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The Design of High-Speed Military Airplanes

CLARENCE L. JOHNSON*
Lockheed Aircraft Corporation

INTRODUCTION

THE DESIGN of present military airplanes is changing so fast that any discussion of the subject is likely to be very far behind the latest trends by the time it is published. At the beginning of the war this was particularly true. It seemed that in a period of a few weeks many factors which should have been apparent in military designs made themselves known. The lack of armor, fuel tank protection and ample armament required hasty revision of many outstanding types. After a short while, the air forces of the major military powers could be evaluated in terms of their outstanding shortcomings or merits.

The success of Great Britain's eight-gun fighter and power turrets was one of the dominating factors in turning back Hitler's attacks last fall. The foresight of the British in providing such fundamentally sound design elements cannot be too highly praised.

Perhaps the outstanding features of the German air force were its great use of the dive bomber, the highly coordinated tactical coordination between the air forces and ground troops and its successful use of fuel injection engines and protected fuel tanks.

As the war developed, it became apparent that our own air force had called the turn very successfullly with its development of the long-range four-engined bomber, which had been greatly criticized in Europe, the turbo supercharger, and its prize bomb sight. While all countries had in some measure at least experimented with most of the above features, and in some cases had carried the respective developments (such as dive bombing) to high degrees of perfection, it is believed that the items indicated above were the outstanding elements in the air forces of the countries named from a point of view of technical development.

When the early war experience showed up the shortcomings of many service airplanes in armor, tank protection and armament, a great hue and cry was raised in the United States bemoaning the fact that our aircraft were so far behind the European types in these factors. Properly analyzing the facts in the case, however, shows that, with the exceptions noted above, all of the major air forces were very nearly on a par in being caught without proper protection and hitting power.

In this paper, the discussion will be limited to a discussion of design trends of the high-speed military fighter, although many of the statements made apply equally well to all types of high-speed airplanes. In considering the fighter airplane, its basic purpose in intercepting and shooting down bombers must be considered. The success of the fighter in stopping daylight raids has been well known, but developments in tactics of night bombing have made very difficult the problems of night interception and fighting. A few simple figures can be used to point out some difficulties which are encountered when it is desired to stop a bombing raid.

A modern bomber flying 300 m.p.h. at 25,000 feet can stop both engines, feather the propellers and glide practically noiselessly for a distance of 45 miles before obtaining an altitude of 5000 feet, eleven minutes after starting its glide. This gives the bomber an excellent chance for surprise raids, particularly at night when they cannot be seen. Naturally, the organization of ground forces, black-outs and various defense means are being developed to overcome the temporary advantage of the bomber, but the technical problems involved are very great. Considering the fact that our present bomber flying at high altitude with full power can add 100 m.p.h. to its speed in a shallow dive of only $5^1/_2$ degrees, it can be seen that sustained high speeds for long distances are obtainable when starting from high altitude. The new bombers of even cleaner aerodynamic design, having high speeds approaching 400 m.p.h., can also add 100 m.p.h. at about the same angle of power glide. Starting at 30,000 feet in such a glide, the bomber covers 50 miles in a period of six minutes while still having an altitude of 10,000 feet at the end of this time.

A pursuit plane ready to take to the air five minutes after the bombing plane has been sighted must have tremendous performance to climb to altitude and catch the bomber at any point on its attack. Under conditions of this nature, a speed advantage of 50 m.p.h. seems to be the absolute minimum acceptable for the fighter airplane over the bomber.

One of the obvious answers to such difficulties, of course, is the continual patrol of fighter squadrons over all vulnerable points at all times of the day and night. Naturally, the number of aircraft required for such patrol becomes very large.

FACTORS EFFECTING DESIGN

The hardest problem which the designer of military airplanes must face is the proper evaluation of these

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* Chief Research Engineer.

fundamental factors in their relative importance, one to the other:

(a) Performance
(b) Armament
(c) Ease of production
(d) Maneuverability
(e) Time required for development
(f) Flight qualities
(g) Cost

All aircraft design is made up of compromises between these considerations and the success of the basic design depends on which of the above factors have been favored without too great a loss in the other items. The element of time is of paramount importance under wartime conditions because the manufacturer, or, more properly, the nation, cannot afford to gamble too far on new and untried design features for fear that trouble experienced in their development may make his airplane obsolete and waste his production facilities at a time when the greatest output is required. It is better to have 1000 four-hundred m.p.h. airplanes in service than to have the finest four hundred and fifty m.p.h. design in the world on paper struggling with problems of design and production. Only after sound fundamental research and the highest type of engineering can the manufacturer afford to use some of the newer developments now on the horizon of progress.

Performance

Of the various items of airplane performance, the most important for the pursuit or interceptor type is speed. Present tendencies in the war indicate that high speed should be obtained at as high an altitude as possible. At the time of this writing, service pursuit craft now being used have high speeds of 330 to 390 m.p.h. between 15,000 and 23,000 feet. The types now in early production stages will reach 370 to 450 m.p.h. between 20,000 and 30,000 feet. In order to obtain such velocities, continual research must be directed on all phases of airplane engine and propeller design. Fig. 1 shows a comparison between the major performance characteristics of a typical present-day fighter and the improvements which might logically be expected for service airplanes in the near future.

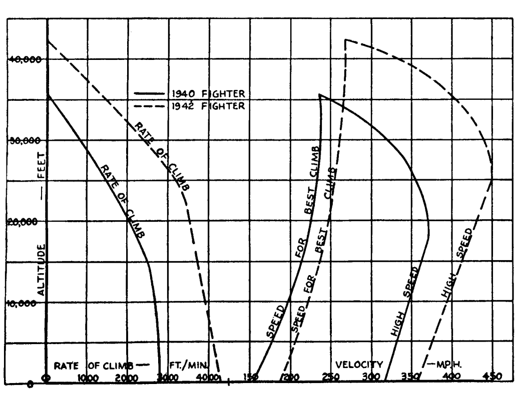

FIG. 1. Comparative performance of typical present fighter and probable 1942 type.

A rapid tendency toward higher wing loadings and lower power loadings can be noted, brought about by the desire for higher speed and greater load carrying ability of the fighter aircraft. Table 1 shows the effect of varying the wing loading only on the basic pursuit function of interception. A measure of the effectiveness of the fighter airplane is the distance it can cover in a given time from take-off, when considered for a certain operating altitude. For wing loading values now in sight, it will be seen that improved performance results with the higher wing loadings. The second factor which forces an increase in wing loading is the great increase in the weight of armament, armor and power plants required for keeping in line with the bomber development. The effect of wing loading on maneuverability seems to be gradually getting lost, due to the limitations of the pilot in withstanding the load factors so easy to develop at high speeds.

TABLE 1

All airplanes designed to carry same engines, armor, armament and crew. Gross weights vary to account for difference in wing and tail weight. Stability is constant.

Wing Loading	Time to 20,000 Ft.	Max. Speed, 20,000 Ft.	Distance from Take-off Point after 30 Minutes (20,000-Ft. Alt.)
30 lbs./sq.ft.	6.15 min.	400 m.p.h.	180 miles
45 lbs./sq.ft.	5.88 min.	425 m.p.h.	192 miles
60 lbs./sq.ft.	5.92 min.	445 m.p.h.	202 miles

Drag

The relation of airplane drag and thrust horsepower for airplanes in the 400 m.p.h. class require that extremely careful attention be given to the reduction of air resistance if the airplane size and power are to remain within the bounds of practicality.

The designer must continually attempt to make the smallest possible airplane for a given power and be sure that the drag of every element is as low as can be obtained without sacrificing stability, control or maximum lift. Figs. 2 and 3 show the energy breakdown for a typical modern fighter airplane in the higher performance brackets. The drag of the various elements of the airplane has been reduced greatly from values in existence several years ago. There is still a possibility of a substantial reduction in the skin frictional resistance, roughness and cooling drag. By using airfoils with shapes which extend the laminar flow area the drag can be reduced considerably, but these wing sec-

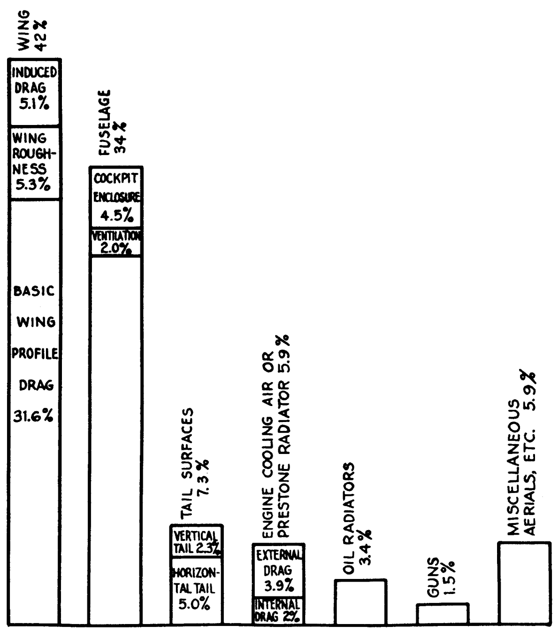

FIG. 2. Drag breakdown for a typical single engine fighter airplane having performance shown in Fig. 1. Total airplane drag = 100%. Total thrust power at high speed = 1041 hp. (see Fig. 3).

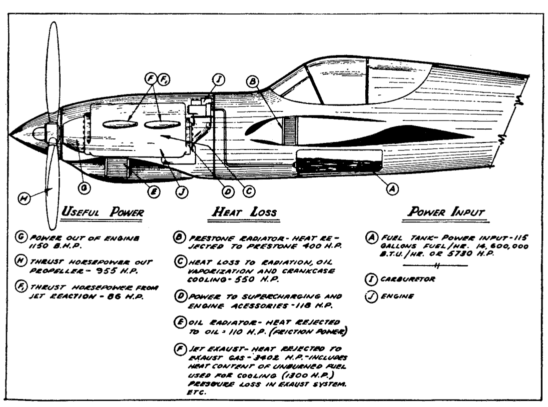

FIG. 3. Energy balance for typical military engine—operating at maximum power output.

tions must be considered from the point of view of manufacturing difficulties, maximum lift and the effect of roughness which is inevitably encountered in service when flying off rocky fields or through hail storms. There is an undeveloped field requiring much additional research on this problem which seems to show much promise.

There has been little change in the heat rejection for cooling of our modern engines for several years. As engine powers increase and operating altitudes go up, the difficulties of providing sufficient cooling assume great proportions. While the projected area of modern engines has decreased, the size of the radiators required for cooling has increased to the point where the design of a modern military fighter attains the condition where practically all equipment items and structure must be developed around the power plant. Even though the projected area of liquid-cooled engines has been held down very well for the power obtained, the fuselage size encountered in the installations of such engines is generally disappointing to everyone concerned because of the problem of installation of superchargers, intercoolers, oil radiators, Prestone radiators and landing gear wheels of a size to take the weight of the engine involved.

The classic argument of the lower drag of the liquid-cooled engine *versus* the air-cooled type for a given power output seems no nearer solution now than it ever has been. The designers of the liquid-cooled engines enjoy drawing pictures of their liquid-cooled engines with fine pointed noses and faired shapes, forgetting to look back a few feet on the airplane and finding under the fuselage, or in the wings, the same type of air entrance that must be used for cooling the air-cooled engine. There is no theoretical reason and little practical evidence to show that lower drag per horsepower can be obtained with a liquid-cooled installation than can be obtained with the air-cooled type. In making a large number of comparative designs, it has also been noted that very little difference in the projected area or fuselage drag results for the two installations. As regards compressibility effects on cowling of the air-cooled type, it is as easy to avoid critical pressure distributions on a cowling nose as it is on a radiator duct.

When considering the drag of the single engine fighter airplane, the remarkable aerodynamic cleanliness of the present type can be shown by comparison with an equivalent flat plate area. The total drag for such an airplane at any given speed is no more than that of a flat plate 22 inches square. The poor designs, however, run up to twice this drag figure. A good twin-engine fighter can be represented in drag by a flat plate 27 inches square.

WEIGHT

It is very distressing to the designer, the manufacturer, the Air Force, and finally to the tax payer, that the trend in military aircraft design is toward higher weight, greater complication and great complexity. It has often been stated that designs should be simplified, weights reduced and the design considered primarily from a manufacturing point of view. Serious efforts have been made by all parties concerned to try to bring about such a trend, but it has been impossible to eliminate any of the fixed equipment or power plant items to obtain greater simplicity. A second best airplane cannot be tolerated in actual combat. Any means of transportation having a speed of 400 m.p.h. is inevitably complicated.

It is interesting to make a weight breakdown of a typical modern pursuit airplane. The percentage of weight over which the airplane designer has control is only 40 per cent of the airplane gross weight. Twenty-eight per cent of the airplane gross weight consists of stressed material working to a very high unit stress under the design load factors (which are of the nature of 12). The remaining weight is made up of power plant and propeller, radio, instruments, tires, wheels, armament, fuel, oil and miscellaneous equipment. These are all items over which the airplane designer has no weight control. Figs. 4 and 5 illustrate typical breakdowns.

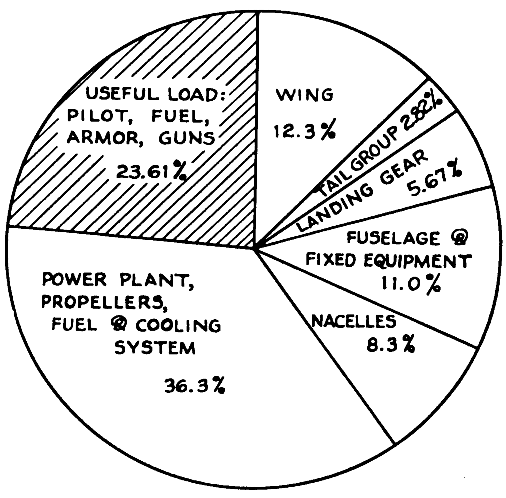

FIG. 4. Gross weight breakdown of two-engine fighter.

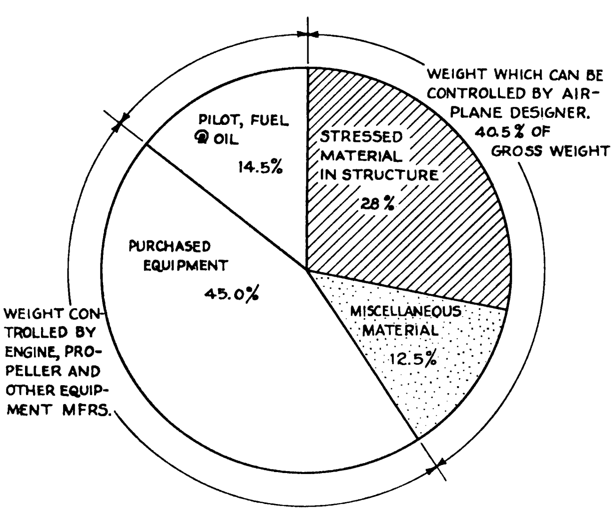

FIG. 5. Gross weight breakdown of two-engine fighter, showing percentage of weight within designer's control.

As airplane speeds increase, the percentage of weight in the power plant increases also. Developments in the present war have shown the need for increased equipment rather than a reduction of what is now used. It can be seen that future military airplanes tend to become larger and more expensive as the performance is pushed up.

ENGINES

The modern high altitude military engine is a marvelous machine when compared to other types of power generating equipment. Restricted in size, weight, fuel consumption and cooling, it represents the most highly developed single unit of the airplane. In order to visualize the thermodynamic cycle and obtain an energy breakdown for a modern power plant, Fig. 3 has been prepared. The energy input at maximum power output at altitude for an engine of approximately 1150 hp. amounts to 115 gallons of fuel per hour. The total energy of the fuel input amounts to 5730 hp. Of this total power supply, a large percentage must be rejected for cooling in order to maintain satisfactory engine stresses. An additional amount is required for supercharging, cooling the oil, etc., as shown. A substantial amount of heat is rejected by radiation and oil vaporization on the bottom of the pistons. This loss amounts to more heat than is carried away by the liquid coolant or from the finned cylinders. The largest source of energy loss is in the exhaust. At maximum power, the fuel-air ratio required to limit detonation is substantially higher than the theoretical ratio for maximum power. The excess fuel provided for this condition is present in the exhaust in the partially burned state and is normally wasted. The exhaust gas leaving the cylinders has a temperature of roughly 1700°F., and the cracking pressure of exhaust valves allows the gas to escape at pressures around 70 to 90 lbs./sq.in. From these figures, the tremendous power loss can be understood.

A part of this power can be regained by the use of jet exhausts or a turbo supercharger, but at the present state of development the recovery percentage has been very low. A great deal of research is being directed toward finding better ways for regaining this power. The exhaust energy can be used not only by kinetic means, but the heat energy can be applied to steam systems for power development. As speeds increase and propulsive efficiency decreases due to compressibility effects, it is not out of the realm of possibility to consider engines which furnish their power for take-off and climb to a propeller which can be feathered for level flight and, in the latter condition, the total engine power output being used by highly developed jets for propulsion.

In order to maintain its power output at altitude, the engine is supercharged one of several ways. The most usual type of supercharger consists in a centrifugal blower geared directly to the engine with a fixed gear ratio. This same unit has been developed whereby a gear shift has been incorporated and two gear ratios are available, one for low altitude and one for high. The most advanced type of gear-driven supercharger incorporates two superchargers with an intercooling stage between the two. The third means of maintaining altitude power involves the use of the turbo supercharger. This unit is driven by exhaust gas and maintains high power to higher altitudes than any other type of supercharging in use. Fig. 7 shows a comparison between the powers available at altitude when the

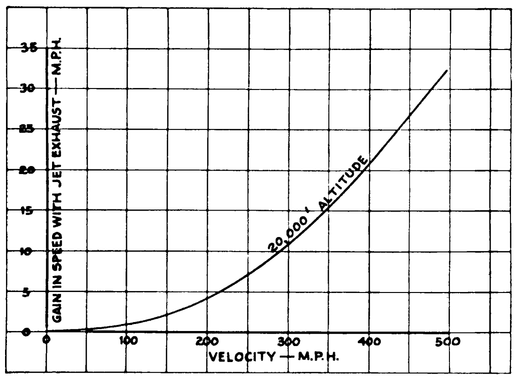

FIG. 6. Increase in speed available from simple jet reaction at 20,000 feet altitude.

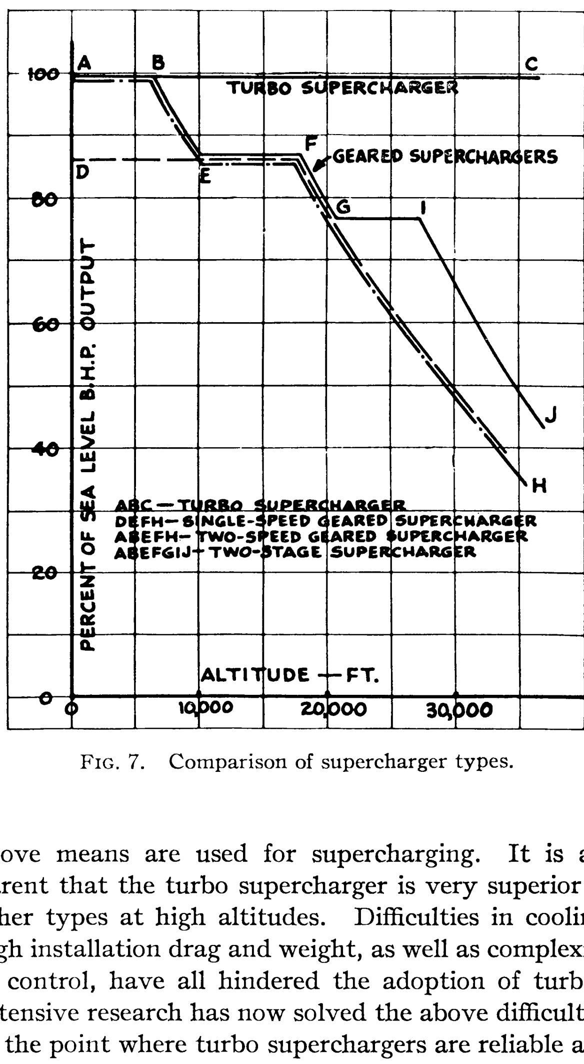

FIG. 7. Comparison of supercharger types.

above means are used for supercharging. It is apparent that the turbo supercharger is very superior to other types at high altitudes. Difficulties in cooling, high installation drag and weight, as well as complexity in control, have all hindered the adoption of turbos. Intensive research has now solved the above difficulties to the point where turbo superchargers are reliable and easily handled items of equipment. The United States Army Air Corps deserves great credit for their fostering this fine development.

Most superchargers now in use in military aircraft are of the single- and two-speed type. The closest approach to overall turbo performances, however, can be obtained using the two-speed, two-stage supercharger engine equipped with jet exhaust. Inasmuch as the turbo derives its power from the engine exhaust by maintaining a constant back pressure in the exhaust system it has not as yet been found possible to obtain any substantial jet reaction in combination with the turbo supercharger at high altitude. At low altitudes there is no reason why jet reaction cannot be obtained with the turbo operating at partial capacity. Fig. 8 shows the comparative net thrust horsepower available in an airplane equipped with the turbo supercharger in one case and the two-stage engine with jet exhaust in the other. For altitudes above approximately 20,000 feet the turbo supercharger has better performance than its rival, but at lower altitudes, present indications are that the two-stage engine with jets is superior. (See Fig. 6.)

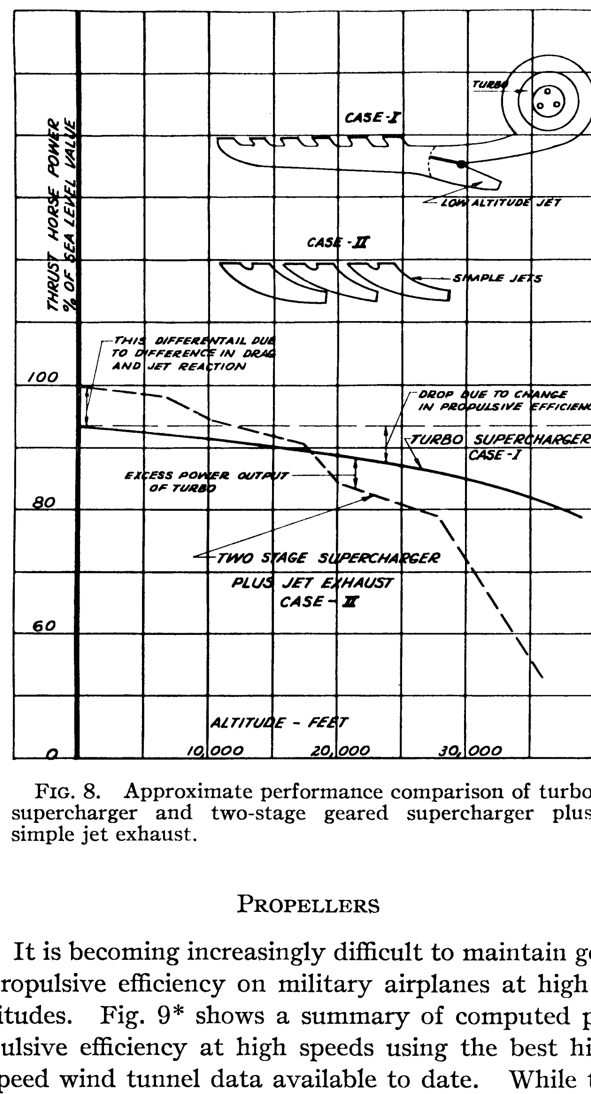

FIG. 8. Approximate performance comparison of turbo supercharger and two-stage geared supercharger plus simple jet exhaust.

PROPELLERS

It is becoming increasingly difficult to maintain good propulsive efficiency on military airplanes at high altitudes. Fig. 9* shows a summary of computed propulsive efficiency at high speeds using the best high-speed wind tunnel data available to date. While this information seems to be very pessimistic, the trend established is, no doubt, correct. The curves shown are derived from wind tunnel tests on airfoil sections subjected to two dimensional flow. It is known that compressibility effects are less for flow in three dimensions similar to that which exists around propeller tips

* *Propeller Design Problems of High Speed Airplanes*, H. B. Dickinson, presented at the Airplane Design session, Ninth Annual Meeting, I.Ae.S., New York, January 31, 1941.

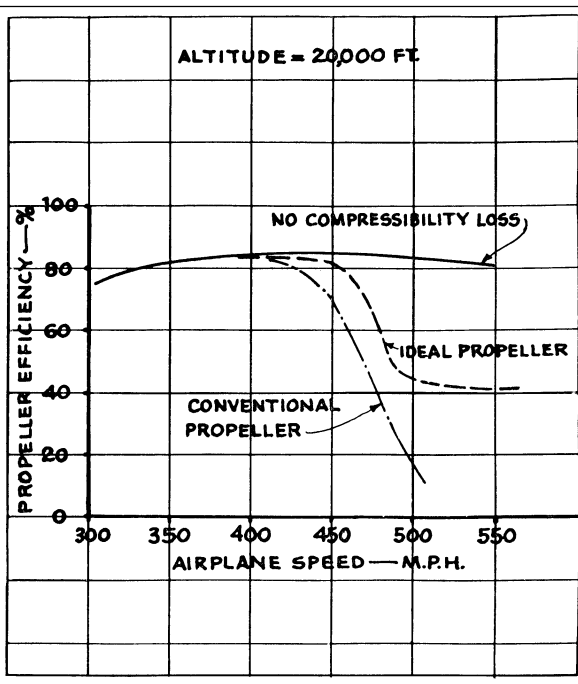

FIG. 9. Computed variation of propeller efficiency with velocity.

and perhaps over considerable sections of the rest of the propeller. Research on propellers operating at very high forward speeds is entirely lacking in spite of the continual requests on the part of the industry for such information from the various Government Agencies equipped to obtain this vital information.

There is increasing need for a gear shift to allow two engine-propeller gear ratios in order to maintain proper tip speeds. The requirements for high blade area necessitates the use of an increased number of propeller blades so the four-bladed propeller is coming into use. Tests run on counter-rotating propellers have not indicated substantial gains for the dual rotation propeller compared to the single rotation unit of the same blade area. The use of pusher propellers, desirable for many points of view when considering drag, is being retarded by practical considerations such as the problem of landing gear wheels throwing rocks back into the blades, flutter conditions developing when wing flaps are extended, pilot escape in emergency and the problem of ground clearance as it affects landing gear length.

At the speeds encountered with fighter airplanes, the compressibility shock wave tends to develop as quickly at the propeller hub where the sections are thicker as it does at the propeller tip where the speeds are greater. To avoid this condition, propeller hub fairings have been developed. These have not as yet proved very satisfactory except for cooling in radial engines, as the practical limitations on the chord of the fairings prevent airfoil sections of the proper thickness ratio from being used. The problem of pitch distribution also must be carefully investigated before any substantial gain in speed will result from their use. Several tests on conventional cuffs have indicated a definite speed loss when placed on an airplane in the higher performance brackets. We can expect to see a definite trend toward wider propeller blades, perhaps obtaining the aspect ratios used on the high-speed Supermarine racers in the Schneider Cup Races several years ago. The application of wide blades or wide fairings near the hub will be limited by the mechanical capabilities of the mechanisms used to obtain variable blade angles and feathering. Considerable study must be directed toward obtaining propeller sections allowing higher critical compressibility speeds.

Armament

The modern fighter airplane must carry a substantial weight of armament to be effective. The number of guns carried and the weight of bullets or shells fired must be carefully evaluated. For instance, should the fighter airplane be equipped with ten 0.30 caliber guns or an equivalent weight but a smaller number of 0.50 caliber guns? Are one cannon and four machine guns as effective as eight machine guns? This type of controversy requires the careful consideration of the airplane designer throughout the design of the airplane. The continual struggle being waged between the armament protection on one side and the increasing caliber of guns on the other makes for continual change in the design as the war progresses. It is possible to protect the pilot and vital sections of the aircraft by means of armor plate between $1/4$ and $1/2$ inch in thickness from the fire of 0.30 caliber guns. Likewise, bulletproof glass $1\,1/2$ inches thick can protect the pilot's face. The use of the 0.50 caliber gun and cannon, however, makes such protection entirely inadequate. Fuel and oil tanks can be protected by the use of rubber composition tanks, but again the cannon changes this condition.

When considering the two-place fighter, flexible guns mounted in a power turret are usually considered. At the speeds of our modern airplanes, it is impossible for a man to swing large guns against an airstream, so electrical or hydraulic means must be used to relieve him of this duty. The installation of power turrets on a high-speed airplane is very difficult, particularly when airplanes pressurized for high altitude are considered.

Structure

One of the amazing things about the modern high-speed airplane is the fact that they are so strong with so many cut-outs made in the basic structure to account for the installation of radiators, guns, landing lights, landing gear, flaps, fuel tanks, intercoolers and a host of other miscellaneous items. Fig. 10 shows a typical example of how much space there is left for structure in the wing of a fighter after providing for the above items. The difficulty of providing rigidity for flutter prevention is easily visualized.

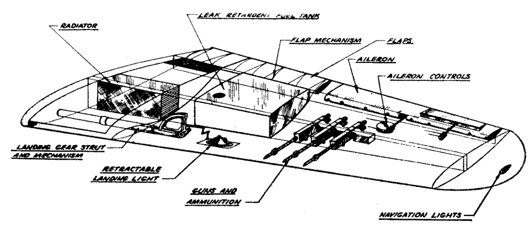

Fig. 10. Typical example of items enclosed by wing structure on a fighter airplane.

One of the outstanding problems of structural design at the present time is the provision of adequate strength to take the loads developed in high-speed dives where large portions of the airplane are subjected to compressibility phenomena. In many cases the normal air loads existing are quadrupled when the shock wave forms over some portion of the surface.

Increased landing speeds, greater sinking velocities and heavier engine installations add to the problems of the structural engineer who is caught by increasing loads on one side and the requirements for thinner wing sections and smaller fuselages on the other.

One Engine or Two?

The relative advantages of the twin engine airplane *versus* the single engine type can be summed up rather easily by making two comparisons. For the first case consider two airplanes, one a single engine type with an engine of a given power and the other a twin engine type having two power plants identical to the single engine airplane. The twin engine airplane will weigh from 75 to 85 per cent more than the single engine type and therefore will have the advantage in drag per horsepower and power loading. For this condition the relative advantages of the two airplanes are indicated below.

Twin Engine Airplane Advantages

1. Higher speed.
2. Greater range at given speed.
3. Safety with one engine out of commission.
4. Ability to use safely higher wing loadings.
5. Higher rate of climb.
6. Higher ceiling.
7. Generally better pilot vision (new types of single engine airplanes may eliminate this advantage).

Single Engine Airplane Advantages

1. Cheaper to build.
2. Easier to service.
3. Greater maneuverability due to smaller size.

The second comparison representing an opposite extreme develops when a single engine airplane having a total installed power equal to the twin engine airplane is considered. In this case, the single engine airplane will weigh about 80 per cent as much as the twin engine type, will have higher performance, greater range, higher ceiling and climb than the twin engine type. It will be almost as expensive to build, however, and as difficult to maintain as the twin engine airplane of the same total power. The above conclusions assume equal excellence of design. The twin engine type will naturally maintain a higher safety, resulting in smaller losses during wartime use.

It is not logical to expect that at equal stages of development we shall see designs developed along the line where the total power of the twin engine airplane is no greater than that of a single engine type, so the comparison between the one- and two-engine fighter will always lie between case 1 and case 2 above. This is true up to the point where the twin engine fighter obtains such velocities that it encounters a large drag increase due to compressibility effects. The single engine type can then overtake its rival in spite of the power advantage of the two-engine type. When this condition prevails, the single engine type is subjected to the same drag increase as its rival. Further speed comparisons cannot be made until some answer is found to the basic problem common to both types. Previous experience has always shown that there is a way to remove seemingly insuperable barriers when the proper time comes.

Compressibility Effects

Throughout this paper, casual references to compressibility effects have been made. Without going into any details, the term will be explained briefly. Whenever the flow speed of the air around any part of the airplane equals the speed of sound, that is, the rate of propagation of a pressure wave in air, a shock wave is formed causing an entirely different type of air flow from the type encountered at subsonic velocities. When such a shock wave forms, a considerable amount of energy is dissipated as heat and the drag of the body increases considerably. Naturally, the first part of the airplane to encounter compressibility effects is the propeller, which is subjected to the rotational velocity as well as the forward speed of the airplane. A continual struggle is being engaged in by the aerodynamicists to find shapes which keep the critical velocity of all the component parts of the airplane as high as possible. The limiting speed of many of our present wing sections, for instance, is about 450 m.p.h. We have every reason to expect that newer developments will put this speed higher. It so happens that every development which tends to increase the compressibility speed also reduces the drag at lower velocities, so definite benefits will be obtained for all performance conditions.

Pilot Limitations

With the airplane advancing technically at such a rapid rate, consideration must be given to the pilot

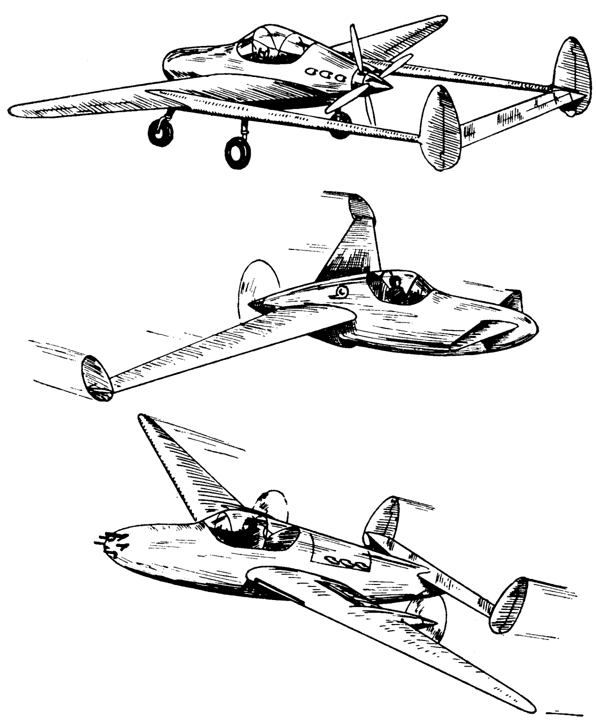

Fig. 11. Probable future types of fighter airplanes.

and his physical limitations. At high speeds in straight flight, of course, there is absolutely no problem involved, but the moment that a turn is made, high accelerations placed on the pilot cause him considerable discomfort and result in rapid fatigue. With the critical altitude of the airplane being increased, the problem of the pressure comfort of the pilot is an important one.

Using pure oxygen, a pilot is fairly efficient at altitudes of 30,000 feet. Above this height, his reflexes become very slow and his strength reduces rapidly. During tests on the Lockheed twin engine interceptor airplane it has been found advisable to have the pilot saturate himself with oxygen on the ground before making rapid climbs to high altitudes. This procedure is hardly suitable for pursuit operation in war time, so it seems that the development of either pressure cabin airplanes or pressurized suits will be necessary to allow the pilot to obtain the maximum performance from the more advanced type of airplanes. This further complication adds to all the difficulties outlined above in this paper and makes the airplane more vulnerable, heavier and more expensive.

It is known that when a pilot is in a prone condition he can withstand approximately twice the acceleration that he can while sitting upright and some study has been made on designs in which the prone position is used for fighting.

The value of increased performance of fighter airplanes must be carefully evaluated against pilot reaction and his physical well-being.

Conclusions

Fig. 11 shows several promising trends in airplane design which bear out the discussion given above. In spite of the fact that the pusher propeller has many problems, it seems fairly certain on the basis of present data that it should be used. Before they can be widely used, the problem of the pilot leaving the airplane with parachute must be considered. With a rotating propeller behind him, it is absolutely impossible to leave the airplane safely, so means for stopping it in a given position, dropping it or throwing the pilot clear, must be incorporated. Fig. 12 shows variation of engine installation weight with critical altitude for maximum power. (Including propellers, accessories, cooling and oiling system, motor mounts, cowling, etc.) The Lockheed P-38, front view, is shown in Fig. 13. Note the small projected area of the different component parts.

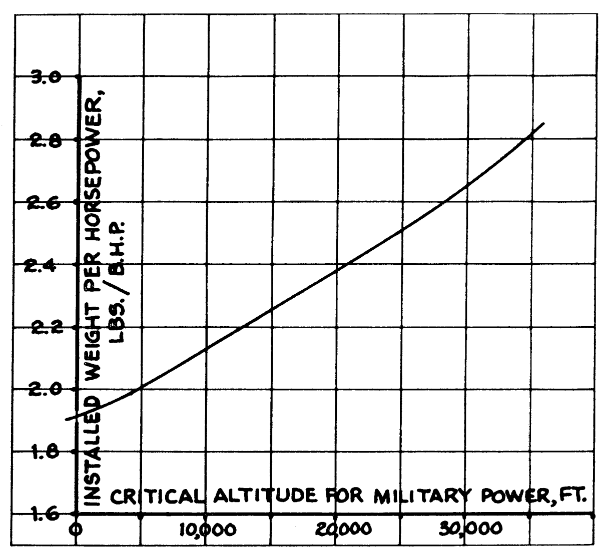

Fig. 12.

Fig. 13.

The military fighter airplane is inevitably becoming larger, more powerful, more costly and complicated. It is useless to discuss limitations to speed, as all such previous discussions have proved in error to date. The most useful outcome from the vast amount of research being put on military types will be its application to commercial models when the war is over. Under the pressure of present times, development is being carried on which, under peace-time conditions, would not have been available for years.