PART 3 : SECTION 1

CHAPTER 1

FLYING FOR RANGE

Introduction

1. To obtain the maximum range from turbo-jet aircraft they must be operated under known and precise conditions of altitude, speed, and weight. Any deviation from these conditions can only result in performance penalties. The operating techniques for turbo-jet aircraft differ from and are more exacting than those used for piston-engine aircraft, and experience of operating piston-engine aircraft for range is of little value in the operation of turbo-jets.

2. Since range flying is of paramount importance it is essential that the basic theory and methods of flight planning and cruise control are understood.

3. This chapter examines the factors affecting the performance of turbo-jet aircraft with particular reference to fuel consumption, and gives the theory underlying the technique of range flying at subsonic speeds. The practical techniques often differ from the theoretical in that some simplification is adopted, accepting any small loss in range ; however, unless the theory is understood the pilot cannot deal efficiently with unexpected circumstances.

AERODYNAMIC CONSIDERATIONS

T.A.S./Drag Ratio

4. With turbo-jet engines, fuel consumption is proportional to thrust and not to power ; this fact makes high altitude and a high T.A.S. essential to economic cruising. Because of the fairly wide range of fuel density used, and since it is the heat content of the fuel that is important, it is necessary to consider the *miles flown per pound of fuel* and not per gallon. (This is one important reason for the use of mass unit fuel gauges in turbo-jet aircraft.)

5. **Specific Air Range.** The miles flown per pound of fuel is known as the *specific air range* (S.A.R.) and can be expressed as :

$$\frac{\text{T.A.S.}}{\text{Gross Fuel Consumption (lb./hour)}}$$

6. Since gross fuel consumption (G.F.C.) is the product of specific fuel consumption (S.F.C.) (lb. fuel/hr./ lb. thrust) and thrust, the S.A.R. can be expressed as :

$$\frac{\text{T.A.S.}}{\text{S.F.C.} \times \text{Thrust}}$$

In level flight, thrust equals drag and therefore S.A.R. can be equally well expressed as :

$$\frac{\text{T.A.S.}}{\text{S.F.C.} \times \text{Drag}}$$

7. Since at high altitudes the turbo-jet is working at high r.p.m., the S.F.C. can be regarded, for all practical purposes, as constant. S.A.R. therefore varies according to the variation in the T.A.S./Drag ratio and this is the principal factor that governs the range. If the T.A.S./Drag ratio is high then greatest range is achieved and vice versa.

Basic Techniques

8. Irrespective of the technique used, it is always necessary to fly at a certain I.A.S. The actual I.A.S. used depends on which technique is in use. It has been shown that the range of a turbo-jet aircraft depends on the T.A.S./Drag ratio. To keep the ratio at its maximum the aircraft must be flown at the optimum angle of attack during the whole cruising period. Since the A.U.W. falls during flight, the lift must be adjusted to balance the reduced weight and this can only be done by reducing the I.A.S. if the angle of attack is to remain at the best setting.

9. There are only two principal techniques for cruising for maximum range :—

(*a*) Constant altitude, reducing the I.A.S. as the weight falls.

(*b*) Climbing cruise, gradually climbing as the weight falls and reducing I.A.S. in this way.

These two techniques must be considered in detail, ignoring initially, compressibility effects.

Basic Constant Altitude Technique

10. Fig. 1 shows a typical level flight drag curve plotted against T.A.S. for a given A.U.W and altitude. The T.A.S./Drag ratio is at a maximum at that speed at which the tangent from the origin just touches the drag curve ; at any other point the proportion of drag is larger and the ratio falls ; even though the drag is least at the lowest point of the curve, the ratio of the corresponding T.A.S. to the minimum drag is less than that found at the point of tangency from the origin.

11. It can be shown mathematically that this speed is about 1·31 times the T.A.S. corresponding to the lowest point of the curve. Flight at this speed means that a particular angle of attack and hence lift coefficient must be used. Thus for a given constant weight the same I.A.S. would apply at all altitudes.

12. So far the speed problem is fairly straightforward but the first difficulty arises when the question of variation in weight is considered. Apart from war load, fuel alone may account for 50 per cent of the A.U.W. at take-off. Obviously advantage can be taken of the reduction in weight as this fuel is used. First, to obtain the best T.A.S./Drag ratio, it is necessary to maintain the same angle of attack. Therefore to reduce the lift necessary for the decreasing weight and keep the angle of attack constant, a lower I.A.S. must be set ; this is done by reducing r.p.m. (thrust). Since thrust equals drag in level flight, less drag occurs, the overall effect being an improvement in the overall T.A.S./Drag ratio and thus range performance. (Even though the T.A.S. is reduced because of the lower I.A.S. at the reduced power, the drag falls faster since it varies as the square of the T.A.S.)

Basic Climbing Cruise Technique

13. Although a good range performance is obtained by using the method described above, this is not the best result. *Maximum range will result when the drag is reduced without decreasing the T.A.S.* The T.A.S. can be kept constant, at a reduced I.A.S., only by an increase in altitude. Therefore the best result is obtained if the aircraft is allowed to climb slowly *at constant r.p.m.* as the weight falls so that the T.A.S. remains constant while at the same time the I.A.S. falls in proportion to the increased altitude.

14. However, when using the climbing cruise technique a small difference arises. Because of the slowly changing altitude the best T.A.S. is no longer 1·31, but 1·19 × the T.A.S. for minimum drag. For simplicity the mathematics of this change are omitted. Using the climbing cruise technique at this slightly lower speed, gains in range of 15 to 20 per cent. are obtained when compared with the constant altitude technique. On a long flight such an advantage cannot be foregone. The constant altitude technique is therefore suitable only for shorter flights where maximum range is unnecessary.

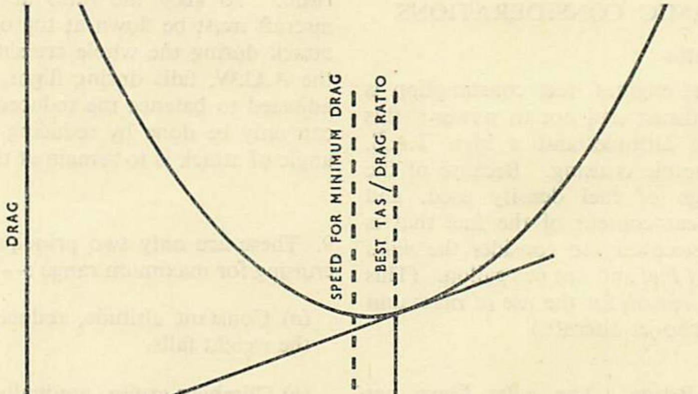

Fig. 1. Variation of Total Drag with Speed

Compressibility Effects

15. Compressibility effects govern the final speed selected, because they have an important effect on the T.A.S./Drag ratio. Above the critical mach number (M_{crit}), compressibility effects increase rapidly to cause a fall in the T.A.S./Drag ratio (because of the higher drag at the same T.A.S.) and therefore a limit is set on the indicated mach number (I.M.N.) for economical cruising.

16. Consider an aircraft operating in the stratosphere in a theoretically constant temperature. The speed of sound is therefore constant and a fixed I.M.N. implies a constant T.A.S.; therefore a cruising I.M.N. limit means a cruising T.A.S. limit. At once, then, if the cruising T.A.S. has a limit then the highest possible value of T.A.S./Drag (and hence the range of a particular aircraft) also has a limit, which is realized when the drag is least. Here, then, under stratospheric conditions, is yet another T.A.S. for cruising—that for minimum drag—which gives the absolute maximum range provided that the aircraft can be handled without undue fatigue at this low I.A.S. for long periods at altitudes near the ceiling. (It is assumed that sufficient thrust is available at these altitudes.)

17. The overall picture is now further complicated in that M_{crit} depends on the angle of attack. Therefore at high angles of attack the compressibility drag rise starts at a lower I.M.N. than at smaller angles of attack, *i.e.* M_{crit} is lower. Consider flight at the speed for minimum drag ; this implies the use of a particular angle of attack which has a certain critical mach number. If the I.A.S. is now increased slightly, the angle of attack for level flight for the particular weight must be smaller ; therefore the lower angle of attack gives a higher critical mach number. In this way a higher T.A.S. is achieved before the compressibility drag rise commences. The higher T.A.S. is more significant than the slight rise in drag due to the higher I.A.S. and, provided that the increase in speed from that of minimum drag is kept small, an improved T.A.S./Drag ratio occurs.

18. In practice, therefore, the best speed under stratospheric conditions is not exactly the speed for minimum drag but a somewhat higher one, the exact figure depending entirely on the aerodynamics of the aircraft concerned. In the remainder of this chapter the variation between types will, for simplicity, be ignored but should be borne in mind when the minimum drag speed is mentioned. For a full understanding of these techniques it is necessary to look more closely into the effects of altitude.

Altitude Effects

19. First, the influence of altitude on the T.A.S/Drag ratio must be considered when the aircraft is at a given weight in level flight at a constant angle of attack at various altitudes. With angle of attack and weight constant, the I.A.S. and drag are unchanged but the same I.A.S. gives an increasing T.A.S. as altitude increases.

20. If there were no compressibility effects, as altitude was increased at a constant I.A.S. the drag at 40,000 feet would still be the same, but the T.A.S. would be about double the I.A.S. Thus the T.A.S./Drag ratio would have doubled and would continue to increase with altitude. (This principle emphasizes the importance of high altitude in obtaining a high S.A.R. from the aerodynamic aspect alone. No matter how low (*i.e.* favourable) the S.F.C. may be at sea level, the very low T.A.S./Drag ratio at this height absolutely precludes a high S.A.R.)

21. Because of compressibility effects, the rate of gain in the T.A.S./Drag ratio is not sustained. At a constant I.A.S. a higher altitude means an increase in I.M.N. As soon as the I.M.N. reaches M_{crit} any further increase in altitude at the same I.A.S. results in M_{crit} being exceeded ; the drag immediately starts rising at a greater rate and the T.A.S./Drag ratio decays rapidly.

22. To understand these points more clearly, Fig. 2 should be consulted. This shows three typical curves of drag versus T.A.S. in level flight for an aircraft at a given weight flying at sea level, 30,000 feet, and 45,000 feet. Also shown is the 0·8 M. line for the standard temperature at the three heights—this is M_{crit} for the aircraft under consideration.

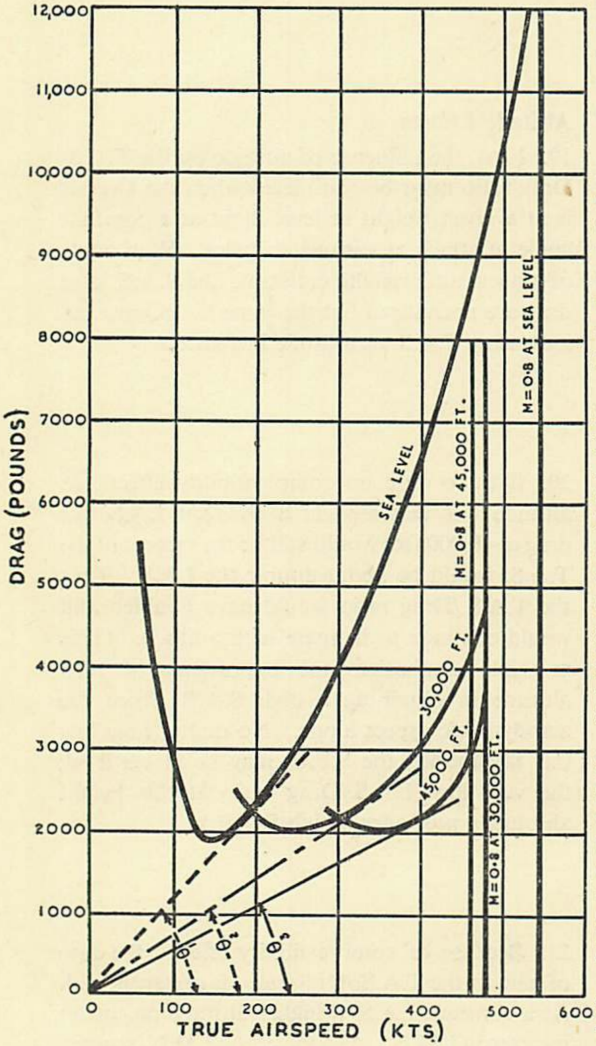

Fig. 2. Variation of Total Drag with Altitude

23. As before, the angle which the tangent to each curve makes with the horizontal is a measure of the T.A.S./Drag ratio ; the smaller the angle, the higher the ratio and the greater the S.A.R. Note first that an increase in altitude causes the angle to reduce. It can also be seen that the best speed to fly at any particular height is 1·31 × the minimum drag speed (I.A.S. or T.A.S.) until the drag curves have moved so far to the right that compressibility causes the drag curve to rise steeply. For this aircraft this occurs at 45,000 feet, and owing to the steep drag rise the best speed is now only 1·1 × the minimum drag speed. As the drag curve moves still further to the right with increase of altitude, towards the limit imposed by M_{crit}, the point of tangency approaches more closely the minimum drag speed and the angle becomes still smaller.

24. The considerations of paras. 20 to 23 apply to cruising at 1·31 or 1·19 times the minimum drag speed, the only difference being in the altitude at which the T.A.S./Drag ratio starts to decay. Since 1·19 is a lower speed (I.A.S.) than 1·31, then at the lower I.A.S. M_{crit} will not be reached until a higher altitude ; therefore the T.A.S./Drag ratio continues to increase to this higher altitude.

25. Consider now two identical aircraft, A and B, flying at these speeds under optimum conditions. A is flying at 1·31 × minimum drag speed at a constant altitude such that the I.M.N. is M_{crit}. B is flying more slowly at 1·19 times the minimum drag speed on a climbing cruise but at a higher altitude, so that the I.M.N. is also M_{crit}. In the stratosphere then, both aircraft have almost the same T.A.S. but B, flying at the lower speed, will have about 9 per cent. less drag. Thus the T.A.S./Drag ratio and S.A.R. of B is about 9 per cent. greater.

26. As time passes and A stays at 1·31 × minimum drag speed by reducing thrust as the weight falls (para. 12), the T.A.S. decreases and the mach number falls below M_{crit}. This decreases the T.A.S./Drag ratio by an amount which increases with time of flight. Thus the S.A.R. of B continues to exceed that of A by a factor which increases with time.

27. It has been shown in para. 16 that the best T.A.S./Drag ratio is obtained by flying at the minimum drag speed. It can now be seen that this is true only if the aircraft has the power to fly at a higher altitude than A or B. Consider C flying at minimum drag speed and therefore higher than B at an I.M.N. equal to M_{crit}. All three

aircraft have almost the same T.A.S. (limited by M_{crit}), but C has the lowest possible drag being about 8 per cent. less than that of B and about 17 per cent. less than that of A at the start of the cruise; the S.A.R. is increased in the same proportion. *This benefit is obtained only by flying at the minimum drag speed at the higher altitude.*

28. If B slowed down to the minimum drag speed at its own altitude, the T.A.S./Drag ratio would decrease; by maintaining the same I.M.N. (and T.A.S.) and climbing to the same altitude as C, the I.A.S. would then automatically fall to that for minimum drag. In this condition the T.A.S. is at its maximum (at the M_{crit} limit) and the drag is least. This then is the absolute maximum T.A.S./Drag ratio obtainable from the aircraft and is the condition for maximum range.

29. **Little m.** The ratio of the cruising I.A.S. to the minimum drag I.A.S. has been given the symbol m; when speaking of this ratio "little m" is generally used, to avoid confusion with mach number (M). If $m = 2$ the cruising I.A.S. is twice the minimum drag I.A.S.; if $m = 1{\cdot}31$ the cruising I.A.S. would be 1·31 times the minimum drag I.A.S., and so on.

30. The ideal conditions for range are therefore obtained when $m = 1$ at such an altitude that the I.M.N. is M_{crit}. In practice some departure from the ideal conditions is often necessary for the following main reasons:—

(*a*) The aircraft may be tiring to fly, from the handling viewpoint, for long periods at the low I.A.S.

(*b*) There may not be sufficient thrust available at this altitude to give the required speed.

31. If the ideal conditions cannot be achieved, the best result is obtained by flying at the highest possible altitude that can be reached, keeping the I.M.N. at M_{crit}. Here, because the altitude is lower, the corresponding I.A.S. is greater than that for minimum drag, *i.e.* it is greater than 1. In fact the lower the altitude at which it is necessary to cruise, still at M_{crit}, the higher is the I.A.S.; *i.e.* the greater does m become until it reaches 1·19 if a climbing cruise is in use, or 1·31 if the constant altitude cruise has been chosen. These conditions are shown in Figs. 5 and 6, which apply to no particular aircraft.

32. Fig. 3 refers to aircraft A, B, and C as considered in paras. 27 and 28 and shows how each has the same M_{crit}, but how, at the greater altitudes, the I.A.S. reduces, *i.e.* m gradually reduces to unity.
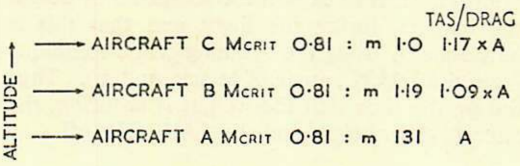
Fig. 3. Possible Range Techniques

33. Fig. 4 refers to para. 31 and shows B and C in a climbing cruise and so gaining height slowly with distance. B is flying at M_{crit} with $m = 1{\cdot}19$ and C (the ideal) at a greater altitude also at M_{crit}, but with $m = 1$. Aircraft D represents the case of an aircraft which either:—

(*a*) Cannot achieve the ideal of C and for some reason is forced to fly at a lower altitude. (D is also at M_{crit} but because of the lower altitude the I.A.S. is greater than that of C and hence m is greater than unity but less than B's figure of 1·19); or

(*b*) Is uncomfortable to fly a speed slower, for example, than $m = 1{\cdot}12$. (In this case D can go no higher without exceeding M_{crit}, and thus represents its practical best cruising altitude.)

34. If it were necessary to use a climbing cruise at an altitude lower than B the speed would be $m = 1{\cdot}19$, and the lower the altitude the more would the I.M.N. fall below M_{crit}.

35. If for some reason the climbing cruise was not used, the speed required for a constant altitude flight would be $m = 1{\cdot}31$ up to that altitude where the I.A.S. corresponded to M_{crit} at the start of the flight, *i.e.* the condition of A in Fig. 4. For level flight at a higher altitude the speed would still be M_{crit} to begin with and m would reduce progressively if the level flight altitude was increased until a speed of $m = 1$ was reached at the maximum altitude.

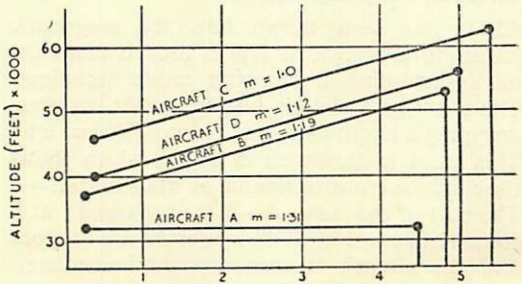

Fig. 4. Comparison of Ranges

Weight Effects

36. It has been shown (paras. 12 and 13) how important it is to exploit the reduction in weight that occurs during the flight and that this is best done by using the climbing cruise technique (constant I.M.N., angle of attack, and m). Thus during the time that the weight is reducing, the aircraft gains height and the I.A.S. falls off.

37. The weight, altitude, and I.A.S. are all closely related during a climbing cruise. Fig. 5 illustrates such a relationship for a cruise at $m = 1$ and shows the increase in altitude and reduction in I.A.S. with decreasing weight.

38. It was stated earlier that if the aircraft was on a climbing cruise at a speed above $m = 1$ (say $m = 1{\cdot}19$) but still at M_{crit}, it would be lower than if it were at $m = 1$ and M_{crit}. The only difference in the graphical representation of such a cruise is that the line is lower than that for $m = 1$, and of course the I.A.S. is higher. This is illustrated in Fig. 6, which shows the relationship between weight, I.A.S., and altitude during these two cruises.

39. From such a graph it is possible to read off the correct cruising altitude and I.A.S. for a given weight during any particular cruise. The line of the graph can be extended in either direction over the entire range of weights which can occur on a given type of aircraft. This information is given in the Operating Data Handbook issued for each type of long-range turbo-jet aircraft, although a different method of presentation is used. The use of these graphs makes the practical task of range flying simple, because all the pilot need do is to keep the I.M.N. constant at M_{crit} and the I.A.S. looks after itself.

Effect of Dropping Bombs

40. It has been shown how the *progressive* reduction in weight as fuel is used is made use of by adopting a climbing cruise technique. The effect of a sudden loss in weight, as when dropping a bomb load, must also be looked into. This effect is illustrated in Fig. 7 which shows the climbing cruise technique at M_{crit} and $m=1$. The part of the curve A—B is unchanged; at B some 12,000 to 13,000 lb. of bombs are dropped and the aircraft is then brought immediately to the situation at D, *i.e.* it should be some 2,000 feet higher and the I.A.S. some 10 knots less. These are the conditions which would have been achieved had the weight of the bomb load been lost gradually during the cruise. A discontinuity occurs because of the sudden loss of weight and the weight scale is shifted to the new position as shown at C—E. The aircraft climbs more quickly until C is reached and thereafter follows the normal cruise path CE.

41. At the start of a long cruise at a high commencing weight the cruising altitude may be in the troposphere; this does not modify a particular cruise technique in any way. The same considerations of m and M_{crit} still hold good and the aircraft must still be allowed to climb at a constant I.M.N. The only difference is that the T.A.S. reduces, owing to the temperature lapse rate, until the tropopause is reached. The T.A.S./Drag ratio still improves, but more slowly than in the stratosphere.

Temperature Considerations

42. *At a given pressure altitude a change in temperature has no effect on the I.A.S. and angle of attack required for the flight condition.* Since the I.A.S. and angle of attack are unaltered the drag remains the same. The only difference is that the T.A.S. changes because of the effect of temperature on the air density. However, M_{crit} is unaffected because the temperature change also changes the speed of sound in the same ratio as it changes the T.A.S.

43. Aerodynamically, therefore, the only change caused, *e.g.* by a rise in air temperature, is to increase the T.A.S. giving a small gain in the T.A.S./Drag ratio. A reduction in temperature causes a drop in T.A.S. and T.A.S./Drag ratio.

Conclusions

44. From the discussion above, certain conditions are required if a high S.A.R. is to be achieved from the aerodynamic point of view. They are:—

(*a*) A high T.A.S./Drag ratio.

(*b*) I.A.S. as close to minimum drag I.A.S. as acceptable.

(*c*) T.A.S. at M_{crit} (never above).

(*d*) Reduction in weight must be turned to advantage (climbing cruise adopted).

(*e*) High altitude.

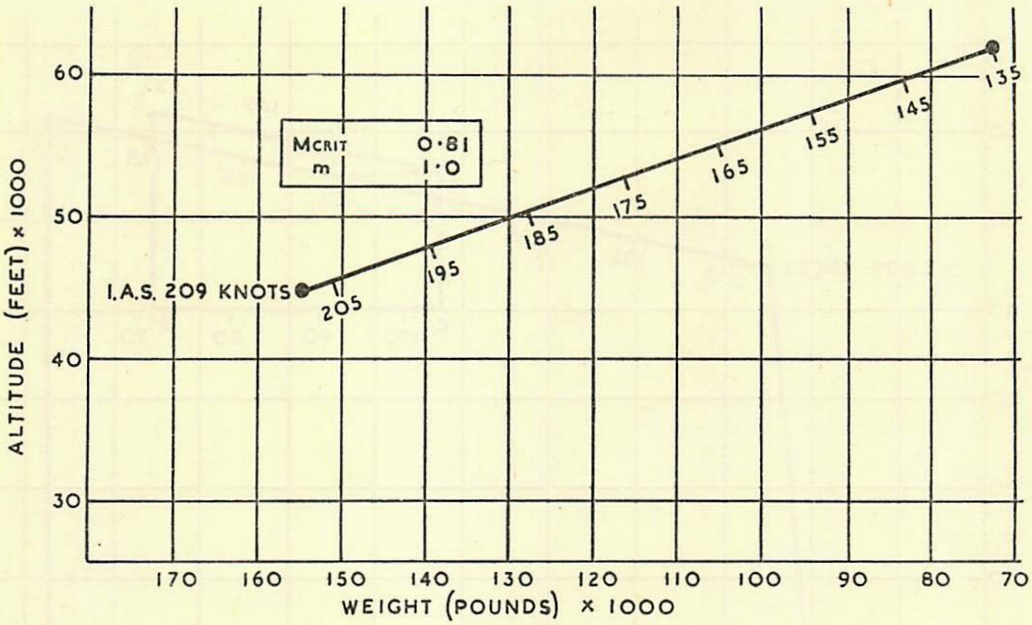

Fig. 5. Climbing Cruise—Ideal Profile

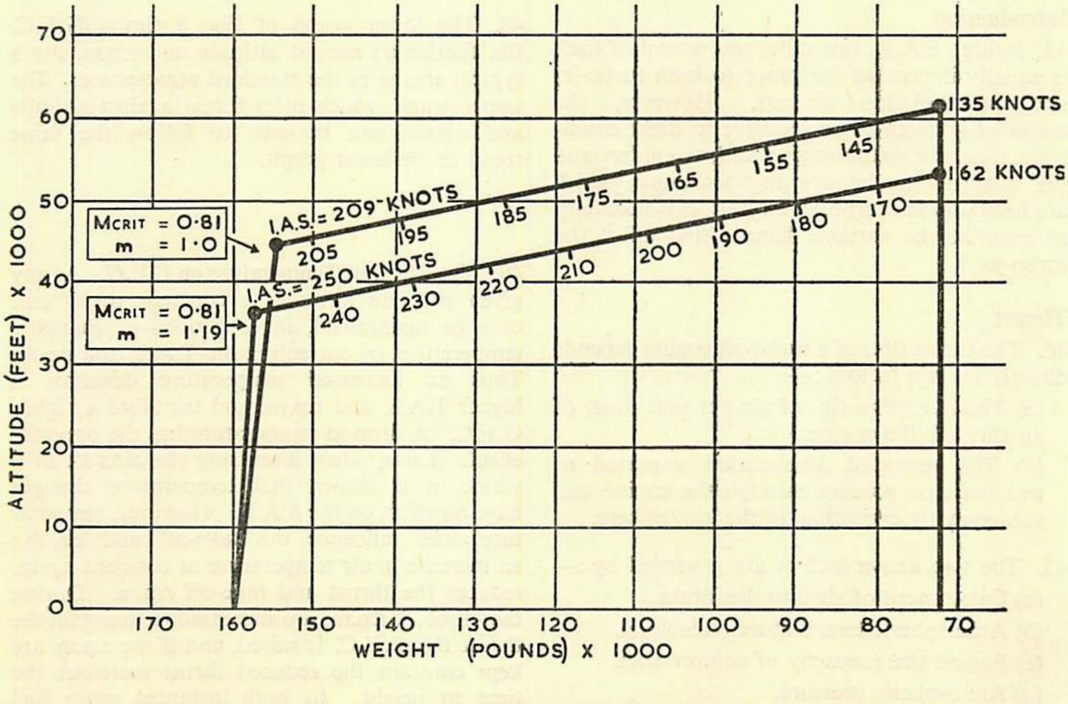

Fig. 6. Comparison of Two Climbing Cruises

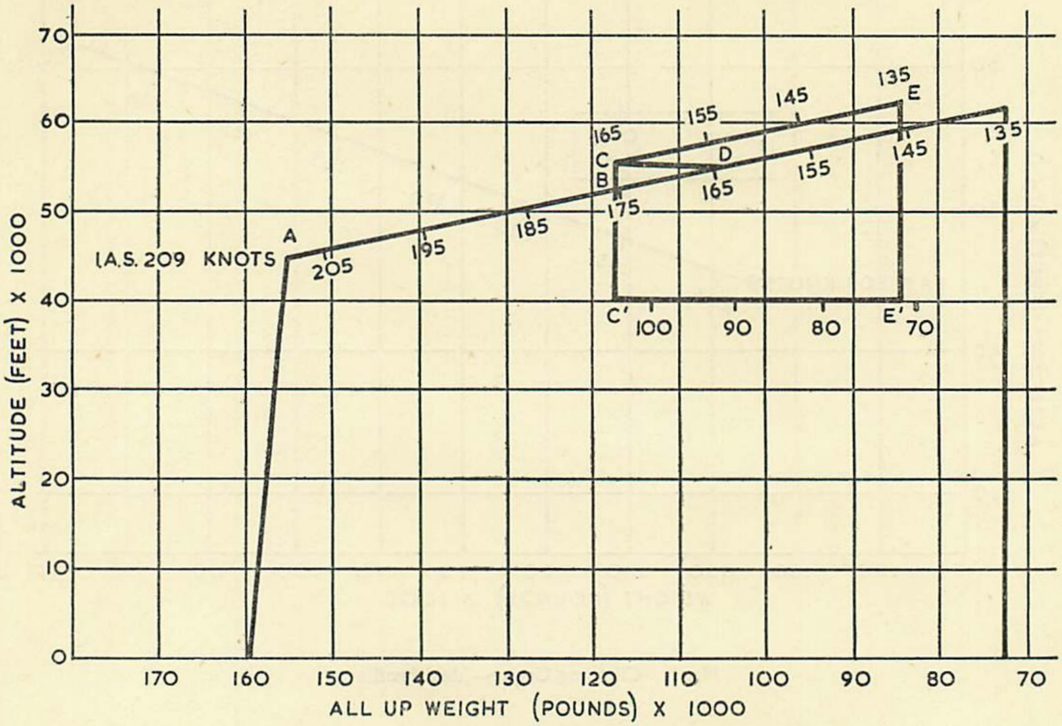

Fig. 7. Effect of Dropping Bombs

ENGINE CONSIDERATIONS

Introduction

45. A high S.A.R. (air miles per pound of fuel) is equally important for range to both turbo-jet and piston-engine aircraft. However, the turbo-jet is much more sensitive to flight conditions than the piston engine and, to understand the changes in the cruising technique which are necessary for turbo-jet aircraft, it is necessary to examine the variable factors that affect the turbo-jet.

Thrust

46. The thrust (lb.) of a turbo-jet engine depends directly on two factors :—

(*a*) The *mass flow* (lb. of air per unit time) of air through the engine.

(*b*) The rearward acceleration imparted to this mass on passing through the engine and subsequently expanding in the atmosphere.

47. The two above factors are governed by :—

(*a*) Entry speed of air into the intake.

(*b*) Atmospheric temperature (Absolute).

(*c*) Engine size (capacity of compressor).

(*d*) Atmospheric pressure.

(*e*) Engine (compressor) r.p.m.

Gross Fuel Consumption

48. The lower graph of Fig. 8 shows G.F.C. (lb. fuel/hour) against altitude and r.p.m. for a typical engine in the standard atmosphere. The upper graph, which plots thrust against altitude and r.p.m., can be seen to follow the same trend as the lower graph.

49. **The Effect of Temperature on G.F.C.** At any given pressure altitude, a constant thrust can only be maintained, in conditions of changing temperature, by correcting the T.A.S. and r.p.m. Thus an increased temperature demands a higher T.A.S. and r.p.m. and therefore a higher G.F.C. A drop in temperature has the opposite effect. Later, when discussing the aircraft as a whole, it is shown that temperature changes have no effect on the S.A.R. However, temperature does influence the take-off and climb ; an increase in air temperature at constant r.p.m. reduces the thrust and take-off r.p.m. During the climb, if r.p.m. are increased to maintain the thrust the G.F.C. is raised, and if the r.p.m. are kept constant the reduced thrust increases the time to height. In both instances more fuel is used to climb to any particular height.

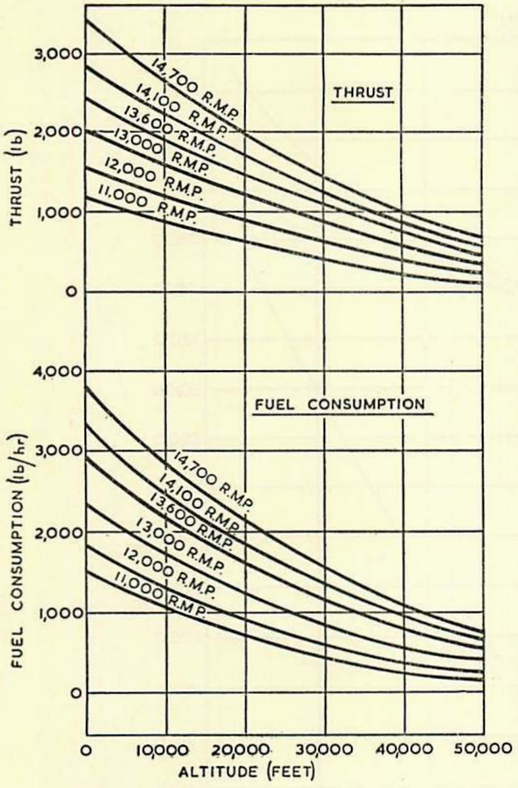

Fig. 8. Thrust and Fuel Consumption

Specific Fuel Consumption

50. Specific fuel consumption is defined as the pounds of fuel used per hour to produce one pound of thrust. The higher the thermal efficiency of the engine, the lower the S.F.C. at a given T.A.S. The biggest single factor affecting the S.F.C. is the r.p.m. Fig. 9 shows sea-level static curves for a centrifugal compressor (Derwent) engine ; it can be seen that the S.F.C. reduces (improves) rapidly with increased r.p.m. until a point is reached where it becomes a minimum. Similar curves for axial flow engines show that the S.F.C. curve is quite flat over a fairly wide band of cruising r.p.m. Provided that the engine is operated within this band of engine speeds the S.F.C. can be taken to be virtually constant.

51. Although r.p.m. have the largest single effect on S.F.C., other factors affect the final figure. At a constant T.A.S. and r.p.m. a decrease in temperature causes the S.F.C. to drop owing to the improved thermal efficiency, since the engine is working between wider temperature limits. Thus under these conditions the S.F.C. decreases up to the tropopause and thereafter stays constant at higher altitudes. At constant r.p.m. and altitude any variation in T.A.S. has little effect on the thrust, but the engine B.P.C. is sensitive to the increased compressor intake pressure and causes an increase in the fuel flow ; the increase in fuel consumption with no increase in thrust causes a higher S.F.C.

Summary of Effects

52. Changes in T.A.S. have little effect on the thrust of a turbo-jet engine (the reasons for this are not within the scope of this chapter). However, the thrust horse-power (given by thrust × T.A.S.) will of course increase. The performance of the turbo-jet is affected by three main variables :—

(*a*) *R.p.m.* Increased r.p.m. :—

(i) Increase thrust at constant altitude and temperature.

(ii) Reduce S.F.C. rapidly at first but more slowly at the higher end of the r.p.m. range. The highest engine speeds increase S.F.C. slightly.

(iii) Increase G.F.C.

(*b*) *Altitude.* Increased altitude :—

(i) Reduces thrust at constant r.p.m.

(ii) Reduces G.F.C. because of (i).

(iii) Reduces S.F.C. up to the tropopause.

(*c*) *Temperature.* Increased temperature :—

(i) Reduces thrust at given r.p.m. and altitude.

(ii) Increases S.F.C.

Conclusions

53. When flying for range the best engine cruising conditions are :—

(*a*) High r.p.m. for lowest S.F.C.

(*b*) High altitude, so that :—

(i) Thrust output at high r.p.m. is just sufficient to obtain the desired speed and so reduce the G.F.C. at these r.p.m.

(ii) S.F.C. is kept low.

THE AIRCRAFT AS A WHOLE

Introduction

54. To obtain an estimate of the range performance of a complete aircraft, the engine and airframe characteristics must be combined. In general, at high altitudes, the aerodynamic considerations are the most important, the engines being simply slaves to propel the aircraft at its most efficient speed.

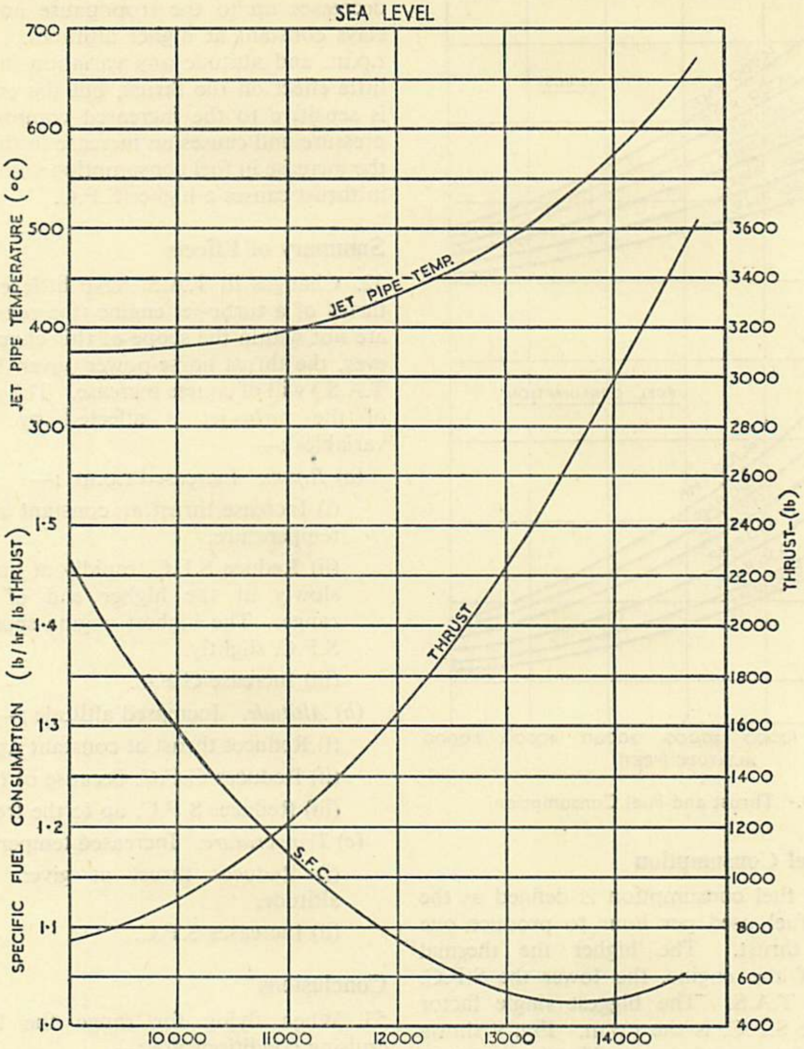

Fig. 9. Static Performances, Derwent 5 and 6

Speeds for Range

55. As far as the range speed at high altitude is concerned, the engine characteristics, with one exception, have no effect on the airframe considerations. The exception is the instance when the engines cannot provide enough thrust to realize the optimum conditions of m and M_{crit}. In this case the cruising altitude must be reduced, thus raising the value of m. However, this state of affairs is unlikely to occur on long-range turbo-jet aircraft, since they are designed with this feature in mind so that just sufficient power is available to realize the optimum speeds at the designed cruising altitude.

56. However, development has resulted in the selected engines giving a higher thrust than that envisaged, so that a reserve of power is available at the designed operating altitude. The higher thrust gives no improvement in cruising altitude or speed because M_{crit} and the speed for minimum drag are dictated by purely aerodynamic reasons, and are closely related to a narrow band of altitudes, departure from which brings a reduction of performance. The power reserve does give one advantage in that it can be used to ensure that optimum conditions are always available despite large variations in temperature, although, if too much reserve is in hand, the more

severely throttled engines, operating at too low r.p.m., would realize a poor S.F.C. and have an adverse effect on range.

57. From para. 56 it follows that, with fully developed engines giving a large margin of thrust over that required for optimum conditions, either the engine must be throttled to give ideal airframe results or the airframe must be sacrificed to the engine. To obtain maximum efficiency, engines are usually required to operate at maximum continuous r.p.m. ; however, if this principle is followed unthinkingly in all cases, eventually more thrust is produced at maximum continuous r.p.m. than is required to give M_{crit} at the correct value for m. Any attempt to keep the speed at M_{crit} results in the aircraft climbing above the optimum altitude ; the same I.M.N. means the same T.A.S. (in the stratosphere), and therefore I.A.S. falls below the ideal figure giving a value of m which may be less than unity. The drag is then greater and so the T.A.S./Drag ratio decays, decreasing the S.A.R. Therefore it is most important that only just enough thrust (r.p.m.) is used to give M_{crit} at the correct value of m at the appropriate altitude.

58. Even though the use of r.p.m. higher than those required for optimum conditions will decrease the S.A.R., the resulting increase in altitude may give an operational advantage that is worth the loss in S.A.R. The ability of the aircraft to gain this extra altitude depends on :—

(*a*) There being a margin of r.p.m. in hand.

(*b*) The aircraft handling well when m is less than unity.

Altitude Effects

59. **Climbing Cruise in Stratospheric Conditions.** During a climbing cruise in the stratosphere at constant M_{crit} and constant m, the drag is decreasing in proportion to the drop in density. At constant r.p.m. the thrust is decreasing in the same proportion. Thus having set the correct r.p.m. (so that the thrust equals the drag) all that need be done is to check that the r.p.m. remain constant so that as altitude is gained the thrust continues to equal the drag.

60. **Climbing Cruise in Tropospheric Conditions.** In the troposphere, owing to the temperature lapse rate, the T.A.S. decreases as altitude is gained at constant I.M.N., and therefore the drag is decreasing faster in proportion to the air density. At constant r.p.m. the thrust is falling off less rapidly than in proportion to the density since the temperature is falling as height is gained. Therefore in the troposphere some adjustment of the r.p.m. may be necessary. Since the time spent at these altitudes should not normally be long these adjustments are not large.

61. Since practically the whole cruise is done in the stratosphere the cruising technique is simple. The pilot merely flies at the correct I.M.N. and checks that the r.p.m. are constant at the appropriate figure. A navigational advantage of this technique is that the T.A.S. remains the same while in the stratosphere at a constant I.M.N.

Temperature Effects

62. In para. 60 it was stated that, for a change in temperature, the r.p.m. have to be corrected to give the same thrust and the T.A.S. is decreasing on a climb at constant I.M.N. For a rise in temperature, higher r.p.m. are necessary for a given thrust and the fuel consumption rises. Provided that the thrust required can be obtained within the r.p.m. limitations, the increased consumption is balanced by the airframe advantage gained from the higher temperature and thus the S.A.R. is unchanged.

Conclusions

63. It has been shown that for aerodynamic reasons alone, increased altitude brings increased S.A.R., and at the same time engine efficiency is improved from the higher r.p.m. needed ; the lower temperature encountered also helps to increase engine efficiency with a negligible loss in airframe performance.

CLIMB, DESCENT, AND EMERGENCIES

Introduction

64. So far only the cruise aspect of the matter has been considered and it now remains to examine the climb and descent. Also, since emergencies often affect altitude, the effects of engine or airframe failure must be considered.

Climb

65. Since high altitude is all-important for a high S.A.R. it is essential to reach the initial cruising altitude as quickly as possible. The climb is therefore made at the highest permissible power. Although this implies a high r.p.m. and G.F.C., it is the most economical method. Increased temperature raises the fuel consumption either because of using more r.p.m. to restore

the thrust or because of a longer time to height because of the reduced thrust. The aircraft must be climbed to a certain altitude at which a certain I.A.S. and I.M.N. are coincident ; the altitude concerned is found from the Operating Data Handbook and, in terms of pressure altitude, is independent of any change in temperature.

66. This can be seen by considering a certain pressure altitude and the effect of a temperature rise to above standard. Because the pressure is the same and the temperature higher, the air density must have dropped ; the speed of sound also increases and therefore the same I.M.N. results in a higher T.A.S. The increase in T.A.S. is balanced by the lower density to give the same I.A.S. Thus a temperature change has no effect on the "coincidence" altitude expressed as a pressure altitude.

Descent

67. The most economical method of losing altitude is to start the descent before the destination is reached at a rate that allows the aircraft to arrive over the destination at the required altitude. In this way the altitude attained during the cruise is most efficiently converted into distance.

68. In a no-engine glide started from 55,000 feet a certain turbo-jet aircraft could glide about 180 miles in still air, the angle of glide being about 3°. For optimum results this would be the best method of descending but, for purposes of pressurizing and operating aircraft services, all the engines cannot be shut down. If the live engine(s) gives 1,000 lb. of thrust (cruising descent) then the angle of glide would reduce to about 2° and the glide range would increase to about 220 miles.

69. At a constant altitude or on a climbing cruise, a turbo-jet bomber with an assumed S.F.C. of 1 lb. fuel/lb. thrust/hour uses some 2,000 lb. of fuel to cover the last 220 miles to overhead at base ; a further 1,000 lb. is used to descend into the circuit giving a total of 3,000 lb. fuel. When using the cruising descent only about 1,000 lb. of fuel would be required to bring the aircraft into the circuit from a point 220 miles away. The more economical descent usually takes longer but this is not necessarily a disadvantage at this stage of a flight.

70. To achieve the best results the descent must be made at a certain I.A.S. (or, at high altitude, I.M.N.) which depends on the A.U.W. This speed is always less than the cruising speed for the same A.U.W. and the I.M.N. is less than M_{crit}. Small changes in speed do not have a marked effect on the descent range, thus enabling some spacing between several aircraft intending to land at the same base.

Engine Failure During Flight

71. If an engine fails the total thrust is reduced and can no longer equal the drag, therefore altitude is unavoidably lost and the lower T.A.S./Drag ratio decreases the range. The amount of loss in range depends on the amount of altitude lost and the latter is governed by the reserve of thrust (r.p.m.) available from the live engines ; at the normal optimum cruising altitude it is unlikely that sufficient reserve thrust is in hand to counter the loss of one engine. Therefore a loss of altitude inevitably follows until the thrust from the live engines increases to the point where it can balance the level flight drag and stabilized conditions are regained.

72. In general the height lost is such that any subsequent climbing cruise should be done at $m = 1{\cdot}19$ and at the I.M.N. at which this value of m is achieved.

73. After engine failure (Fig. 10) maximum continuous r.p.m. should be set and the aircraft allowed to drift down at the I.A.S. corresponding to $m = 1{\cdot}19$ for the prevailing A.U.W. If this is done the stabilization height is approached gradually and once level flight is attained the I.M.N. should be noted and the climbing cruise started once more at this constant I.M.N. If a large power reserve is available after failure of one engine, it may be possible to maintain M_{crit} at a higher altitude at a value of m somewhat lower than 1·19, *i.e.* under more favourable altitude conditions.

74. The technique for range after failure of one or more engines is, then, to assume a certain lower cruising I.M.N. and to allow the aircraft to lose height by a certain amount before resuming the cruise climb at the same I.M.N. The machmeter continues to be the master instrument and the A.S.I. serves purely as a reference instrument. The Operating Data Handbook gives details of the speeds and altitudes concerned with range flying after engine failure.

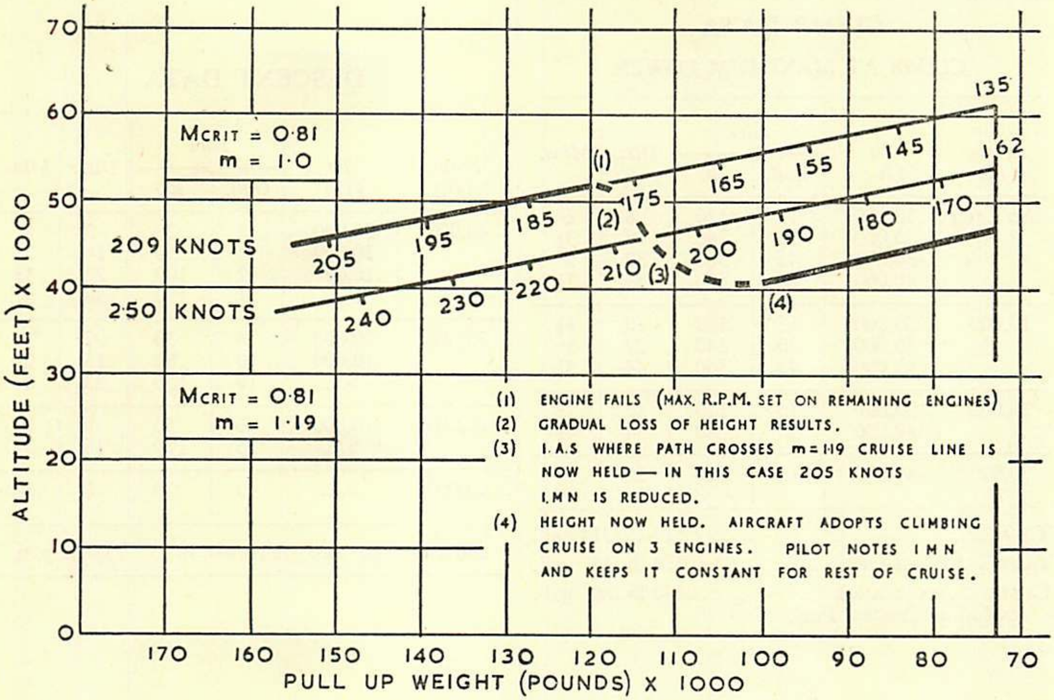

Fig. 10. Failure of One Engine

Pressure Cabin Failure

75. If cabin pressure is lost the aircraft is forced to descend rapidly, to about 36,000 feet, and thereafter to cruise at a constant altitude. Maximum range is then achieved by flying at $m = 1{\cdot}31$. As the A.U.W. falls, the I.A.S. must be reduced by throttling or stopping some of the engines. However, for operational purposes and in the interests of navigation, the speed is often kept constant ; the resulting loss in range is not great and if the recommended landing reserve of fuel is available a constant speed can be justified in most cases.

FLIGHT PLANNING

Introduction

76. For the attainment of the *maximum* range the advantage gained by using the climbing cruise technique is such that it rules out any but the smallest deviations. On flights for which the maximum range is all-important, therefore, the climbing cruise is the correct technique. To attain the optimum range performance the aircraft must be flown at precise speeds and altitudes which are adjusted to fit the A.U.W. and other variables. Even though the technique so far as the pilot is concerned is simple, the speeds and altitudes obtained for a particular flight from the Operating Data Handbook must be carefully observed.

Long-Range Aircraft

77. For long-range aircraft the Operating Data Handbook contains in graphical form all the performance data required for flight planning and includes figures for the engine failure case. Full instructions and examples are given on the use of the graphs and on the flight planning procedure.

78. The speeds given for the cruising stages of a flight are given as I.M.N. or I.A.S., whichever is more convenient, but I.M.N. is usually employed.

Short-Range Aircraft

79. For short-range aircraft, range data is given in Pilot's Notes in tabular form. An example of such a table is shown in Fig. 11, and includes climb, descent, and cruise data. In the cruise data tables it should be noted that the individual speeds are those for maximum range, and that a constant altitude technique is used because it is simpler from the operational aspect and the

CLIMB DATA

CLIMB AT MAXIMUM POWER

From (ft.)	*To (ft.)*	*Fuel*		*Dist.*	*Mins.*
		Gall.	*lb.*		
Sea Level	10,000	15	120	8	2
	20,000	30	240	18	3¼
	30,000	45	360	30	5
	40,000	60	480	52	7½
10,000	20,000	15	120	10	1¼
	30,000	30	240	22	3
	40,000	45	360	44	5½
20,000	30,000	15	120	12	1¾
	40,000	30	240	34	4¼
30,000	40,000	15	120	22	2½

Total Fuel	2,510 lb./314 gall.
Taxy and Take-Off	280 lb./35 gall.
Landing Allowance ... ... (excluding Descent Fuel)	480 lb./60 gall.

DESCENT DATA

From. (ft.)	*To (ft.)*	*Fuel*		*Dist.*	*Mins.*
		Gall.	*lb.*		
40,000	30,000	2	20	7	1
	20,000	6	50	14	2
	10,000	12	100	22	3¼
	S.L.	21	170	30	5
30,000	20,000	4	30	7	1
	10,000	10	80	15	2¼
	S.L.	19	150	23	4
20,000	10,000	6	50	8	1¼
	S.L.	15	120	16	3
10,000	S.L.	9	70	8	1¾

280 knots, 40° flap Airbrake in 7,000 r.p.m.

CRUISE DATA

Fuel State—Galls.	(Avtag)	290	260	208	155	104
Sea Level	*Range (ft.)*	227	195	144	93	**42**
I.A.S. 380K.	10,000	287	246	174	**102**	29
(210—420)	20,000	324	270	183	96	—
ANM/100 lb.:—12·9	30,000	356	292	**187**	82	—
lb./hr.:—2,960	40,000	**363**	**295**	184	72	—
10,000 ft.	*Range (ft.)*	—	259	187	115	**43**
I.A.S. 360K.	20,000	—	288	200	**115**	27
(275—390)						
ANM/100 lb.:—17·8	30,000	—	316	**210**	106	—
lb./hr.:—2,240	40,000	—	**322**	210	98	—
20,000 ft. I.A.S. 330K. 0·72M	*Range (ft.)*	—	304	217	**130**	**43**
(260—350)						
ANM/100 lb.:—21·7	30,000	—	338	233	128	23
lb./hr.:—2,000	40,000	—	**350**	**237**	125	—
30,000 ft. I.A.S. 290K. 0·77M.	*Range (ft.)*	—	358	252	**147**	**42**
(230—310)						
ANM/100 lb.:—26·2	40,000	—	**365**	**254**	142	30
lb./hr.:—1,720						
40,000 ft. I.A.S. 245K. 0·82M.	*Range (ft.)*	—	382	270	158	46
(220—260)						
ANM/100 lb.:—28·1	—	—	—	—	—	—
lb./hr.:—1,640						
Fuel State—Galls.	(Avtur)	280	250	200	150	100
Fuel State—Lb.		2,240	2,000	1,600	1,200	800

percentage loss in what is in any case a small range is not large. Beneath the maximum range speed, a speed band is given in brackets ; use of any speed within this band should not cause more than 5 per cent. reduction in the range obtainable at the optimum I.A.S. *All the ranges shown are calculated to leave the recommended landing allowance of fuel* (480 lb./60 gall.).

80. For intermediate altitudes the correct figures should be obtained by interpolation. The climb and descent data tables give the information used when changing altitude. The times given in the sea-level climb data are from "wheels rolling". *Distance covered on the climb is included, where necessary, in the cruise data, but descent distances must be allowed for separately,* since the descent can be made either from overhead or some distance from the destination ; however, allowance is made in the cruise data for *fuel used on the descent. Similarly, the fuel used for taxying and take-off has been allowed for in the cruise tables, i.e.* the fuel figure shown in the first column of the cruise data table is the fuel remaining after the taxying and take-off allowance has been subtracted.

81. The cruise table shown consists of five separate altitude blocks which show :—

(*a*) The level flight range to the let-down point at a particular height for various fuel states.

(*b*) The optimum range I.A.S. at the particular altitude with the approximate A.N.M. per 100 lb. fuel used and the approximate gross fuel consumption in lb./hr. Also shown is the band of speed (I.A.S.) within which not more than 5 per cent. loss in range will occur. At altitudes above 20,000 feet, the I.M.N. is also given.

(*c*) The range *including* the distance covered on the climb if a climb is made to any other altitude during flight.

Pre-Flight Planning

82. First, enter the cruise data table in the sea-level (top) block at the fuel state applying immediately after take-off ; in most cases this will be in the first column.

83. Select the altitude that gives maximum range for the fuel state. The range includes the climbing but not the descent distance. (Absolute maximum range is obtained by adding on the descent distance, *provided that the let-down is started at that distance from the destination at the correct r.p.m. and aircraft configuration.*)

84. For short flights, inspect the sea-level block and select that altitude at which the distance to be covered requires the least amount of fuel—this is the best altitude for the flight.

In-Flight Planning

85. At any stage of a flight the available range can be found by comparing the prevailing fuel state with the level flight range in the altitude block concerned.

86. If an increase in range is required or if the cruising altitude has had to be increased, the new range can be obtained by entering the appropriate altitude block at the immediate fuel state and then moving downwards within the block until the new altitude is reached. *Figures in heavy type are opposite the best altitude for the maxim m increase in range.* Above this altitude no improvement is obtained if the flight is made to overhead, but reference to the descent table may show that some advantage can be gained by climbing to a higher altitude if the distance covered on a range let-down is added to the range shown for the higher altitude and the let-down is then started at the appropriate distance from the destination. (See example in para. 93.)

87. If a descent to a lower altitude is necessitated, the new range is shown by moving direct from the range shown for the prevailing altitude for the immediate fuel state to the range for the lower altitude.

Specimen Flight Plan

88. As an example of the use and flexibility of the charts, consider a proposed flight using the data in the specimen tables. Assume that a distance of 335 miles is to be covered.

89. Since the tables allow for the fuel used during taxying and take-off, and climb and descent, no separate allowance need be made. Further, the cruise table also leaves the aircraft with the landing allowance in hand after having flown the distance indicated.

90. Therefore, for a flight of 335 miles, the cruise data table should be entered at the *sea-level block* where it can be seen that under the column headed 290 galls. AVTAG (2,240 lb.), *i.e.* fuel available immediately after take-off, the range at

20,000 feet is shown as 324 miles. This is 11 miles short of the required distance, but on looking at the descent data it can be seen that a gradual descent from 20,000 feet at the specified r.p.m. and aircraft configuration realizes a further 15 miles. This distance added to 324 miles gives 339 miles, slightly more than required. Therefore provided a gradual descent is started 15 miles before the destination at the r.p.m. and configuration shown in the descent data table, 20,000 feet is the minimum altitude.

91. If the flight is to be made to overhead at the destination before letting down, then 20,000 feet (324 miles) is too low for cruising. By interpolating between the figures for 20,000 feet and 30,000 feet it is evident that at 25,000 feet the range is 340 miles ; therefore for an overhead flight 25,000 feet would be the minimum altitude.

Example of In-Flight Planning

92. Assume that the flight is being made at 20,000 feet as in para. 90 and that at the point when 208 gallons AVTAG (1,600 lb.) of fuel remains it becomes necessary to divert to another airfield 230 miles away. The tables are then used as follows : if the aircraft is kept at the same altitude, it can be seen, from the 20,000 ft. block, that a distance of 217 miles can be covered with the fuel remaining. However, if the aircraft is climbed to 30,000 feet the range increases to 233 miles and at 40,000 feet to 237 miles. Therefore it is necessary to climb to at least 30,000 feet and cruise at the appropriate speed for this altitude *i.e.* 290 knots. *Maximum* range for the fuel available is shown in bold figures and entails climbing to and cruising at 40,000 feet. If a gradual descent were made from these altitudes the respective distances shown in the descent data table should be added to the range shown in the cruise data table, and the let-down started at the appropriate distance from the destination. If the fuel remaining were 155 gallons AVTAG at the same altitude, then the cruise table shows that there would be a loss in range if the aircraft were climbed.

93. A final example of the in-flight use of the tables is given by considering the aircraft at 20,000 feet with 155 gallons AVTAG (1,200 lb.) fuel remaining. The range available under these conditions is 130 n.m. and no advantage is indicated by climbing to a higher altitude. However, if a range let-down is made from 20,000 feet, then, and from the descent table, a further 16 miles can be added making a total of 146 n.m. If the aircraft is climbed to 40,000 feet the range is reduced (125 n.m.), but if the distance covered on a range let-down from 40,000 feet (30 n.m.) is added to the reduced range, the total range is 155 n.m. It can be seen in this example that, if the flight were to be made to overhead at the destination followed by a maximum rate descent, the flight would best be continued at 20,000 feet ; if a range let-down could be used it would pay to climb to 40,000 feet and start the let-down 30 n.m. before the destination, even though the indicated range was less because of the advantage gained from the greater let-down distance.


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