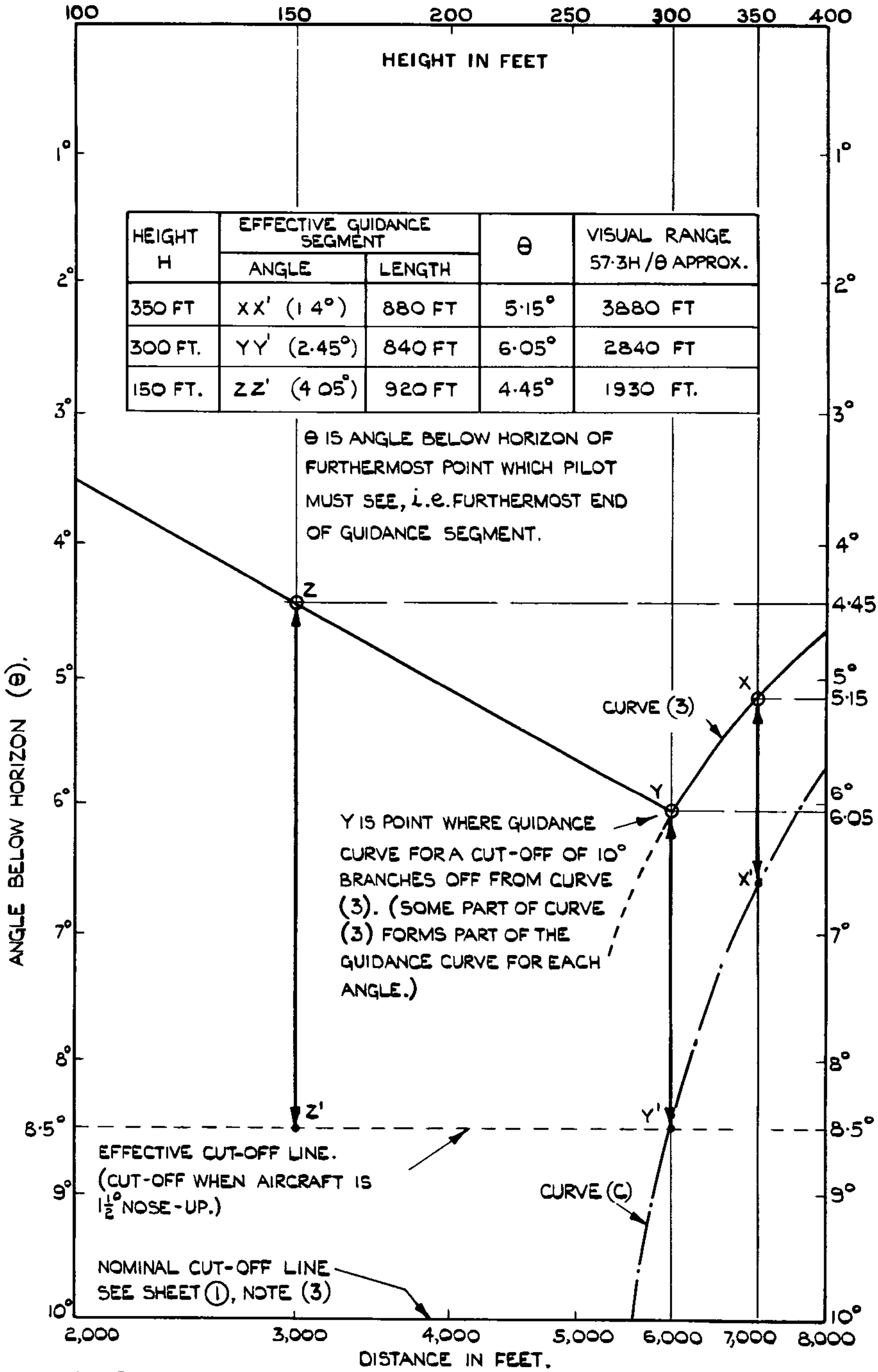


FIG.1 GUIDANCE REQUIREMENTS FOR STANDARD VISUAL PILOT FOR A GLIDE PATH OF 1 IN 20, (2 86°).

(1) RUNWAY WITH STUB BARS BUT NO APPROACH LIGHTING PATTERN
(2) RUNWAY WITH STUB BARS & WITH A CROSSBAR PATTERN 1,500FT LONG
(3) RUNWAY WITH STUB BARS & WITH A CROSSBAR PATTERN 3,000FT LONG

EXAMPLE ILLUSTRATING USE OF CURVES SHOWN ON SHEET (1)



HEIGHT H	EFFECTIVE GUIDANCE SEGMENT		θ	VISUAL RANGE 57·3H / θ APPROX.
	ANGLE	LENGTH		
350 FT	XX' (1·4°)	880 FT	5·15°	3880 FT
300 FT.	YY' (2·45°)	840 FT	6·05°	2840 FT
150 FT.	ZZ' (4·05°)	920 FT	4·45°	1930 FT.

FIG. 1(a) GUIDANCE CURVE FOR CUT-OFF ANGLE 10° & APPROACH LIGHTING PATTERN 3000 FT. LONG.

(GUIDANCE CURVE IS XYZ. CURVE C IS ANGLE BELOW HORIZON OF END OF PATTERN.)

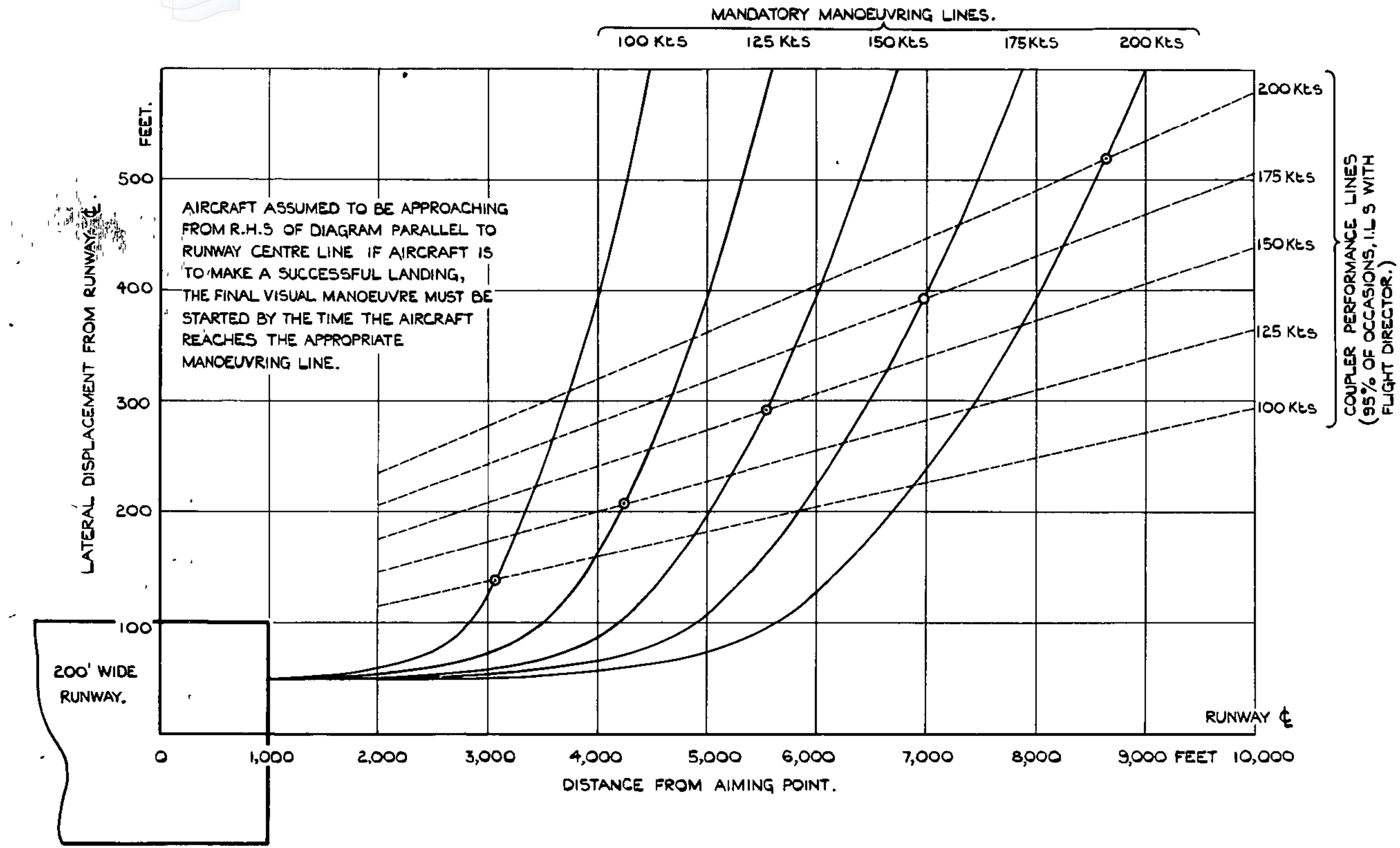


FIG.2. CURVES SHOWING POINT ON APPROACH WHERE VISUAL MANOEUVRE MUST START TO ACHIEVE 95% LANDING SUCCESS WITH I.L.S. FLIGHT DIRECTOR.

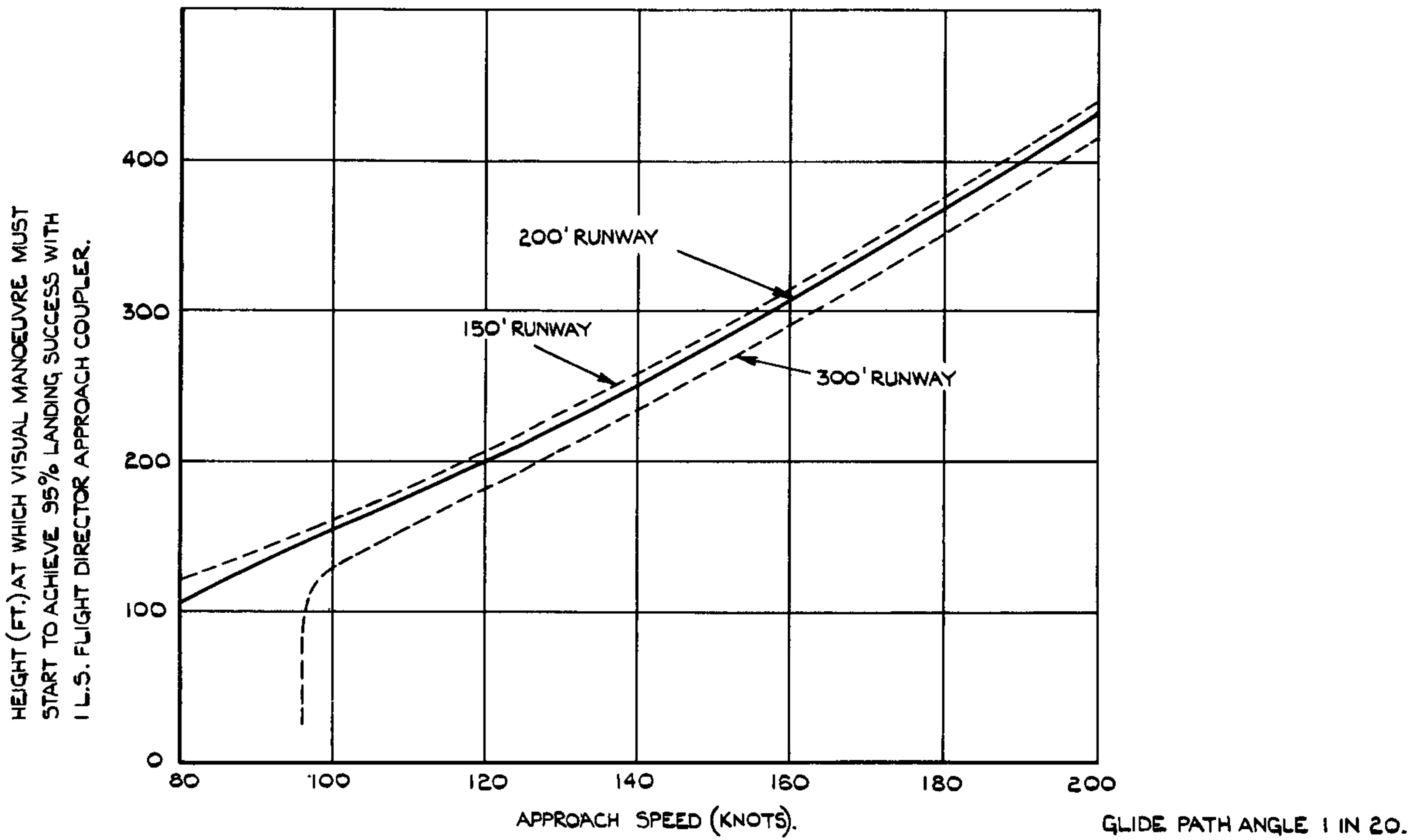


FIG. 3. EFFECT OF APPROACH SPEED AND RUNWAY WIDTH ON HEIGHT AT WHICH THE VISUAL MANOEUVRE MUST START, USING I.L.S. FLIGHT DIRECTOR.

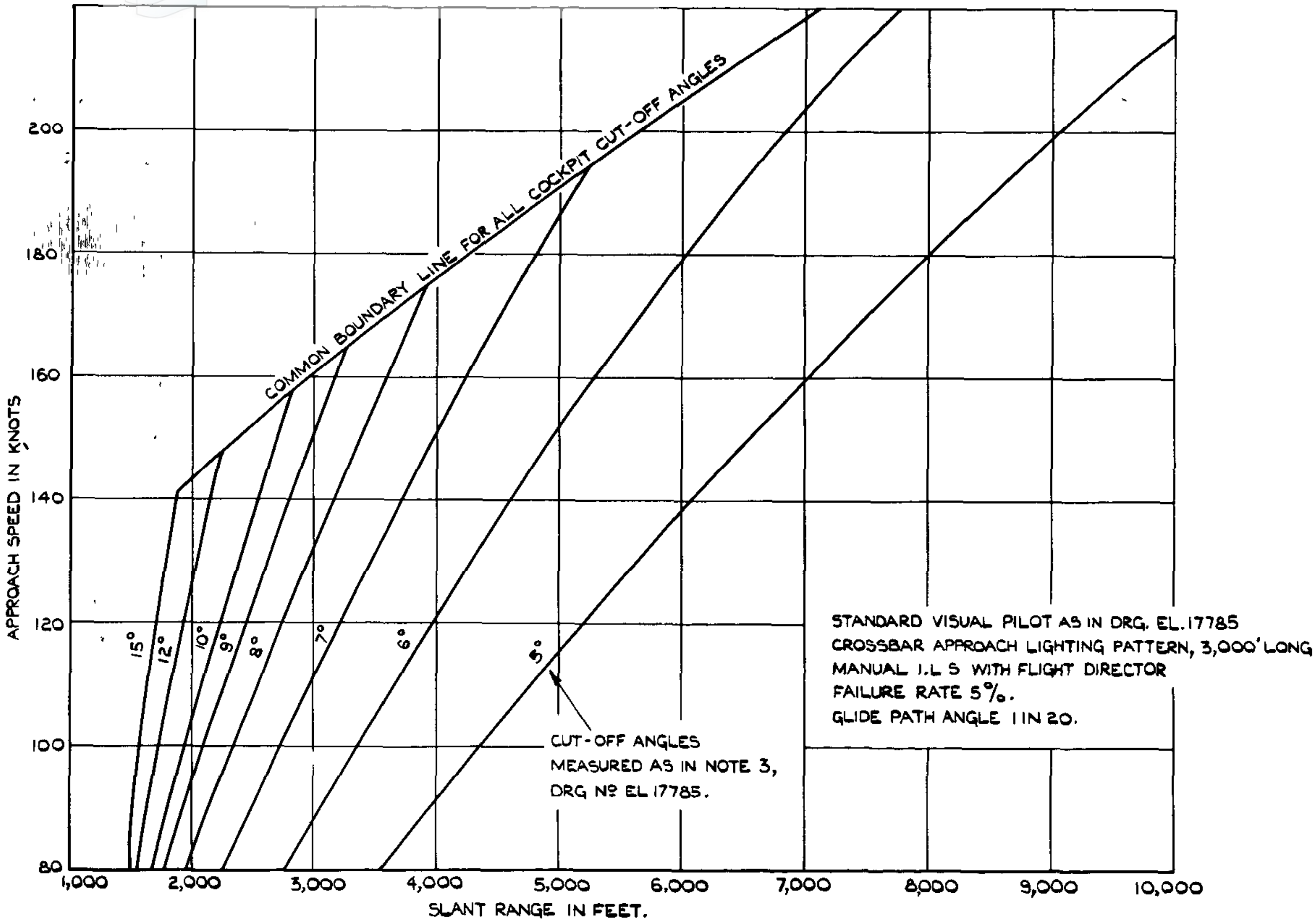


FIG. 4. EFFECT OF APPROACH SPEED AND COCKPIT CUT-OFF ANGLE ON SLANT RANGE REQUIRED FOR LANDING.

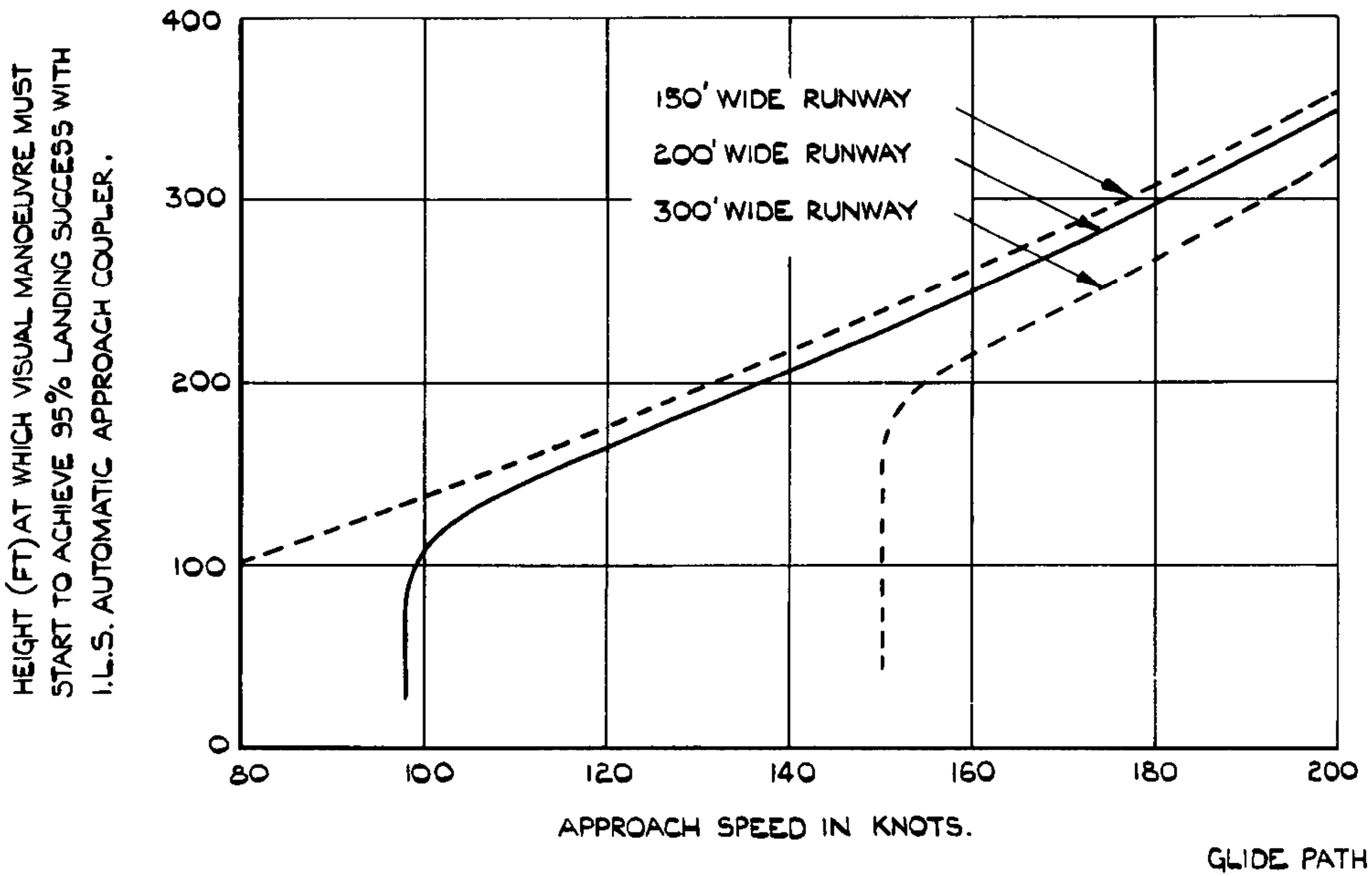


FIG. 5. EFFECT OF APPROACH SPEED AND RUNWAY WIDTH ON HEIGHT AT WHICH THE VISUAL MANOEUVRE MUST START, USING I.L.S. AUTOMATIC APPROACH COUPLER.

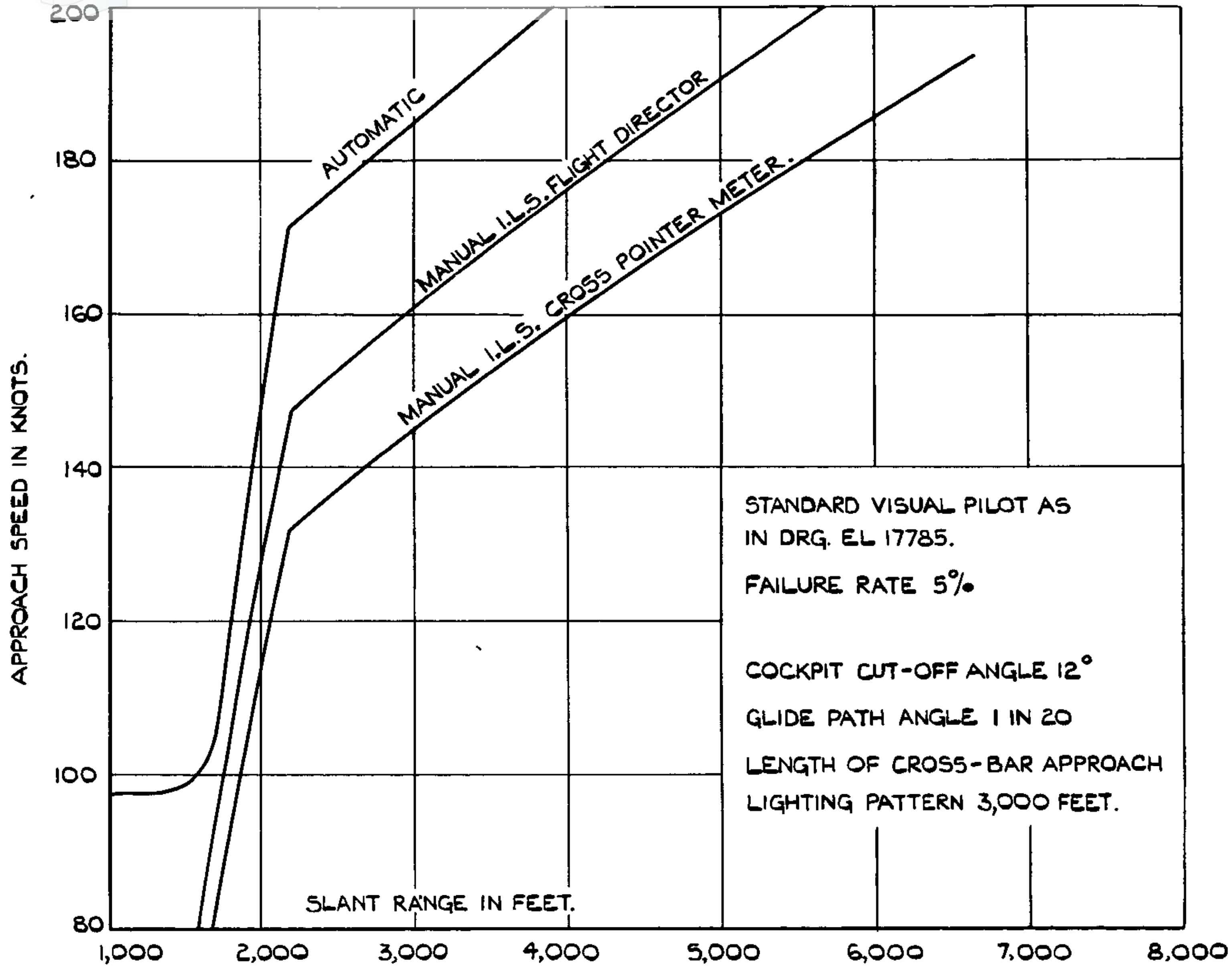


FIG. 6. EFFECT OF APPROACH SPEED & TYPE OF APPROACH COUPLER ON SLANT RANGE REQUIRED FOR LANDING. APPROACH LIGHTING SYSTEM 3,000 FT. LONG.

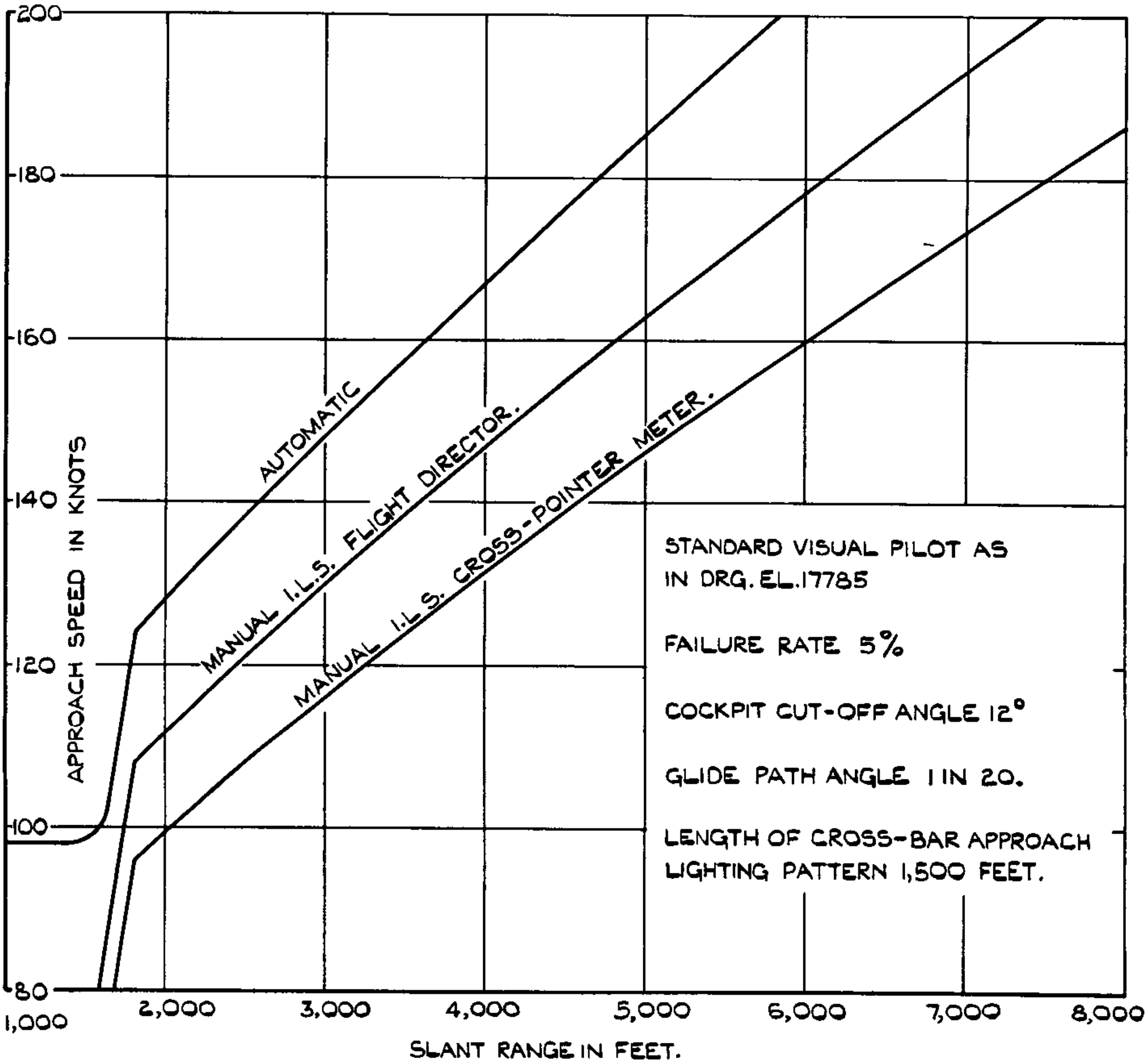


FIG.7. EFFECT OF APPROACH SPEED AND TYPE OF APPROACH COUPLER ON SLANT RANGE REQUIRED FOR LANDING. APPROACH LIGHTING SYSTEM 1,500 FT. LONG.

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