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PROBLEMS ASSOCIATED WITH THE ADVENT OF TURBINE-ENGINED AIRPLANES

Published by authority of the Secretary General

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INTRODUCTION

The information contained herein, was originally presented in a paper to the Air Navigation Commission of ICAO by the Secretariat. Subsequently, because of its general interest to many aviation authorities, the Council approved its distribution to Contracting States in the form of an ICAO Circular.

As in the case of the preparation of Circular No. 17-AN/14, (1)* the Secretariat has drawn upon statements by experts in this specialized field, made at the IATA Turbine-engined Aircraft Symposium (18 and 19 May 1950 - Asbury Park, New Jersey, U.S.A.) and upon the views presented in lectures, articles, etc. that have appeared in full or have been reported upon from time to time in the aeronautical and engineering press. The information contained in Part IV, relative to 'Rules of the Air and Air Traffic Control' is an extract from the Final Report of the Fourth Session of the RAC Division held in Montreal in November and December 1950. This material was also approved by the Council for distribution to Contracting States as an ICAO Circular.

Those who are able to contribute additional information or suggestions are invited to communicate their views to ICAO Headquarters. The fact that fresh evidence and data are being accumulated daily precludes completeness or up to date accuracy but it is hoped that this study will prove of interest to those who may be concerned with these problems.

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* Documents, reports, etc., to which reference is made throughout circular, have been listed under "Bibliography" - page 45.

PROBLEMS ASSOCIATED WITH THE ADVENT OF TURBINE-ENGINED AEROPLANES

PART I - GENERAL

Although some study has been given by the technical bodies of ICAO to special problems arising from the operation of turbine-engined aeroplanes, the activities of ICAO in the field of air navigation since the Provisional Organization was established six years ago, have been primarily concerned with the preparation and adoption of Standards and Recommended Practices and Procedures related to aeroplanes powered with reciprocating engines. Although it is unlikely that these aeroplanes will be entirely replaced by turbine-powered aeroplanes for many years to come it is already apparent that the time is near when both types of aeroplanes will be used side by side in international air transportation.

The prototype of a turbo-propeller airliner was first flown two years ago and during August 1950 it was flown on scheduled services between London and Paris. This was the first occasion that a turbine-powered aeroplane had been used for carrying fare-paying passengers in international civil air transportation. It is expected that this particular turbo-propeller aeroplane will be regularly used for scheduled air transportation by 1952.

The prototype of the first turbo-jet aeroplane designed for civil air transportation has already completed its first year of test flying during which more than 300 hours of operating experience has been gained and good progress made in assessing its performance characteristics and establishing the most economic operating techniques. It is claimed by the manufacturers of this particular aeroplane that it should prove to be outstandingly economical on stage lengths of the order of 1,000 - 1,700 nautical miles and that the fuel reserves will be comparable in terms of time with those of existing reciprocating-engined aeroplanes (2). The prototype of yet another turbo-jet aeroplane has already completed its first year of test flying and it now seems likely that the progress made in introducing the turbine-engined aeroplane into civil air transportation could be reviewed with advantage.

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PART II.- THE MORE IMPORTANT CHARACTERISTICS OF TURBINE-ENGINED AEROPLANES

Before attempting to reach a conclusion concerning the action that might be taken by Contracting States or by ICAO in the light of the development of turbine-engined aeroplanes it seems desirable to review their more important characteristics particularly where these differ from those of aeroplanes powered with reciprocating engines. In a working paper presented to the Air Navigation Commission in 1950 (3) the Secretariat described in some detail the more important differences between turbine engines and reciprocating engines that will have to be borne in mind when ICAO Standards are established for turbine power-plant installations. Some of the more important problems normally attributed to the advent of turbine or jet-engine aeroplanes would have arisen in any case had some other method been found for providing, within a relatively short period of time in the history of aviation, so large an increase in the speed and operating altitudes of civil aircraft. This creates its own special problems, in addition to those which depend on characteristics that are peculiar to the gas turbine aeroplane, and which are discussed in the following paragraphs.

1.- FUEL CONSUMPTION DURING FLIGHT

At Appendix "A" are tables based on well tried types of turbine engines. These tables compare the power and fuel consumption of a turbo-propeller engine, a turbo-jet engine and a reciprocating engine giving the same thrust and show how the thrust and fuel consumption of these engines varies with the speed of the aeroplane. It will be seen that the turbo-jet engine becomes relatively more efficient as speed and altitude increases. One of the prototype turbo-jet aeroplanes to which reference is made in Part I - General, cruises at nearly 400 knots at an optimum altitude of between 30,000 feet and 40,000 feet, i.e. approximately one and a half times the cruising speed and nearly twice the cruising altitude of a modern airliner powered with reciprocating engines. However, the disadvantage of the sensitivity of the fuel consumption to speed and altitude provides for less flexibility in operation.

Tables I and II in Appendix "A" also show that an aeroplane in which a turbo-jet engine of the type under consideration is installed would burn 52 lbs. of fuel if flown for one minute at 200 knots at sea level, representing approximately 4% of the fuel required to cruise for one hour at 400 knots at 35,000 feet. Fuel consumption at sea level is therefore more than double the consumption at the optimum cruising altitude whereas the speed at sea level is only half the speed at optimum cruising altitude. Compared with airliners powered with reciprocating engines, turbo-jet airliners would be much more heavily penalized if stacked at low altitudes and all engines kept running. The penalty of increased fuel consumption would, however, be reduced if aeroplanes powered with turbo-jet or turbo-prop engines could be stacked at or near their optimum cruising altitudes, since the consumption at 35,000 feet when flying at 200 knots is less than half the consumption at sea level at the same speed.

If, however, stacking at lower altitudes is unavoidable it has been found that the penalty of increased fuel consumption can be lessened by shutting down say two out of four turbo-jet or turbo-propeller engines as the case may be. This increases the endurance and the aeroplane can remain longer in the stack but since the fuel consumption reckoned in air miles per gallon is unlikely to be improved, the practice of shutting down engines does not improve the chances of reaching an alternate if only a narrow margin of fuel is available. In the latter case range rather than endurance becomes important and in flying to a distant alternate, it may be found advantageous to proceed at the optimum cruising altitude with all four engines running. Opinion seems to be divided as to the advisability of shutting down gas turbine engines during flight since there may be difficulty in restarting them. However, restarting during flight has been reported to be almost 100% successful in the case of the turbo-propeller airliner mentioned in Part I - General.(4) Tables I and II at Appendix "A" also show that the fuel burned during a missed approach involving an additional five minutes of flying time would be equal to the fuel used during fifteen minutes of cruising at 400 knots at 35,000 feet.

The substantial penalty in increased fuel consumption for flying at an altitude other than the optimum one needs no emphasis. It may, nevertheless, be worthwhile to accept a small fuel penalty by climbing or descending two or perhaps three thousand feet to avoid regions of rough air although, unlike the reciprocating-engined aeroplane, it will seldom by advantageous for the turbine-engined aeroplane to leave its optimum cruising altitude in order to take advantage of a more favourable wind component. A descent would cause an increase in fuel consumption, and the actual increase would depend on the characteristics of the particular aeroplane, the turbine engines installed and on the speed and altitude. In most instances the increase in fuel consumption would cancel out any increase in ground speed. In the case of a typical turbo-jet aeroplane designed to cruise at 400 knots at 40,000 feet the rate of fuel consumption, if the aeroplane is flown at 30,000 feet at the same indicated airspeed, would be approximately the same but the true airspeed would be about 100 knots slower. The wind at 30,000 feet would therefore have to be 100 knots more favourable than at 40,000 feet before the descent became worthwhile.

2.- FUEL CONSUMPTION WHEN TAXYING AND IDLING

The gas turbine engine has to be run at almost its maximum r.p.m. in order to achieve its lowest specific fuel consumption and consequently the fuel consumption when taxying and idling is relatively high. Some indication of fuel consumption in taxying and idling may also be obtained by taking as an example an aeroplane fitted with turbo-jet engines of the type considered in Tables I and II and designed to cruise at 400 knots at 35,000 feet. Assuming the Lift/Drag ratio of the aeroplane to be of the order of 15 and the rolling friction to be 0.3, the consumption during taxying would be 916 lbs. per engine per hour, i.e. about 25 lbs. per engine per mile at a speed of 36 knots. The fuel consumption when taxying at 36 knots would therefore be as large as 70% of the fuel consumption when flying at 400 knots at 35,000 feet, but the fuel used for taxying to the take-off point can be allowed for and need not be included in the take-off weight unless it is necessary to start with full tanks.

A turbine engine consumes more fuel in idling than a comparable reciprocating engine and it is therefore desirable to reduce idling time as much as possible. It has been found advantageous to use a special engine idling setting for use on the ground by shutting down the turbine engine to a point from which the desired acceleration during flight could not be obtained. This is defined in Annex 8 to the Chicago Convention as ground idling. It is claimed that such a setting reduces the fuel consumption when idling to about 10% of the full throttle consumption on the ground.(5) From the ground idling setting it takes some considerable time to open up a turbine engine, a delay in acceleration which is acceptable for use on the ground, as for example when awaiting clearance from the Tower to taxi to the take-off point. An approach idling setting is however used in flight and this ensures that an adequate acceleration can be made in the event of a missed approach or a baulked landing. The fuel consumption at the approach idling setting is approximately the same as the fuel consumption when taxying at 30 knots but this relationship varies with the type of turbine engine installed.

3.- FUNDAMENTAL ASPECTS OF TAKE-OFF AND CLIMB PERFORMANCE

One of the fundamental features of the turbo-jet engine is its ability to provide a propulsive thrust at a given altitude which is approximately independent of forward speed, in contrast to propeller-driving engines whose thrust decreases as speed increases. At zero speed a reciprocating or turbo-prop engine equipped with a variable pitch propeller develops a thrust approximately $2\frac{1}{2}$ times its thrust at cruising speed. The thrust available for take-off on an aeroplane powered with turbo-jet engines is however approximately the same as its thrust at cruising speed and it might be concluded therefore that this would result in a requirement for runways that are longer than those now used by modern airliners powered with reciprocating engines.

This is however not necessarily true since the thrust/weight ratio of an aeroplane powered with turbo-jet engines will be high because these aeroplanes can only be operated at optimum efficiency at altitudes and speeds which are appreciably higher than those at which reciprocating-engined aeroplanes are operated. Moreover, since the thrust of a turbo-jet engine decreases with increasing altitude at a greater rate than for a supercharged reciprocating engine, the desired performance of a turbo-jet engine at high altitudes can only be obtained if provision is made for a very large static thrust at sea level. This offsets the tendency for the aeroplane fitted with turbo-jet engines to need a longer take-off distance. The two turbo-jet aeroplanes mentioned in Part I - General use the runways that have been built for contemporary reciprocating-engined aeroplanes of comparable size. It is possible that aeroplanes may have higher wing loadings in the future in order that full advantage may be taken of the potentialities of the turbine engine and this may probably lead to an increase in take-off distances.

Reference has already been made to the comparatively high thrust of the reciprocating engine available at the beginning of the take-off run. If for example a comparable turbo-jet engine has slightly less thrust available when at rest it will be at a disadvantage initially but as the speed of the aeroplane increases during the take-off run the thrust of the reciprocating engine will decrease whereas that of the turbo-jet engine will remain approximately the same. Later, during the take-off run, or perhaps shortly after take-off, the thrust of the reciprocating engine will be overtaken by the thrust of the turbo-jet and thereafter the latter engine will be developing the greater thrust. It may be assumed therefore that the turbo-jet engine will provide the better climb performance at least initially but having left the ground its thrust will be more adversely affected by the decrease in atmospheric pressure with altitude, than will the thrust of a supercharged reciprocating engine.

4.- EFFECT OF CHANGES IN ATMOSPHERIC TEMPERATURE AND PRESSURE

Compared with the reciprocating engine, the gas turbine is more sensitive to changes in air temperature and pressure and consequently the take-off performance of turbo-jet and turbo-propeller engines is more critical in tropical temperatures and on high elevation airfields. For example the turbo-jet engine considered in Tables I and II in Appendix "A" would lose 12% of its static thrust at sea level if the temperature increased from 15°C (59°F) to 36°C (100°F). The effect of temperature on the power of turbo-propeller engines is still more marked. The thrust of a turbo-jet engine or the power of a turbo-propeller engine is proportional to the pressure of the intake air and the gas turbine is therefore more sensitive to variations of pressure than is the supercharged reciprocating engine.

The marked decrease in the take-off performance of aeroplanes powered with gas turbine engines, caused by high air temperature and low pressure is overcome in the case of at least one turbo-jet aeroplane by injecting water into the engines. Similar results have been obtained by the injection of a mixture of water and methanol but it is claimed that this introduces a risk of contaminating the cabin air if the main compressor of the turbine engine is being tapped to pressurize the cabin. The injection of water or water methanol lowers the temperature in the combustion chamber and the fuel introduced to restore the temperature to its previous figure results in an increase in thrust. This increase is however limited to approximately 10% in the aeroplane referred to in Part I - General. The fitting of rocket motors to compensate for loss of thrust in extremely low atmospheric density is also contemplated.

It is also important to take into account the variations in upper air temperature. Considering again the turbo-jet engine referred to in Tables I and II of Appendix "A" an increase in temperature of 23°C (41°F) would reduce the thrust by 25% when flying at 500 knots and 35,000 feet. For the turbo-jet aeroplane to which reference is made in Part I - General, a variation in temperature of 5°C (9°F) at a cruising altitude of 40,000 feet over a long stage would have the effect of exacting a penalty on the fuel consumption equivalent to 8 knots in wind speed. (6)

5.- EFFECT OF ENGINE FAILURE ON FUEL CONSUMPTION

The possibility of failure of the turbine engine in flight must be taken into account. In the case of one of the turbo-jet aeroplanes referred to in Part I - General the penalty in fuel consumption for the loss of one engine is not great, particularly after the fuel load has been largely exhausted. An engine failure at half distance on a stage length of say 1,500 nautical miles, followed by a gradual descent to the most economical three-engine cruising altitude, would reduce by less than fifteen minutes the normal stand-off time allowance at 1,000 feet. The rate of climb on three engines with flaps and undercarriage up exceeds 1,100 feet per minute, the landing weight being relatively low due to the high fuel consumption and there is therefore an ample margin of safety in the event of a baulked landing. (7) If two engines fail, the most economical cruising altitude for this particular aeroplane is 10,000 feet. Tests carried out on several aeroplanes powered with four turbine engines have shown that the fuel consumption in air miles per pound is only increased slightly when flying on two engines at the most economical two-engine cruising altitude. (8)

6.- SIMPLICITY OF ENGINE DESIGN AND MAINTENANCE

There seems to be good reason for the belief that the latest civil airliners have been allowed to become too elaborate partly due to the demands of the operator and partly due to the complexity of the modern high powered reciprocating engine and unless something is done to check this tendency civil airliners of the future may well spend more and more time on the ground and not be operated at a profit. The introduction of turbine engines into civil air transportation, particularly the turbo-jet engine, offers an opportunity for sweeping simplifications that should result in increased efficiency and economy in airline operation provided that the gas turbine engine is not allowed, as the piston engine has been allowed, to lose too much of its original simplicity.

Experience to date has shown that the service life of the major components of gas turbine engines is already approaching the reliability reached by the major components of reciprocating engines. The representative of one manufacturer has said that a warranty of 1500 hours will be given on the major components of turbine engines built by his firm. (8) The periods between overhaul of gas turbine engines are also fast approaching those normally associated with modern reciprocating engines. Representatives of other manufacturers of turbine engines have reported that the minimum period between overhauls is only 500 hours and that this is shortly to be extended to 800 hours. (8) It has also been pointed out that the higher cruising speed of the turbine-engined aeroplane as compared with the reciprocating-engined aeroplane gives the advantage of more miles flown between overhauls.

7.- HANDLING ON THE GROUND

Advantage can be taken of a valuable auxiliary braking medium in the case of all aeroplanes fitted with reversible pitch propellers. At the present time aeroplanes fitted with turbo-jet engines lack any comparable means for applying reverse thrust and aeroplanes having high wing loadings and fast landing speeds may need some form of auxiliary braking such as tail parachutes to supplement the wheel brakes. The use of tail parachutes has however not been found necessary in operating the turbo-jet aeroplanes to which reference is made in Part I - General. Experience in operating these aeroplanes has served to dispel many misgivings regarding the ground handling of turbo-jet aeroplanes. They can be taxied slow or fast and can manoeuvre on the ground in the same way as any other modern airliner and can be taxied on two engines if desired. The thrust required for starting from rest is not excessive, and the use of tractors for towing as an alternative to taxying an aircraft under its own power, has not been found necessary. Some examples of the objections raised to the use of tractors include the comparatively slow rate of towing, the complication of the tow truck and the possibility of traffic difficulties at busy airports. On the other hand it has been suggested that it would be more economical if tractors were used to tow a turbo-jet aeroplane to a taxi apron adjacent to the take-off runway. Here the engines would be started and the aeroplane taxied under its own power to the take-off point.

The starting of turbo-jet engines on the apron has in practice caused no inconvenience and it has been found possible to start up engines close to airport buildings without intolerable noise or commotion. Grass has been burned for a distance of about 100 feet behind the run-up point but there has been no pitting of the surface. A clearance of 150 feet has been found sufficient for following aircraft. Tables III and IV at Appendix "A" show the temperatures and velocities, at varying distances from the nozzle, of the exhaust gases of the turbo-jet engine considered in Tables I and II. The temperatures given in Table III will no longer apply if extra fuel is burned in the tail pipe in order to increase the velocity of efflux, but the opinion has been expressed that this system, commonly known as after burning, will probably not be used for civil aeroplanes.(9)

In operating the prototype turbo-jet airliners referred to in Part I - General, there has been no sign of deterioration of concrete runways as a result of jet blast. Some of the smaller jet fighter aeroplanes have caused considerable damage to the surface of bituminous runways both by jet blast and the spillage of kerosene but this has not been noticeable in the case of the prototype airliners, probably due to the large ground clearance of the jet pipes and the near to horizontal thrust line. It has, however, been found that the spillage of kerosene due to overflowing, mishandling or merely closing down the engines has caused fairly rapid deterioration of the bitumen filling material in the joints between the concrete slabs of runways, taxiways or ramps. Similar deterioration is also caused by spilled gasoline but it is less serious than that caused by kerosene, the latter fluid being less volatile.

An important advantage of the turbine engine over the reciprocating engine is that the time for warming up of the former is negligible. Timed tests carried out at several different aerodromes on the turbo-propeller aeroplane referred to in Part I - General have shown that the time occupied in carrying out an initial cockpit check, starting the four engines and having the aeroplane ready to taxi to the take-off point, averaged nearly three minutes. For one of the turbo-jet aeroplanes mentioned in Part I - General the corresponding time has been found to average five minutes. In general, turbine engines require a greater battery capacity for starting on the ground than do contemporary reciprocating engines, and engine starters of approximately double the horse power are required.

In view of the comparatively high fuel consumption when taxying and idling it would be advantageous for the turbo-jet aeroplane to be cleared by aerodrome control to proceed direct from the ramp to the take-off point. Such a procedure may however be found to be impracticable at congested airports. The turbo-jet aeroplane which taxies at approximately 30 knots and does not have to spend a considerable time in having to run up its engines at the end of the runway would suffer a disproportionate penalty in fuel consumption if required to take its turn in the line at the gate position. There may be several reciprocating-engined aeroplanes ahead, also waiting their turn to take off, and each one will have to spend a considerable time in running up all its engines one after the other before starting the take-off run. It might be possible to avoid this by dividing the taxiway just before it meets the end of the runway so as to provide access via one or perhaps two alternative routes. This would permit aerodrome control to give a turbine-engined aeroplane direct access to the take-off point. At aerodromes equipped with parallel runways it might be possible to use one for take-off and landings of turbine-engined aeroplanes and the other for reciprocating-engined aeroplanes. It has also been suggested that aeroplanes powered with turbo-jet engines should be towed to a taxiway parking apron and should not have their engines started until take-off clearance has been received. They could then taxi quickly to the take-off point and would not be held up by other aeroplanes.

8.- EFFECT OF ICING

The effects of icing on the airframe are, generally speaking, common to all aeroplanes regardless of the type of powerplant but there are some aspects of airframe icing that are peculiar to airframes in which gas turbine engines are installed. For instance aeroplanes powered with turbo-jet engines will normally cruise well above icing levels and the ability to climb and descend rapidly will reduce the time during which the de-icing system has to be operated as compared with modern reciprocating-engined aeroplanes. Moreover it has been stated that the gas turbine has been found to provide more heat in a convenient form for thermal de-icing of both airframe and engines, than has been available in the past from reciprocating engines. This method carries, however, the penalty of increased fuel consumption during the de-icing process particularly during descent. It has been found, for instance, that 1,000 lbs. of fuel has been used for supplying the power needed for this method of de-icing during a gradual descent, from 20,000 feet, of a four-engined turbo-jet transport aeroplane, over a distance of fifty miles. (10)

Thermal de-icing is normally used to heat the air intake of turbine engines and even when ice has formed and fairly large pieces have broken off and passed through the engine, there seems to have been no evidence of damage in the case of gas turbines fitted with centrifugal compressors. It seems less likely, however, that engines fitted with axial flow compressors escape damage in similar circumstances. In one of the turbo-jet airliners referred to in Part I - General, thermal de-icing, in the form of hot air tapped directly from the centrifugal compressors of the four turbo-jet engines, is used for de-icing the wings and tail surfaces in addition to the air intakes. (11) The building up of ice around the air intakes tends to reduce the thrust of any engine and in the case of typical turbine engines, this loss has been compensated for by spraying alcohol or methanol into the air intakes. This increases the thrust and prevents or delays the deposit of ice on the intake screens and is more efficacious if the spray is switched on before icing starts. In aeroplanes powered with turbo-propeller engines electrical de-icing is normally used for the spinners and propeller blades in the same way as for reciprocating engines.

Although it may be assumed that gas turbine powered aeroplanes will normally be less exposed to prolonged icing risks, there is as yet insufficient evidence to show that these aeroplanes are as well equipped to fly through ice for an indefinite period as contemporary aeroplanes powered with reciprocating engines. The most successful methods of de-icing used on gas turbine aeroplanes appear to carry substantial weight penalties either in the form of extra fuel or some de-icing agent such as alcohol or methanol. Until the duration, intensity and location of the icing likely to be encountered can be forecast with more certainty it will not be possible to estimate the weight penalties with the necessary accuracy. There seems to be a requirement for a non-expendable system which can deal with moderate icing conditions encountered during flight without any substantial payload penalty.

9.- EN-ROUTE NAVIGATION

The high speed of the turbo-jet aeroplane will no doubt give rise to new en-route navigational problems and most of these would be common to reciprocating-engined aeroplanes if they were able to cruise at comparable speeds. The contemporary reciprocating-engined aeroplane needs expert handling in order to achieve maximum efficiency in operation and this is no less true of the turbo-jet aeroplane, the penalty for mishandling in the latter case being the more severe when measured in terms of fuel consumption. It will therefore be even more important for pilots to be thoroughly conversant with the characteristics of their engines under all possible operating conditions. On the other hand, in view of the inherent simplicity of the power-plants, accessories and cockpit layout of the turbo-jet aeroplane and the substantial reduction in the number of instrument dials, it may no longer be necessary to carry a flight engineer as a member of the operating crew. The need for a flight radio operator will depend on future developments of long distance voice communication rather than on the comparatively high speed of turbo-jet airliners. There will in any case be a search and rescue requirement for routine position reports to be made at more frequent intervals than once hourly whether this is done by R/T or W/T. In an extreme case it would be possible for an aeroplane cruising at 500 knots with the help of a tail wind of say 200 knots to have covered 700 nautical miles since its last position report.

The effect of a twofold increase in cruising speed will also make it necessary for the flight navigator to work twice as fast. In astro navigation more reliance may have to be placed on pre-computation so that positions can be determined if possible within one minute of taking sights. There has been some tendency in the past for flight navigators to disregard the coriolis correction. This particular correction varies directly as the ground speed, and at 500 knots would represent a shift in position line of 12 nautical miles in latitude 70°N and 11 nautical miles in latitude 60°N. Care will therefore have to be taken to ensure that this correction is applied. It is unlikely that astrodromes will be provided in turbo-jet airliners due to the high pressure difference at the normal cruising altitudes and the use of hand-held sextants may no longer be feasible unless an optically flat glass plate having the strength to withstand the pressure difference, could be designed. Periscopic bubble sextants would seem to be necessary if astronomical navigation is desired. Some attention may have to be given to charts to be used for en-route navigation, particularly in the choice of the scale. A turbo-jet aeroplane having a ground speed of 600 knots would cover nearly four inches of the world aeronautical chart (ICAO 1:1,000,000) in five minutes. These charts would be needed in the vicinity of the terminals and alternates but for en-route navigation a scale of approximately 1:5,000,000 may be required.

It will undoubtedly be worthwhile to continue with and to develop the technique of pressure pattern flying because the ratio of wind speeds to airspeed at the cruising altitude of the contemporary reciprocating-engined aeroplane will not be materially different to the same ratio in the case of the turbo-jet aeroplane, the twofold increase in airspeed being matched by a similar increase in wind speeds. It is probable that the error of radio altimeters now available does not exceed 50 feet at 40,000 feet, an error which will probably be reduced in the near future, to 25 feet. On the other hand there is little prospect of guaranteeing a comparable accuracy at the same altitude in the case of the barometric altimeter. (12)

It has been suggested that drift sights will not be worth installing in turbo-jet aeroplanes, and the practical difficulties of fitting a drift sight in a pressurized aeroplane are well appreciated. However it has been reported by an experienced airline captain that he has often found a drift sight useful when cruising at 25,000 feet even when the surface was obscured. On several occasions his first indication of the presence of a jet stream has been obtained by observing an unusually large drift angle. If the surface is not visible, such drift readings are taken on cloud formations many thousands of feet below and beyond the influence of the abnormal wind speed at the altitude of the aeroplane.

There are still long periods during which astro navigation cannot be used in modern reciprocating-engined aeroplanes because the sky is obscured by cloud. Turbine-engined aeroplanes particularly those powered with turbo-jets will normally cruise above the weather and there will be few occasions when astro navigation cannot be used. There will however still be an urgent requirement for a long distance radio navigational aid and although it is important that the indications given by such an aid are both accurate and reliable the emphasis will be on speed of interpretation. It has already been pointed out that the flight navigator will have to work much faster and the development of a long distance radio navigational aid that can provide a near to instantaneous indication of position will undoubtedly make a valuable contribution to the safety of air navigation particularly in the case of high speed aeroplanes operated at high altitudes over areas where short distance navigational aids are not available.

It is important, for example, that the flight crew should have a timely indication of any substantial change in ground speed which might be caused by an unexpected encounter with a jet stream. In these circumstances the earliest possible warning should be given so that full advantage can be taken of a strong tail wind or appropriate measures taken to avoid a head wind. The need for a long distance radio navigational aid that can give a reliable indication of position in the shortest possible time becomes particularly acute when the flight crew are too preoccupied in dealing with an emergency to cope with any time-consuming method of fixing position that requires undivided attention. The marked increase in speed brought about by the introduction of turbine-engined aeroplanes will also bring about a corresponding increase in the need for speeding up radio communications such as aircraft movement messages, position reports, meteorological information and navigational warnings.

PART III.- PROBABLE EFFECT ON AIR NAVIGATION PROCEDURES OF THE OPERATION OF TURBINE-ENGINED AEROPLANES

As already mentioned in Part I. - General, a prototype turbo-propeller airliner has already been flown on a scheduled service between London and Paris a distance of some 200 nautical miles. The services were operated between 10,000 and 12,000 feet at a true airspeed of approximately 240 knots. The average block-to-block time was about one hour and the fuel consumed approximately 2,300 lbs which was slightly less than half the total fuel carried. This particular aeroplane can, however, be operated more economically on longer stage lengths of the order of 500 - 1,000 nautical miles. The fact that a turbine-engined aeroplane was first used in the summer of 1950 for carrying passengers on an international air route is perhaps not remarkable in itself, since the aeroplane concerned had been flying successfully for two years. It is perhaps of greater significance to note that it fitted unobtrusively into the regular air traffic pattern on a fairly heavily congested route. No special landing priority was granted by air traffic control and the flights, which took place during the holiday season, i.e. a time when the traffic density on that particular route was at its highest, were operated in just the same way as those carried out on the same route by contemporary reciprocating-engined aeroplanes.

It may perhaps be assumed, in the light of this particular experience, that any air navigational problems that may arise in operating turbine-engined aeroplanes on comparatively short hauls will be resolved without such difficulty. Difficulties are, however, more likely to arise on the longer routes where much more will depend on the accuracy of meteorological information, the efficiency of the air navigational services and the skill of the operating crew. A more realistic appraisal of the probable effects of introducing turbine-engined aeroplanes into civil air transportation can perhaps be obtained by reviewing the more important problems that may arise in operating turbo-jet airliners non-stop over a typical stage length of 2,000 nautical miles and comparing these problems with those associated with the operation of contemporary aeroplanes powered with reciprocating engines. This has been done in Appendix "B" to this circular.

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PART IV.- PROBABLE EFFECT OF THE OPERATION OF TURBINE-ENGINED AEROPLANES ON THE WORK OF ICAO

As already pointed out in Part I - General, the time seems to be close at hand when aeroplanes powered with turbine engines and aeroplanes powered with reciprocating engines will be used side by side in international air transportation. It will also be apparent from the problems described in the preceding paragraphs and the illustrations given that the advent of the turbine-engined aeroplane will have an important bearing on the future work of ICAO. In the following paragraphs reference is made to some of the more important items that will fall within the scope of the various activities of this Organization.

1.- AIRWORTHINESS

It is probable that the bulk of the additional work load arising from the advent of turbine-engined aeroplanes will be related to Airworthiness and Operations. The Standards and Recommended Practices for type tests of turbine engines and associated propellers, which were proposed by the Airworthiness Division at its Third Session, were adopted by the Council for incorporation in Annex 8 to the Chicago Convention on 26 June 1950 and became effective on 1 January 1951.

The Division, at its Fourth Session, in March-April 1951, proposed Standards and Recommended Practices for the installation of turbine powerplants, the acceptance tolerance of overhauled turbine engines, and the effects of atmospheric humidity and free water on the power output of turbines. These were adopted by the Council for incorporation in Annex 8, on 13 November 1951. The Division also discussed the following subjects in their relation either to high speed, high altitude aeroplanes in general or specifically to turbine-engined aeroplanes:- design airspeeds, gust magnitude and frequency, aerolastic problems, cabin pressurization, effects of atmospheric temperature and icing. Recommendations were made concerning the keeping up-to-date of the standards for turbine-engine type approval already adopted, and the standards for the installation of turbine powerplants recommended for adoption in the near future.

In addition, the Division proposed to organize at future meetings an exchange of views on problems related to powerplants and to the period between engine overhauls.

2.- OPERATIONS

One of the reasons for the establishment of the previously mentioned International Standards and Recommended Practices for turbine-engined aeroplanes was that several of these aeroplanes would shortly be submitted to national airworthiness authorities for certification, for use in civil air transportation and that delay in the establishment of international requirements would increase the likelihood of marked divergences in national practices for certification. This also applies to any special treatment that may be required for these aeroplanes in the Operating Limitations of Annex 6 which are complementary to the performance standards of Annex 8. However, with regard to the other standards of Annex 6, the likelihood that delay in standardization would tend to increase divergence in national practices cannot be questioned but this possibility must be weighed against the disadvantage of convening a meeting at a time when the delegates are insufficiently prepared to discuss new standards and the danger that undue haste may lead to the preparation of immature standards. The standards contained in Annex 6 to the Chicago Convention are based on operating practices that have proved their worth during the past decade or so of experience in aeroplane operation. It is true that some of the difficulties experienced in reaching agreement on certain of the OPS standards might have been lessened had it been possible to prepare Annex 6 some ten years earlier, but it is equally true that no great amount of experience has been accumulated in operating turbine-engined aeroplanes in civil air transportation so far.

It is important that the requirements for operating these aeroplanes should be specified by ICAO as soon as possible e.g. the accuracy required in terminal forecasts, in order that the related work of other activities of the Organization is not unduly delayed but it is doubtful whether the time is ripe for the preparation of international operating practices and procedures for turbine-engined aeroplanes. No Contracting State suggested that the operation of turbine-engined aeroplanes should be discussed at the Fourth Session of the Division in April 1951, and no such discussions have as yet taken place within the Division. However, it is probable that in the near future, the need for a possible modification of the standards of Annex 6 will have become clearer and should this be so, suitable discussions can then be arranged.

3.- METEOROLOGY

The operation of turbine-engined aeroplanes, particularly those powered with turbo-jet engines, will benefit considerably from increased accuracy in the science of meteorology and from the provision of additional observation facilities. In effect however this will be a reciprocal process since the knowledge gained by actual experience of sub-stratosphere flying will make valuable meteorological data available to the meteorologists.

Cognizance has been taken of the importance of accurately forecasting the wind velocity and temperatures of the upper air (owing to its effect on performance) and the weather at the terminal and alternates, in view of the penalties in terms of increased fuel consumption and additional hazard, that may accrue as a result of inaccurate forecasts. Furthermore, emphasis has been placed on the importance of forecasting the position, extent and severity of icing conditions and areas of dangerous turbulence. It is axiomatic that to meet such requirements an accurate knowledge of wind and weather extending up to 45,000 feet and a more extensive and accurate knowledge of air temperature must be realized.

Apart from means of providing the necessary forecasts and in-flight data, additional radar wind and radio sonde ascents will be required in certain areas to obtain more basic data. The routine collection of more data on upper air movements and conditions should lead to general improvements in meteorological forecasting, the benefits of which will be shared by all aircraft and not only turbine-engined aeroplanes.

The extent to which operational planning of routes, to be flown by turbine-engined aeroplanes is dependent on reliable meteorological and climatological data needs no emphasis. In addition, it is apparent that the high cruising speed and necessity for early change of flight plan necessitates a rapid means of communicating to the aircraft meteorological information relating to the specific flight.

The MET Division has already recognized the importance of many of these problems and the recommendations made at the Third Session of the MET Division held in March 1950 (13) include the following items that will have an important bearing on the operation of turbine-engined aeroplanes:-

a) Requirements for gust information at high altitudes;

b) World network of upper air observation stations and upper air analysis centres.

c) Procedure for pressure pattern flying.

d) Standard classification for types of aircraft icing.

e) Meteorological information for flights at high levels.

f) Application of temperature and humidity accountability as applied to international air navigation.

The possibility of increasing the accuracy of terminal forecasts was discussed at the Third Session of the MET Division but since full consideration to this problem could not be given at that time it was placed on the Division's Work List and classified as very urgent. Spectacular improvements in the accuracy of meteorological forecasting cannot be expected to occur over night. Even in a comparatively well organized region such as the North Atlantic, the frequency and distribution of upper air observations are by no means adequate and more money and effort is needed, not only to improve the observational network itself but to improve the accuracy of the instruments used. Some of the onerous operational requirements for meteorological and climatological information that will accompany the advent of turbine-engined aeroplanes in air transportation are already known and all possible steps to meet these requirements are being taken.

4.- RULES OF THE AIR AND AIR TRAFFIC CONTROL

Air Traffic Control will also be vitally concerned with the operation of turbine-engined aeroplanes particularly since such aeroplanes will be more heavily penalized by traffic delays, especially delays in landing, than contemporary reciprocating-engined aeroplanes. With regard to take-off, both air speed and rate of climb are much higher in turbine-engined aeroplanes than in piston-engined aeroplanes but the net effect is that the angle of climb is not significantly different up to an altitude of approximately 10,000 feet.

The speeds of turbine-engined aeroplanes are such that reliance can no longer be placed on pilots seeing each other in time to take any necessary avoiding action, even in the best visibility. Furthermore, the prolonged changes of altitude on climb and descent, and the inaccuracies of barometric altimeters at great altitudes, indicate that the present Quadrantal Rule itself will no longer suffice for separation purposes. The range of turbine-engined aeroplanes decreases rapidly with decrease in altitude and under maximum range conditions the speed will also decrease somewhat with decrease in altitude. The cruising speed for the turbine-engined aeroplanes will also be close to the speed at which maximum continuous power is required. Reductions in cruising speed may result in reduction in range. Because of these trends, turbine-engined aeroplanes will usually cruise at altitudes close to their operating ceiling and may be somewhat inflexible with regard to changes in cruising altitude.

It appears, therefore, that Air Traffic Services should provide turbine-engined aeroplanes with separation at all times during flight. This applies both en route and near aerodromes. This is particularly important near aerodromes if a turbine-engined aeroplane experiences a balked landing and has to overshoot because of unexpected interference from other aircraft, as it will saddle the operator with unnecessary expense due to the heavy fuel-consumption of turbine-engined aeroplanes at lower altitudes.

It is not anticipated that high traffic density will occur at altitudes above 20,000 feet in the immediate future so that separation by air traffic services at such altitudes should not impose a great deal of difficulty. Separation of turbine-engined aeroplanes at high altitudes may be more effectively accomplished by lateral separation than by vertical separation. This is indicated by the fact that for extended periods of flight, turbine-engined aeroplanes may be required to change altitude, for operational reasons, in order to reduce fuel consumption. These changes in altitude would require the vertical separation to be sufficiently large to compensate for the inaccuracies in the present barometric altimeters, in order to ensure safe separation. This does not necessarily mean, however, that vertical separation should be completely ruled out. It may well be that many aspects of the current methods of providing separation can continue to be effective. If it is determined that the presently used system of controlled airspace is deemed inadequate, it naturally follows that different procedures should be applied within the upper airspace above 20,000 feet. It is suggested that the air traffic control procedures could be patterned after those presently applied in the North Atlantic Region. Whatever term may be given to these upper airspaces, for efficiency, they should be as large as communications will permit. It would appear desirable to further the application of HF R/T.

Below about 20,000 feet, the operation of turbine-engined aeroplanes becomes very uneconomical in fuel consumption. This suggests, therefore, that when practicable, pilots-in-command should be given as much warning as possible of any anticipated landing delay before descending from cruising altitude. The pilot-in-command can then absorb the major portion of the delay be adjusting air speed or by holding en route at high altitude. Secondary holding may sometimes be necessary to absorb errors in the estimated delay and in ETA at the control zone "gate" and also to phase in the approach with those of piston-engined aeroplanes. The approach path and secondary holding point should be chosen so as to permit the turbine-engined aeroplane to make an unobstructed approach to land in its correct turn. It may be necessary to provide the turbine-engined aeroplanes with a descreet track separated from that followed by piston-engined aeroplanes so as to accomplish the unobstructed approach. The secondary holding point should be at as high as altitude as possible so as to obtain the most efficient operation. The problem of safeguarding aircraft whilst they are descending from high altitudes into the control zone naturally depends upon circumstances. For example, where control areas exist, air traffic control might be required at all times at those altitudes likely to be occupied by regular services. Consideration should also be given to the problem of providing adequate separation at busy airports at all times, irrespective of weather. This may require a change in the present concept of control zones.

On the question of diversion, except in the case of very short-range diversion, it may be necessary for diversion arrangements to be made while the aircraft is at a high operating altitude. This leads to recognition of the necessity for efficient operational control and of adequate fixed and air/ground communications for this to be exercised swiftly. Another significant factor is the need for close liaison between air traffic control and operational control so that decision can be made well in advance as to whether diversion is necessary and to which alternate. By this means, the fuel reserves of turbine-engined aeroplanes will be employed to the best advantage and the greatest possible margin of safety together with the avoidance of inconvenience to other traffic may be obtained.

It appears that whole time flight separation is advisable for turbine-engined aeroplanes operations and this is likely to necessitate the introduction of a new concept of controlled airspace at altitudes above approximately 20,000 feet providing such separation by procedural or radar methods. It is not considered that, in most lower airspaces, the concept of regulations based on IFR and VFR require alteration at his stage by the introduction of turbine-engined aeroplanes. However, at the most important aerodromes, which are those likely to be used by turbine-engined aeroplanes in the first place, consideration should be given to the possible need for the provision of separation by Air Traffic Control at all times, irrespective of weather, within what are presently known as control zones. The safeguarding of turbine-engined aeroplanes in their descent from high altitude into such zones needs to be considered according to circumstances and could be effected by either radar or procedural means.

The following are considered to be the essential features respecting the controlled airspace at high altitudes:

1) Such upper airspace may be defined without reference to national boundaries;

2) Flight information and alerting services will be provided within them:

3) An additional requirement will exist that all aircraft flying in those regions will be subject to control at all times irrespective of weather conditions.

5.- AERODROMES

The Standards and Recommended Practices for the physical characteristics of aerodromes and for obstruction clearing and marking, as set out in Annex 14 to the Chicago Convention, are based on the operation of reciprocating engined aeroplanes and may have to be revised in the light of turbo-jet aeroplane requirements. The Aerodromes, Air Routes and Ground Aids Division, at its Fourth Session held in November 1949, was well aware of this possibility and included in its work list an item entitled "Aerodrome design in relation to jet aircraft". The Secretariat has issued, in accordance with a recommendation made by the Division, ICAO Circular 17 - AN/14 entitled "The effect of turbine-powered civil aircraft on the design, construction and equipment of land aerodromes".

Present indications are that it will be possible to operate turbine-engined aeroplanes from existing aerodromes handling reciprocating engined aeroplanes of similar size except where high temperatures are experienced whereat it may be necessary to increase runway lengths. Certain other changes may also be found desirable in the interests of efficiency as for example some reduction in the complexity of runway and taxiway layouts to enable both the air and ground traffic patterns to be simplified, improvement in taxiway design to permit of taxying at high speed, the provision of branched taxiways to enable stationary aircraft to be bypassed, etc. In addition, some consideration may have to be given to the surface treatment of aprons, taxyways and the ends of runways where "blast" and fuel spillage effects may cause deterioration.

6.- PERSONNEL LICENSING AND TRAINING

The need for revising the Personnel Licensing Standards to take account of the sharp upward trend in cruising speeds is less than might be expected because these Standards have been drafted in very general terms. Some minor amendments may however be necessary in the knowledge requirements for the air traffic controller, flight navigator, flight radio operator and flight operations officer to take into account any important change in the technique of air navigation brought about by a nearly twofold increase in cruising speeds. With regard to the operation of turbine-engined aeroplanes per se, some amendments may be necessary in the knowledge requirements for the various pilot licences to provide for a thorough understanding of the fuel consumption characteristics of the turbine engine and for more emphasis on the importance of correct engine handling.

It is probable that more extensive amendments will have to be made to the curricula for courses of approved training which have to be prepared in more detail than the basic knowledge requirements included in Annex 1 to the Chicago Convention. These curricula will have to be revised, not only to take into account airspeeds of the order of 500 knots, but also the special characteristics and operational problems associated with turbine-engined aeroplanes. The need for revision will also apply to the Training Manuals and in particular to the specimen examination questions which have so far been based almost entirely on the operation of modern reciprocating-engined aeroplanes.

7.- COMMUNICATIONS

In the sphere of communications it is recognized that the advent of turbine-engined aeroplanes with their high cruising altitudes and substantially increased cruising speeds, accentuates an existing need for a reliable long range navigation aid along trunk routes. For the present the principal aids will be Loran, Consol, and LF/MF radio ranges and beacons in conjunction with the radio compass.

To facilitate an accurately controlled let-down by turbine-engined aeroplanes, which is so important in view of their large fuel consumption at low altitudes, an accurate navigational aid is essential. It is believed that the most suitable navigational aid would be some form of track guide together with distance measuring equipment on 1000 megacycles, which would indicate position and track for distances up to 200 nautical miles, provide range indication up to 200 nautical miles at high altitudes, and in addition permit homing facilities to be employed if necessary. Pending the availability of such an aid, MF beacons and ranges together with VHF/DF will be the principal navigation aids. Provision of additional beacons or increase of power, and additional VHF/DF in certain areas along trunk routes may be found necessary.

At turbine-engined aeroplane cruising altitudes, the range of VHF will be extended considerably, as will the area of interference. This will give rise to serious problems in congested areas such as Western Europe, until such time as new frequency dispensations, using more channels, become practicable. Saturation of VHF channels in other areas is not believed to be a very serious problem and special arrangements for turbine-engined aeroplanes well be unnecessary.

The effects on performance of turbine-engined aeroplanes at low altitude and of engine failure, requiring as they do, early decision on change of flight plan, increase the value to the pilot of information and instructions received by radio. Since change of plan is frequently determined by conditions at destination or alternate aerodromes, means of direct communication with the terminal aerodromes may prove to be desirable, in which case the provision of rapid and efficient means of long range air/ground communications would require to be considered.

The advantages of HF R/T for air/ground communications are widely recognized and the recommendations and decisions of ICAO RAN Meetings indicate a definite trend towards the employment of this medium. That HF R/T will have even greater advantages at turbine-engined aeroplane cruising speeds is clear, nevertheless the requirements of turbine-engined aeroplanes cannot be divorced from the overall policy on HF R/T which must be designed to meet the requirements of all aircraft. As one of the means of establishing direct speech communication between turbine-engined aeroplanes and Flight Information Centres, consideration may have to be given to the provision of HF R/T at all Flight Information Centres.

The introduction of turbine-engined aeroplanes brings into stronger relief some weaknesses which exist with regard to the rapid transmission of movement traffic messages over Aeronautical Fixed Telecommunications Circuits. The COM Division (4th Session) (14) has already given consideration to this matter and has formulated recommendations (Nos. 118 and 119) relative, not only to treatment of the problem but to how best it may be resolved.

8.- OTHER AIR NAVIGATION FIELDS

It would appear that other Air Navigation fields i.e. Search and Rescue, Accident Investigation and Maps and Charts will also be concerned with the problems arising from the advent of the turbine-engined aeroplane in civil air transportation. No new search and rescue problems of a general nature are expected to arise but the equipment of rescue units may have to be adopted. If experience shows that turbine engined aeroplanes are substantially different from reciprocating engined aeroplanes in matters such as those associated with ditching and flotation properties, it will be necessary for Search and Rescue to study the effect of such differences. Annex 13 to the Chicago Convention deals mainly with administrative problems and should not be affected by the advent of turbine engined aeroplanes, however, some additional material may have to be included in the Manual of Aircraft Accident Investigation.

Reference has already been made to the scale of charts used in air navigation and an exchange of views on this subject might be required. The scale of 1:3,000,000 contemplated for a world series of plotting Charts may prove to be too large for the operation of aeroplanes flying at ground speeds which may reach 700 knots. At this speed an aeroplane would cover approximately seventeen inches on these charts in one hour's flying. A stage length of say 2,500 nautical miles would be represented on these charts by a distance of about sixty inches and this would make the chart too large. There are many advantages in carrying out the navigational plotting required for any one stage length on one sheet and it seems that a scale of 1:5,000,000 would be a better choice for the operation of turbine-engined aeroplanes over stage lengths of 2,000 - 3,000 nautical miles.

APPENDIX A

THRUST AND FUEL CONSUMPTION DATA OF SELECTED TURBINE AND RECIPROCATING ENGINES

Many arbitrary assumptions would have to be made in making a precise quantitative evaluation of the differences between the fuel consumption characteristics of turbine engines and those of reciprocating engines. Assumptions would have to be made concerning a variety of factors such as the aerodynamic characteristics, range and operating altitude of the aeroplanes in which the engines are installed. If such an analysis were made it could be argued that the conclusions were valid only for the particular aeroplanes under consideration. However, for the purposes of this circular, it is considered that reliable conclusions can be drawn from a qualitative evaluation based on the data for the engine itself and the following Tables (see overleaf) have been prepared on this premise.

Table I
Sea Level

1	Aeroplane speed	knots	200	400
2	Thrust, jet engine	lb.	2200	2350
3	Consumption, jet engine	lb./hr.	3120	4000
4	Power, engine driving a propeller	HP	1682	3580
5	Consumption, turbo-propeller	lb./hr.	1360	2900
6	Consumption, reciprocating engine	lb./hr.	841	1790

Table II
Altitude: 35,000 feet

1	Aeroplane speed	knots	200	400	500
2	Thrust, jet engine	lb.	980	1020	1070
3	Consumption, jet engine	lb./hr.	1090	1265	1370
4	Power, engine driving a propeller	HP	748	1555	2040
5	Consumption, turbo-propeller	lb./hr.	605	1270	1652
6	Consumption, reciprocating engine	lb./hr.	396	778	1020

Note 1 - Propeller efficiency of 80% assumed.

Note 2 - The figures given for the consumption of a reciprocating engine do not give a true indication of the fuel consumption of an aeroplane equipped with reciprocating engines and travelling at 400 or 500 knots. The rating of the engines would need to be much higher than the power required to drive the propeller at cruising speeds, particularly for the higher altitude operations. Reciprocating engines able to develop the necessary power would have a much higher drag than the turbine engines, which would increase the power required and the consumption.

TEMPERATURE AND VELOCITY OF EXHAUST CASES

Table III

Distance from nozzle (on axis of nozzle), feet	Temperature, °F
0	1062
18	616
26	318
33	248
41	205
52	157

Table IV

Distance from nozzle (on axis of nozzle), feet	Velocity, Ft/sec
0	1840
15	940
22	600
30	370
42	260
63	160

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APPENDIX B

THE MORE IMPORTANT PROBLEMS THAT MAY BE ENCOUNTERED DURING A TYPICAL FLIGHT

1.- ASSUMED AEROPLANE AND ENGINE CHARACTERISTICS

It is assumed for the purposes of this illustration that an aeroplane powered by four turbo-jet engines is available and has been designed to cruise at 500 knots. The optimum cruising altitude for its gross weight of 110,000 lbs. is assumed to be 38,000 feet and the fuel consumption at optimum altitude 1,250 lbs. per hour per engine or 5,000 lbs. per hour in all. This would represent a specific fuel consumption of about 0.9 lb. per hour per pound of thrust. It is further assumed that the tanks hold approximately 45,000 lbs. of kerosene fuel, i.e. sufficient for about nine hours cruising at optimum altitude without any allowance for taxying or climbing. With 45,000 lbs. of fuel on board only 10,000 lbs. of payload can be carried but the desired minimum payload on the particular stage length concerned (2,000 nautical miles) is 20,000 lbs. To obtain this payload, only 35,000 lbs. of fuel can be carried.

2.- PROCEDURE FOR CLIMB AND DESCENT

After take-off a steady rate of climb is maintained along the desired track to the destination so that the aeroplane reaches its optimum cruising altitude about half an hour after take-off. The optimum cruising altitude increases as the weight of the aeroplane decreases and since 5,000 lbs. of fuel have been consumed during the initial climb, the weight has been reduced to approximately 105,000 lbs. and the optimum cruising altitude increased to approximately 39,000 feet. The air distance covered during the climb to the optimum cruising altitude is approximately 200 nautical miles. Thereafter the rate of climb is considerably reduced being maintained at approximately

1,200 feet per hour until an altitude of about 43,000 feet is reached in the vicinity of the destination. Alternatively this gradual climb can be carried out in a series of steps, for example 600 feet every half hour, without any appreciable reduction in specific fuel consumption.

The climb procedure used for the turbo-jet aeroplane is therefore quite different from that currently used by the contemporary reciprocating-engined aeroplane on a comparable stage length. The latter aeroplane is climbed to its optimum cruising altitude and power is progressively reduced in order to maintain a constant airspeed as fuel is consumed and the aeroplane becomes lighter. Alternatively if fuel conservation is not considered to be of primary importance, a constant power setting may be used, in which case the airspeed increases as the weight of the aeroplane decreases. If the density of the upper air is considerably below normal, the long range reciprocating-engined aeroplane is sometimes flown initially at an altitude below its optimum cruising altitude, but as soon as sufficient fuel is consumed for its normal climb performance to be regained, it is then climbed to its optimum cruising altitude. Apart from exceptions such as this, long range reciprocating-engined aeroplanes are normally flown at a constant altitude.

It is assumed that the descent of the turbo-jet aeroplane under consideration is commenced approximately 150 nautical miles short of the destination and the rate of descent adjusted so that at a point thirty nautical miles short of the destination, the altitude is reduced to 20,000 feet. At this point there is still sufficient altitude for stacking without incurring an undue penalty in fuel consumption and the aeroplane can, if necessary, be climbed again to optimum altitude and flown to a distant alternate without too serious a drain on fuel reserves. After final clearance to land a much steeper descent is made so that the aeroplane can, in approximately seven minutes, reach a point from which the final approach is commenced. This method of descending from optimum cruising altitude can, however, be regulated within wide limits in co-operation with Air Traffic Control without materially affecting the fuel reserves, in order that arrival in the aerodrome control zone can be made at an agreed time. It is unnecessary for the contemporary reciprocating-engined aeroplane to descend in two stages, since it can cruise over a wide range of altitudes at approximately the same specific fuel consumption and has in this respect, more flexibility in operation than the turbine-engined aeroplane.

3.- CALCULATION OF FUEL LOAD

In calculating the fuel required for the flight, allowance will have to be made for the extra fuel used during the climb to optimum cruising altitude and unlike the aeroplane powered with reciprocating engines there will be no substantial compensation in the form of decreased fuel consumption during the descent. On the contrary, if hot air for thermal de-icing and pressurization is supplied by the engines, it will be necessary to maintain a comparatively high thrust during the descent and this will increase the fuel consumption. The normal allowance for wind velocities will have to be made, plus an allowance for a possible error of say 20 knots in the forecast of the head wind component. It will also be necessary to allow for a possible error of up to 10°C in the forecast temperature, particularly at the optimum cruising altitude since an error of this size would, in the case of the turbo-jet aeroplane described in paragraph 1, be equivalent to an error of approximately 15 knots in forecasting the wind speed. It may be possible to reduce these allowances if, in the light of experience, it is found that the upper air wind velocities and temperatures can be reliably forecast within finer limits. The normal allowances would also have to be made for minor navigational errors, diversions to avoid adverse jet streams and for departures from the optimum cruising altitude to avoid localized regions of rough air.

Provision must also be made for sufficient fuel to fly to the designated alternate and provided that the diversion can always be made at the optimum cruising altitude, the fuel carried for this purpose need not necessarily exceed the corresponding reserve carried by a reciprocating-engined aeroplane. These ideal conditions for diversion will not always obtain and it will be prudent to calculate the fuel allowance for diversion on the assumption that the decision to fly to an alternate may not be taken until the aeroplane is at an altitude of 20,000 feet or even lower, in the vicinity of the destination. An allowance must also be made for stacking, either at the destination aerodrome or at the alternate, the actual amount of fuel depending on the traffic density statistics and the efficacy of the aids to approach and landing. The proposal that the turbo-jet aeroplane should be stacked at an economical cruising level and make a steep descent as soon as landing instructions are received has found general approval in principle by air traffic services authorities. The fuel reserve for stacking the turbo-jet airliner described in paragraph 1 could therefore be based on say, one half hour's stacking time at 20,000 feet. The same endurance could be obtained by shutting down two engines if it became imperative to stack at a low altitude but in this event it would usually be necessary to accept a commitment to land at the aerodrome concerned.

The penalty of increased fuel consumption following the failure of one engine on the type of turbo-jet aeroplane under consideration will be small, provided that the altitude is reduced by about 5,000 feet to the optimum altitude for cruising on three engines. The fuel reserves of contemporary reciprocating-engined aeroplanes operating trans-ocean crossings such as the

North Atlantic are however based on the ability to reach a landing point if failure of two engines occurs at the most critical time. For the turbo-jet airliner under consideration, the optimum two-engine cruising altitude would be about 12,000 feet and again the fuel consumption in air miles per pound would not be much increased. The fuel reserve to provide for a failure of two engines on the turbo-jet airliners would therefore not exact a substantial penalty unless there was a possibility of having to deviate in order to avoid very high terrain or a region of dangerous weather. It is assumed that an allowance of 1,000 lbs. of fuel is carried to provide for the possibility of failure of two engines.

Failure of cabin pressurization and the concomitant need to fly at an altitude of 12,000 feet or less would handicap the turbo-jet airliner more than the contemporary reciprocating-engined airliner. The fuel consumption would become prohibitive at such a low cruising altitude if all four engines were kept running and if it were not possible to make an emergency landing at some point along the route, it would be necessary to shut down two engines in order to increase the range. If this were done the operational handicap described in the previous paragraph for the "two engine out" case, would apply. Problems arising from a failure of cabin pressurization coupled with the need to retain sufficient altitude for clearing high terrain, or avoiding dangerous weather would be common to both turbine and reciprocating-engined aeroplanes.

In calculating the fuel load it will also be necessary to allow for the fuel needed for taxying to the unloading ramp at the destination aerodrome but it can be assumed that the fuel used in taxying and idling at the departure aerodrome will have been expended before take-off and need not be included therefore in the gross weight, unless it is necessary to take on a full load of fuel at the outset. Finally, the amount of methanol or similar fluid for spraying into the engines to maintain thrust in icing conditions and to prevent or delay the formation of ice must also be determined. It can be assumed that climb and descent through the normal icing layers will be of short duration and on the assumption that the engines will provide enough hot air for heating the wings, tail surfaces and air intakes under normal icing conditions, it is probable that sufficient fluid for combatting 15 minutes of severe icing, will be adequate. Some allowance will also have to be made for the weight of any water or water methanol that may be left over after take-off.

Taking into account the fuel reserves that would have to be carried on a stage length of 2,000 nautical miles by the turbo-jet airliner described in paragraph 1, 35,000 lbs. of fuel would have to be put into the tanks and it would therefore be possible to carry the desired payload of 20,000 lbs. Should the requirement to fly for two hours at cruising speed be applied to the turbo-jet aeroplane, it may in some instances exact a disproportionate fuel penalty since, in two hours of flying, it can cover a distance of about 1,000 nautical miles, i.e. about twice the distance that its contemporary reciprocating-engined aeroplane can fly. The opinion is held however, by some airline operators, that since turbine-engined aeroplanes provide for less flexibility in operation than reciprocating-engined aeroplanes, more stringent requirements for fuel reserves will be needed.

4.- TAKE-OFF AND CLIMB

It will be necessary to reduce the time spent on the ground at intermediate stops in order to obtain the maximum advantage from the comparatively high speed of turbine-engined aeroplanes. It will therefore be important to speed up the rate of refuelling and it is probable that under-wing refuelling will be essential. It would take 22-1/2 minutes to fill the tanks of the turbo-jet aeroplane described in paragraph 1 even with a refuelling rate of 2,000 lbs. per minute. It may be assumed that the engines would be started at the ramp after passengers have embarked and the pilot, having received clearance from aerodrome control would taxi to the take-off position at a speed of approximately 30 - 35 knots using two engines, the remaining two running at the ground idling setting. Small quantities of kerosene are most likely to be spilled when engines are started, shut down or stopped and it would therefore be necessary for the ramp to be surfaced with concrete. This applies also to the taxiways and approximately the first 200 feet at both ends of the runways. On arrival at the take-off point and with brakes on, engines would be opened up until full power is developed and the brakes then released in order to shorten the take-off run.

It seems unlikely that any of the turbo-jet engined aeroplanes already designed or to be designed in the future would fail to meet the ICAO transport Category A Standards and Recommended Practices for take-off and accelerate-stop distance, take-off path, and climb with one or two engines inoperative. In order to comply with these Standards and Recommended Practices when the take-off is being made in low atmospheric density it will no doubt be necessary to use water or water methanol injection during the first one or two minutes after the start of the take-off run, in order to regain the thrust that would normally be available in standard atmospheric density.

Similarly, compliance with the accelerate-stop requirements in low atmospheric density may only be possible by taking into account the braking effect of a tail parachute in the case of the turbo-jet aeroplane and reversible pitch propellers in the case of the turbo-propeller aeroplane. The effect of runway slope and wind on take-off performance will be roughly the same as for a reciprocating-engined aeroplane and there is as yet no evidence that high relative humidity has any adverse effect on the thrust of the turbine engine although it may reduce the effectiveness of water or water methanol injection. The average rate of climb of the turbo-jet airliner described in paragraph 1 would be approximately 1,300 feet per minute until the optimum cruising altitude is reached.

5.- APPROACH TO THE DESTINATION

Three hours after take-off the turbo-jet airliner described in paragraph 1 would be approximately 550 nautical miles short of its destination, on the assumption that the average ground speed has remained approximately equal to the true airspeed. It is assumed that during the flight the weather at the destination has been deteriorating and is now expected to be below the minimum limits at the estimated time of arrival. A decision is taken to divert to Alternate "A", where the weather is good, flying at the optimum cruising altitude which is now 42,000 feet. For the purposes of this illustration Alternate "A" is assumed to be 400 nautical miles from the destination and 2,000 nautical miles from the departure aerodrome. A diversion at this time adds a distance of approximately 130 nautical miles, representing about 16 minutes of additional flying time and about 1,300 lbs. of fuel.

Even had there been some prospect of an improvement in the weather at the destination by the time the aeroplane was due to arrive, the decision to divert to an alternate where the weather was favourable would still have been well justified in view of the fuel consumption characteristics of the turbo-jet engine. There will naturally be a preference to land at the destination aerodrome if at all possible and in the case of the reciprocating-engined aeroplane there is not so large a penalty for "going down to have a look". The turbo-jet aeroplane on the other hand has more to lose if the landing cannot be completed, since the fuel penalty for descending to say 500 feet above the destination followed by a climb to optimum cruising altitude to go to an alternate, is about 2,000 lbs. for the particular turbo-jet aeroplane under consideration. An extra 2,500 lbs. of fuel would also be needed to fly the 400 nautical miles to Alternate "A", i.e. 4,500 lbs. in all. The extra distance necessary for the diversion is only 130 nautical miles provided that the decision to fly to Alternate "A" is taken at the proper time. This illustrates the importance of accuracy in terminal forecasts since an inaccurate forecast may have particularly adverse effects on the operation of turbine-engined aeroplanes. There is an obvious requirement for a short period terminal forecast having an accuracy as near to 100% as possible.

When still 500 nautical miles short of Alternate "A" it is assumed that one engine fails. Altitude is reduced slowly to 36,000 feet which is the optimum altitude for three-engine cruising, taking into consideration the weight of the aeroplane at that time (approximately 90,000 lbs.). There is no appreciable rise in the fuel consumption in air miles per pound after the engine failure but the true airspeed is reduced to 430 knots. Following the normal procedure, the descent to Alternate "A" is commenced approximately 50 minutes after the occurrence of the engine failure and 20 minutes later the aeroplane reaches a height of 20,000 feet at a point 30 nautical miles short of Alternate "A". It would be normal Air Traffic Control procedure to give priority in landing to an aeroplane approaching with one engine out and clearance would ordinarily be given to descend for a landing without undue delay.

There would however still be about 9,000 lbs. of fuel left and even if it were necessary for the airliner to be held at 20,000 feet before being cleared for the final descent and landing it could remain at that altitude for at least an hour. It is most unlikely that final clearance to land would be delayed for so long, but even if this occurred and 5,000 lbs. of fuel was used, there would still be 4,000 lbs. of fuel left for the final descent and approach, landing and taxying. This would provide for an ample margin for two missed approaches. In calculating the amount of fuel available at the end of the flight it has been assumed that 1,500 lbs. of fuel was used in supplying the power needed to combat severe icing for a period of 20 minutes during the descent from optimum cruising altitude.

During the approach to land it is particularly important to have the turbo-jet engines at the approach idling setting, i.e. running fast enough to permit the regaining of full thrust with no appreciable delay so that the aeroplane can be readily accelerated and climbed away in the event of a missed approach or a balked landing. In the case of the aeroplane described in paragraph 1 all four engines are kept running at about 7,000 r.p.m. during the critical stage of the approach prior to touch down and air brakes used for keeping the forward speed in check. The engines are not completely throttled back until the pilot is satisfied that a safe landing can be made and the aeroplane is then brought to rest by the use of the wheel brakes. An auxiliary braking device such as a tail parachute would only be used if the pilot is unable to stop within the limits of the runway for some reason such as failure of the brakes, ice on the runway surface, a particularly low air density or lack of head wind. As the aeroplane rolls to the end of the runway it is normal practice to stop the two inner engines and to taxi to the unloading ramp using the outer engines only.

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