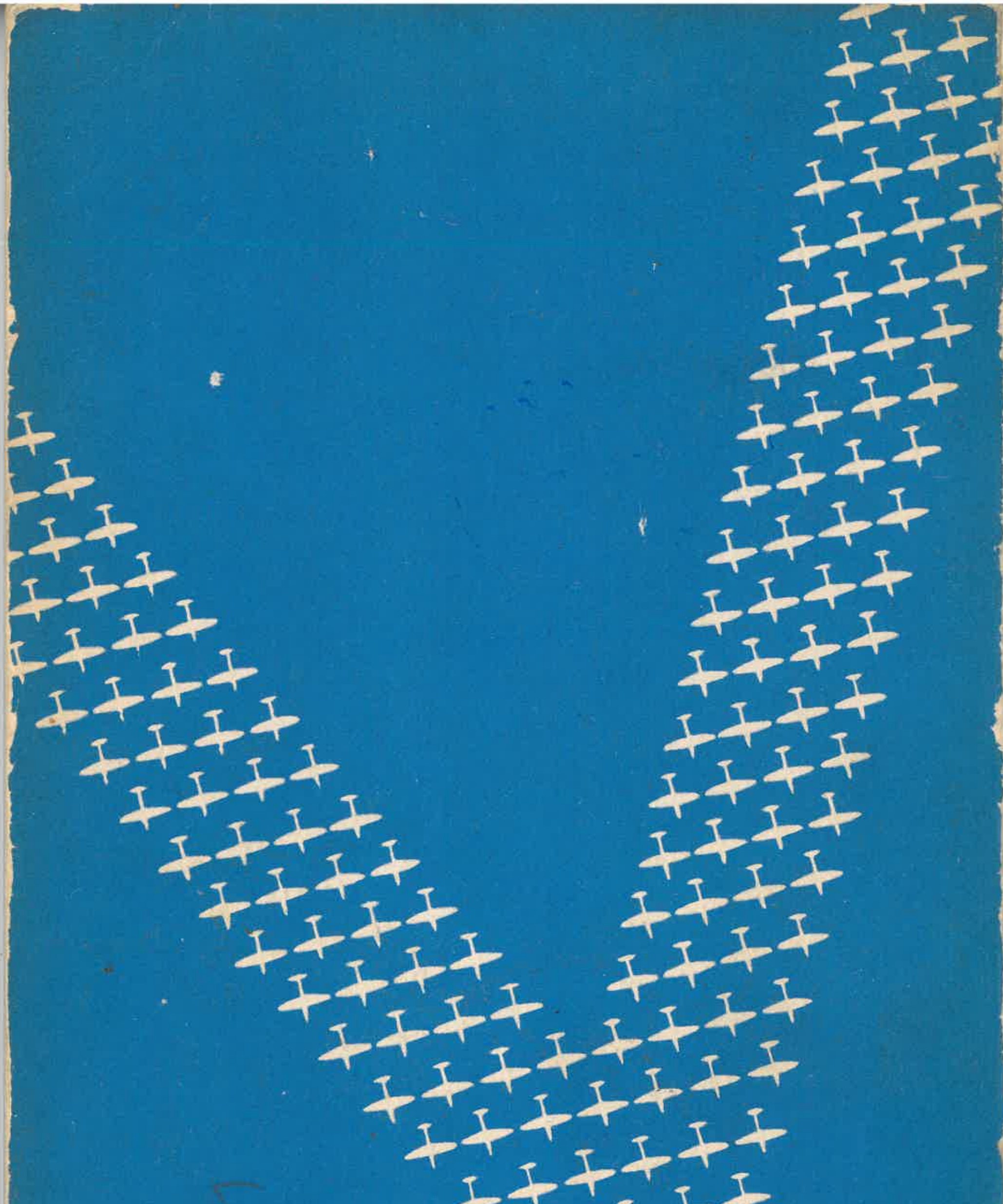


AIRPLANE POWER

with special reference to engines and altitudes

Although this book was written primarily for the thousands of G. M. employes who have turned their hands and their skills to the manufacture of aviation equipment, we feel that it should be of interest to various groups of the American public including:

—men in the air service, or who plan to join the air forces.

—their families and their friends.

—journalists, war reporters, aviation editors and radio commentators.

—and, last but not least, the coming generation of young Americans who are destined to live in a world that will be vastly changed through wartime innovations applicable to peacetime aviation!

→ *See Page 4* ←

Engine Design as Related to

AIRPLANE POWER

With particular reference to performance at varying altitudes

PUBLISHED BY

GENERAL MOTORS

DETROIT MICHIGAN

In the following pages we will try to take you behind the scenes and acquaint you with a few of the problems involved in the design of military aircraft—with special reference to engines and supercharging equipment. ★

★

The discussions are confined to problems that are common to all types of aircraft engines—*irrespective of whether they are liquid-cooled or air-cooled.*

IMPORTANT FACTS

that are not generally understood

1. **It takes less power to fly at high altitudes than at low altitudes . . . . *See Page 53***

2. **The performance characteristics of an airplane are determined by many factors other than the engine itself . . . . *See Page 5***

3. **The same basic engine may be used in planes of widely varying characteristics of performance . *See Page 49***

4. **A certain American engine, used in one of the fastest, highest altitude fighters ever produced in this or any other country is also used in low altitude fighters and ground attack planes designed for fighting at 10,000 feet and under! . . . . *See Page 68***

5. **The difference is in the design of the plane and the supercharging equipment . . . . . . *See Page 54***

6. **A given type of supercharger may provide outstanding performance in a certain altitude range, but may be at a decided disadvantage at other altitudes. *See Page 51***

7. **There is no such thing as an all-purpose plane and probably never will be . . . . *See Page 67***

8. **Airplane design, like all engineering design, is a compromise . . . . *See Page 10***

9. **In one important respect the American philosophy of war plane design is exactly opposite to that of a certain enemy nation . . . . *See Page 70***

AUTHORS' NOTATION

While the information upon which this book is based was gathered from General Motors Research Specialists and Aircraft Engineers, the actual writing has been done by a non-technical group with the aim of presenting the subject in a simple and understandable fashion—the way the engineers talk at lunch time, rather than in the manner of a scientific discourse.

We have tried to avoid the more unfamiliar technical terms.★

Certain minor factors have been ignored where they did not seem to have a vital bearing on the broader aspects.

In the interest of simplicity and to speed the flow of the text, we have been dangerously sparing in the use of the phrase *"other variables remaining constant."*

Furthermore, we have had to omit certain data in conformance with the necessities of military censorship.

Such compromises have naturally worked at cross purposes to the attainment of scientific adequacy.

★ **Perhaps it might be well to glance over the glossary on pages 73 to 80 before reading the book.**

"An Engine is Just a Package of Horsepower"

One of the questions most frequently asked aircraft engine designers is:

"How fast is your engine?"

When the engineer answers, with meticulous accuracy:

"Three thousand revolutions per minute"— or whatever it happens to be—the average questioner looks puzzled and insists:

"Yes but HOW FAST is it?"

Whereupon the engineer may quite properly ask:

"What do you mean HOW FAST?"

"I mean, how fast will it drive a plane?"

Then complications really set in, because the engineer could truthfully answer:

"That depends on what type of plane it's to be used in and how fast the plane is designed to go."

The primary responsibility of the engine designer is to supply a given amount of dependable horsepower in the smallest, lightest, most compact package that he is able to produce—and while he works in closest cooperation with those responsible for the design of the overall plane, the use that is to be made of the horsepower is determined by the designer of the complete airplane.

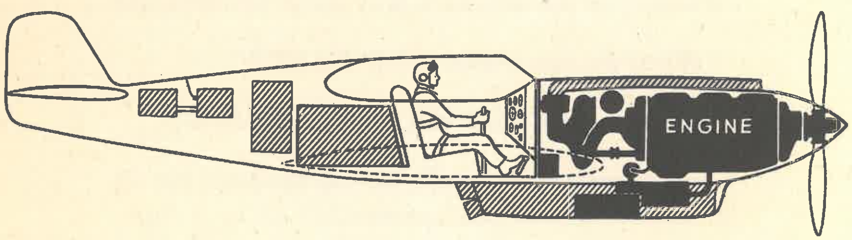
The same basic engine may be adapted to use in different types of planes having widely varying characteristics as regards speed, rate of climb, altitude performance, cruising range and load carrying ability. And even in a given type of plane the performance characteristics may be widely varied through the use of different super-

charging equipment or by varying the weight of the plane, or by using a different type of propeller.

The designer of military planes may make certain sacrifices in equipment, fuel capacity, armor, etc., in order to reduce weight and get extra performance.

Or he may go in the opposite direction and sacrifice some performance so as to obtain extra capacity for gasoline, guns, ammunition, etc.

The route taken by the plane designer depends on what the armed services have asked him to build—and that in turn depends on the needs of military strategy.



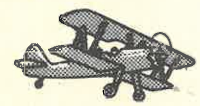
With reference to the above and as bearing on some of the discussions to follow, perhaps it may clarify things to observe that the word "ENGINE" does not mean the same thing as "POWER PLANT"

In motor car parlance the two terms are used rather loosely—*as being more or less synonymous*. But in aviation the term "*Power Plant*" or "*Power Plant Installation*" implies not only the engine with its usual accessories, but the cooling apparatus, the exhaust system, the supercharging equipment, the propeller, the propeller drive gears, pitch control, etc. —*in fact everything that has any relation to the propulsion mechanism.*

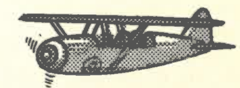
In this book, however, the important distinction will be between what is known as a "Sea Level Engine" and engines with special auxiliary equipment designed to improve performance at high altitudes.

DIVERSIFIED NEEDS

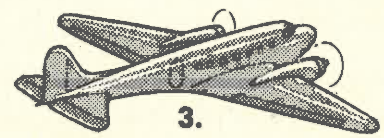
AERIAL WARFARE, just as in the case of naval warfare, demands a wide variety of equipment to meet the diversified requirements of our fighting forces. In a broad general sense, military planes may be grouped under five classifications based on the jobs that they are designed to do:

1. 

TRAINERS

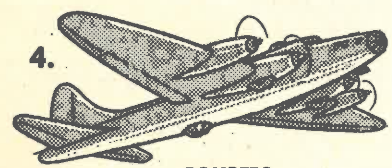
2. 

OBSERVATION

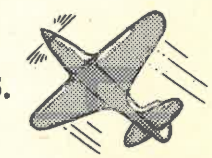


3. TRANSPORTATION and CARGO

See marked paragraphs Page 68

4. 

BOMBERS

5. 

FIGHTERS

The uses of the first three are obvious, whereas the duties of Bomber and Fighter planes may not be so generally understood.

Bombers are essentially attack planes, although their attack may be for the purpose of repulsing an enemy thrust. Their mission is to drop their bombs on the target and return safely to their operating bases. The arms that they carry are primarily for their own defense.

The work of the fighter plane is very different and its duties have become more diversified as the war goes on.

It must protect our own bombers from enemy attack, and it must seek out and destroy enemy bombers and enemy fighters.

The fighter plane has become increasingly important as an attack instrument. It is being used more and more extensively by both sides to collaborate with infantry and tank operations and for light bombing operations in instances where its speed and maneuverability permit a lightning thrust not possible with the slower and less agile bombers.

As the fire power of the fighter has been increased, it has become an effective weapon against enemy tanks and other motorized units.

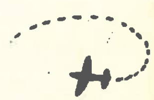
Because of their growing importance and the diversified requirements that must be reckoned with in their design, it seems appropriate to use the fighter plane as a basis for illustrating some of the problems confronting aircraft engineers.

To fulfill its wide variety of functions with maximum effectiveness, the *ideal fighter plane* would have the following fundamental characteristics:

1. It would be much faster than a bomber—and should be as fast or faster than enemy fighters.

2. It would be able to take off quickly from limited areas and climb rapidly to the maximum altitude at which it is to fight.

3. It would be extremely maneuverable as compared to a bomber—as good or better than enemy fighters.



4. It would be small so as to present the least possible target and to make the fighter pilot feel that the plane is "a part of him", so to speak.

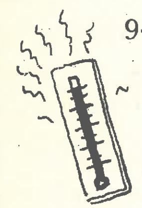
5. It must be built strong and sturdy in order to withstand the terrific strains and stresses imposed by power dives and emergency maneuvers.

6. It must have enough fuel carrying capacity to "take it there and bring it back".

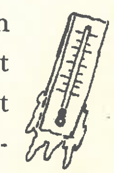
7. It must carry adequate fire power and ample ammunition.

But—

8. Weight must be kept within reasonable limits so as not to penalize the performance characteristics.



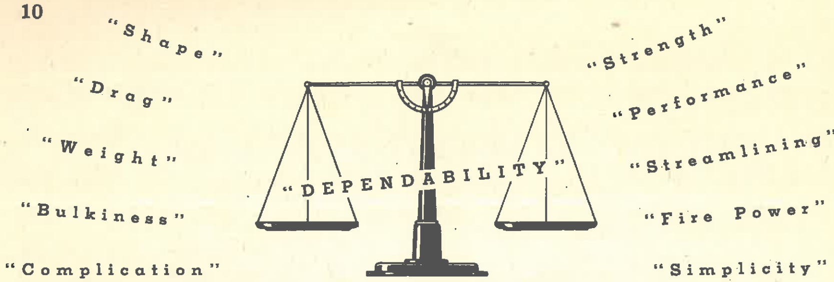
9. The design would provide for the ready installation of special equipment to meet the requirements of all climatic conditions from the heat of the equator to the sub-zero temperatures of the Arctic—the dust of the desert or the dampness of the English Channel, and such special equipment should be readily detachable so that maximum performance can be obtained in any specific area.



And last, but not least—

10. A fighter plane should be equipped with adequate protection for the pilot including armor, complete instrumentation, "self-sealing" gas tanks, etc.

While this viewpoint is not reflected in the design of certain enemy aircraft, it is a definite part of the engineering philosophy of our American plane designers and our military strategists who believe that *the life of a pilot is more important than the saving of a few pounds of material—also that our pilots will be more effective as fighting men if they are better protected and provided with adequate instrumentation.*



The Necessity for Compromise

THE IDEAL FIGHTER plane would have all the qualities and characteristics suggested on the preceding pages—but since the full attainment of certain of these things works at cross-purposes to the attainment of other equally desirable things, the aircraft engineer must continually weigh the advantages of various designs and equipment against the disadvantages—in an effort to get the best balanced combination for the particular job or jobs for which the particular type of plane is to be used.

Natural laws and physical limitations simply do not permit the designers to do everything they would like to do.

Engineering is an eternal compromise.
The laws of nature make it so.

This is true in all fields of engineering, but it is doubly true in aviation because of the intricate and vast new set of problems created by the third dimensional aspects.

Take for example the aircraft engine in comparison with the automobile engine:—

An automobile engine remains on an approximately "even keel", but the airplane zooms up at steep angles, dives, banks sharply for turns, and frequently flies upside down! To keep the engine operating properly in all possible flight positions, special features are required in the design of the carburetor, the fuel system, the oil system and the engine itself.

In contrast to the automobile engine, the engine for a fighter plane may, within a few minutes time, be hurtled through space—from desert temperatures of 130 degrees above zero to altitudes where the temperature is 67 degrees below zero—from sea level air up into air that has only 1/3 the density of sea level air.

The power output of an aircraft engine for military use must be far greater than that of an automobile engine. In fact, it is not unusual for one cylinder in an aircraft engine to develop as much power as an entire automobile engine. The extra power must be attained through refinements and ingenuity in design and choice of materials, with maximum dependability *but a minimum increase in size and weight.*

Not only must every surplus ounce of weight be kept out, but the designer must concern himself with size and bulk in order that the engine may be fitted into the trim outlines of a fighter plane.

Thus, the problems of mechanical design must always be weighed against aerodynamic considerations and these problems become increasingly difficult when we get into the special equipment required to maintain performance at high altitudes.

It is rather generally recognized that a plane designed for low altitude performance will not be effective at high altitudes—but it is not so generally recognized that the opposite is also true:

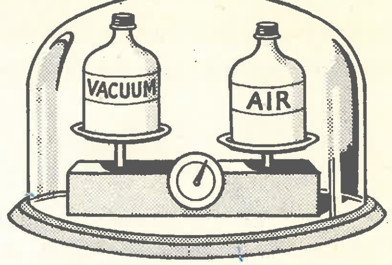
Equipment suitable for adequate performance at high altitudes is at a distinct disadvantage when operating at low altitudes.

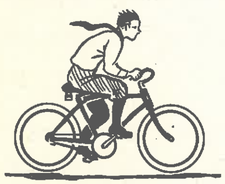
The reasons for this will be brought out in a later chapter.

But first, let us briefly review a few fundamentals of engine design as a background for discussing the problems of altitude performance.

In a casual, offhand sort of way we think of air as having no substance or weight—although we know that this is not true.

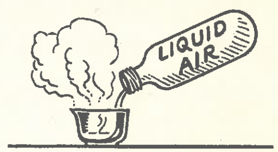
If we set up, on a very delicate scale, two identical containers, as shown, it would be possible to weigh air.

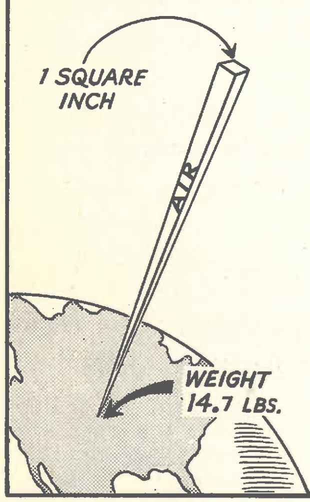




If air did not have any substance, you would not feel its force when you move through it..You wouldn't be able to feel the wind when it blows against you--in fact, there wouldn't be any wind if air did not have substance.

The weight of air depends on the degree to which it is compressed. If you compress it enough (and keep it plenty cold) it will turn into a liquid that resembles water.





The air enveloping the earth's surface is heavy enough to exert a pressure of about 14.7 pounds per square inch at sea level -- or expressing it a different way, a column of air one inch square extending from the surface of the earth clear on up into the sky as far as there is any air, would weigh 14.7 pounds.

The "ABCs" of Combustion

A GASOLINE ENGINE gets its power from the burning of a mixture of gasoline and air. This burning or combustion is a chemical process in which the gasoline vapor combines with the oxygen in the air to produce heat energy.

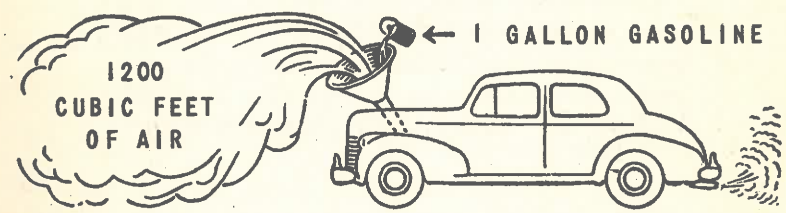
As automobile owners we are accustomed to think of gasoline as being the more important of the two. That's only natural because we have to pay for it and it's more trouble to get it. But the air is just as important as the gasoline—in fact from the viewpoint of the engine designer it's even more important because getting the proper quantity of air into the cylinders is much harder than getting the right quantity of gasoline into the cylinders.

Gasoline is compact and easy to handle whereas air is just the opposite.

As indicated in the sketch at the bottom of the page, an automobile engine uses about 1,200 cubic feet of air to burn a gallon of gasoline.

That, however, is not a very good way to express it because it's the *WEIGHT* of air that's the really important thing—or rather the *weight* of the *Oxygen* in the air.

Assuming perfect combustion, it takes about 14 pounds of air to provide enough oxygen to burn 1 pound of gasoline, although in actual practice we get better fuel economy if we use up to around 17 pounds of air to a pound of gasoline.



In ordinary everyday language, we say that the piston "sucks" air into the cylinder but that is not a very good way to express it. What really happens is that the pressure of the outside atmosphere *PUSHES* the air into the cylinder. In other words, when the piston descends on its intake stroke a partial vacuum is created within the cylinder and the outside air rushes in to fill it.

The weight of air that gets into the cylinder depends on the pressure of the outside air—or what we call "*ATMOSPHERIC PRESSURE*".

As indicated on page 12, the Atmospheric Pressure at sea level is 14.7 pounds per square inch and the ordinary automobile engine is designed to operate at around that pressure.

If the pressure were greater than that—say about 18 pounds to the square inch—it would be possible to get more horsepower with the same size engine. Conversely, if the atmospheric pressure were only 10 or 12 pounds to the square inch, your automobile engine would develop correspondingly less power.

This is all by way of emphasizing that, other things being the same, the horsepower of an engine depends on the weight of air that we are able to pass through it.

Thus, the designing engineer looks upon the gas engine as though it were an air pump. Within certain limits, the greater the "pumping capacity" the greater will be the horsepower.

Except where otherwise stated, the general term *"horsepower" or "H.P."* as used in this book refers to "BRAKE HORSEPOWER", *i.e. the NET power output available for driving the propeller mechanism*—as distinguished from the *TOTAL or "INDICATED HORSEPOWER".*

See Horsepower Definitions on Pages 76, 77, 78.

OTHER THINGS BEING THE SAME, the power developed by a gasoline engine depends on the quantity of air that we are able to pass through it—or what we might call its "pumping capacity" which depends mainly on three factors:—

1. **SIZE of the engine, *i. e., number of cylinders and the bore and stroke or "displacement".***
2. **SPEED at which it runs efficiently, *i. e., revolutions per minute.***
3. **PRESSURE or density of the air that is taken into the cylinders.**

1 When we increase the SIZE we increase the weight, and this, of course, is undesirable if the engine is to be used in an airplane—where everything is done to keep weight at a minimum.

2 Offhand one would think that the power could be increased by merely running the engine at HIGHER SPEEDS, because the pumping action of the pistons increases with speed. Unfortunately, however, this is true *only within certain limits* because the restriction to free air flow through the manifolds and valve passages increases as the velocity of flow increases.

Thus we do not get as much air into the cylinders as we would like to get and we soon reach an engine speed beyond which the power falls off instead of increasing.

In the case of aircraft engines there are other and more important considerations that make it undesirable to depend on extra speed as a means of increasing the power:

Aircraft engines, generally speaking, are much larger than automobile engines and because of the size of the reciprocating parts it is desirable to avoid high speeds in order to insure maximum reliability.

Furthermore, the speed of the engine must be kept in reasonable relation to the speed at which the propeller is to run; otherwise it would be necessary to use bigger reduction gears—which

would take up too much space and add to weight. ★

These considerations make it desirable to keep the speed of aircraft engines within reasonable limits.

3 Next we come to the possibility of boosting the power by increasing the density of the air *before it is supplied to the cylinders.* In other words, if instead of using the outside air just as it is, we could compress it to a greater density, we would then be able to get more of it into the cylinders *thus providing greater power without increasing the size of the engine and without having to run it at undesirable speeds.*

This can be accomplished through the use of a blower mechanism or pressure fan connected with the air-fuel intake system.

Such a mechanism is called a "*SUPERCHARGER*". A supercharger boosts the pumping capacity of an engine and enables us to get the power equivalent of a bigger engine, but with a much less increase in weight than if we were to increase the bore and stroke or the number of cylinders.

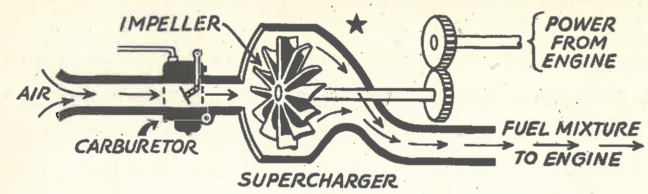
Practically every aircraft engine for combat service is equipped with some form of supercharger. It may be what is known as a "*SEA LEVEL SUPERCHARGER*"—or one of the several types of "*ALTITUDE SUPERCHARGERS*".

First let us consider the *SEA LEVEL SUPERCHARGER* which is the simplest of all types being of the same general design as the superchargers used to step up the power of racing cars.

A proper understanding of it will make it easier to understand the more complicated types of altitude superchargers which will be discussed later on.

★ For efficient operation the rotational speed of the propeller must be limited to a rate that will prevent the tips from travelling at a speed approaching the speed of sound. *See Page 80.*

THE SEA LEVEL SUPERCHARGER



THE SEA LEVEL SUPERCHARGER or "*GROUND BOOST BLOWER*", as it is sometimes called, consists of a pressure fan connected to the air intake or fuel system and driven from the engine's crankshaft through a train of gears as indicated in the accompanying sketch. ★

The capacity of the pump depends on the *size* of the impeller and the *speed* at which it is driven.

Other things remaining the same, the gain in engine power will be proportionate to the increased pressure. But, unfortunately, the "other things" do not remain the same and there are limits beyond which it is inadvisable to go.

Compressing air raises its temperature—the greater the degree of compression, the greater the rise in temperature.

This is objectionable for several reasons. For one thing, it reduces the efficiency of the supercharger because when the air gets too hot it's hard to manage. It tries to expand and this increases the work or power required to compress it and push it into the cylinders.

Furthermore, any gas engine works better *if the intake mixture is kept cool*, and when the mixture is allowed to get too hot we get into serious difficulties resulting from disorderly combustion which not only causes loss of power but is very injurious to the engine.

A gas engine to be efficient must burn its fuel in a smooth, even and orderly fashion. But when the fuel mixture is allowed to reach

★ See Page 79 for a more accurate drawing of the impeller construction.

excessive temperatures, we get what you might call "wildcat explosions" which pound the working parts to destruction. *See "Pre-ignition" and "Detonation"—Page 75.*

It should be borne in mind that the rise in temperature resulting from the supercharging operation is added to the heat generated by the compression within the cylinders of the engine itself. So the combined compression must be kept within proper limits in relation to the anti-knock qualities or "*OCTANE RATINGS*" of the fuels which will be available for use in actual service.

For purposes of illustration, let us assume a Sea Level Supercharger that has been designed with sufficient capacity to raise the pressure of sea level air from 14.7 pounds per square inch up to around 20 pounds per square inch.

With such equipment we are able to get about 40% more power than if we depended on atmospheric pressure alone.

As a specific example, this means that a 1,000 horsepower Sea Level Supercharged Engine would be of the same piston displacement as a 710 H.P. engine which had no supercharger.

But right here it should be pointed out that it is not just a matter of adding a supercharger to a 710 H.P. engine—*because an engine that is to be equipped with a supercharger*

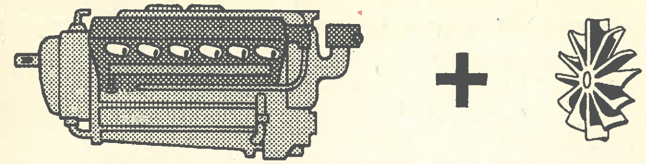
must be especially designed to stand the higher stresses and temperatures resulting from the extra power.

To raise a 710 H.P. engine up to a 1,000 H.P. output would mean a net increase of 290 H.P. (*710+290=1,000*).

Furthermore, it would take about 70 H.P. to run such a supercharger, so the total increase in H.P developed *within the engine* would have to be 290+70, or 360 H.P

In other words, in order to get a net increase of 290 H.P. we have to use a supercharger of sufficient capacity to add 360 H.P. which represents extra load that must be taken into account in the design.

TYPICAL 1000 H.P. SEA LEVEL ENGINE



Without any supercharger, engine would deliver only

710 H.P.

Supercharger adds a net gain of

290 H.P.★

Engine weighs much less than if we tried to get the same power by increasing the piston displacement, but it must be designed to withstand the extra strains and stresses and greater temperatures resulting from the higher pressures.

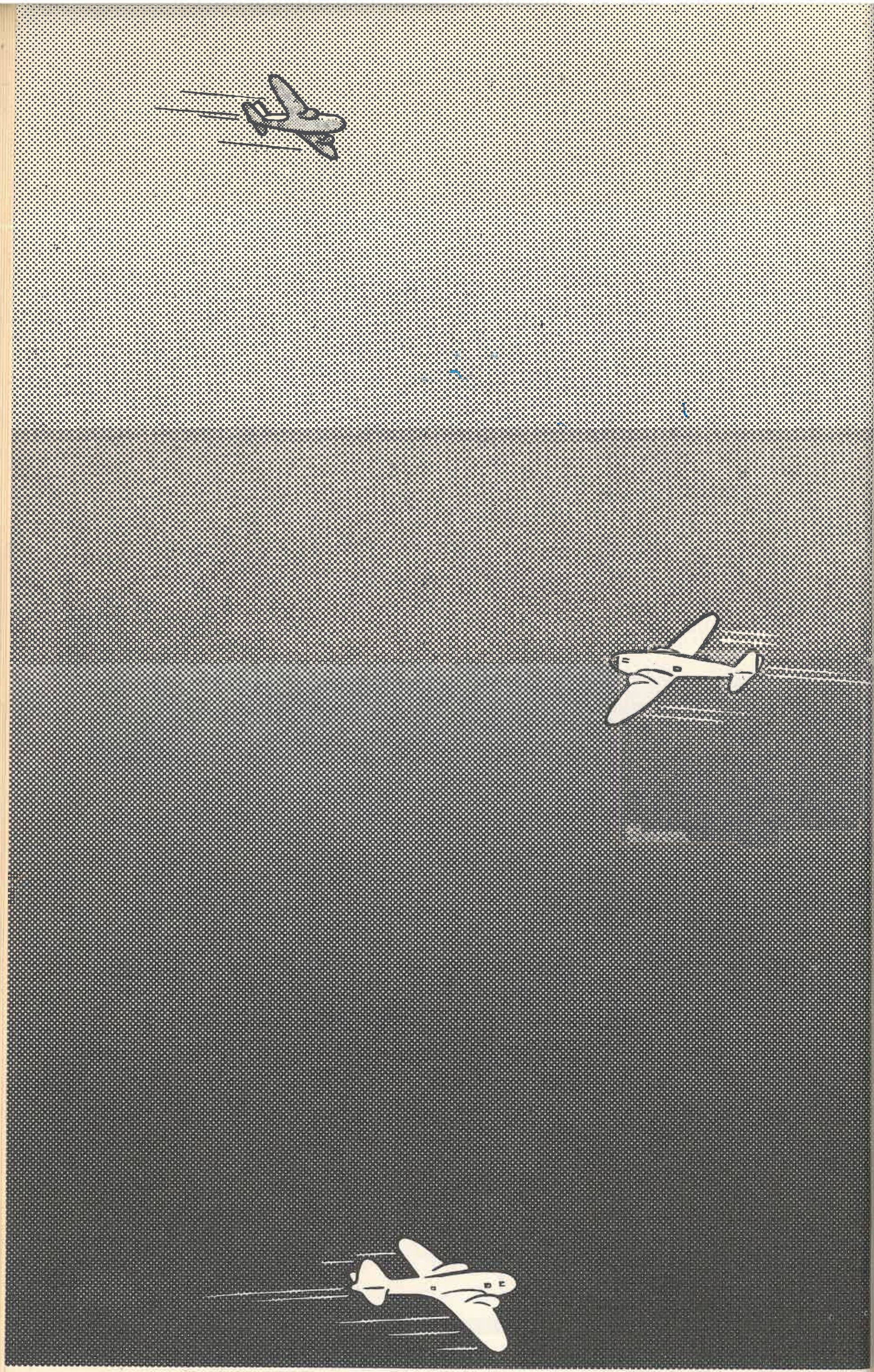
★As explained on preceding page, supercharger really adds 360 Horsepower, but since it takes about 70 H. P. just to run it, the net gain in power output is only 290. See "HORSEPOWER" page 76.

The use of a SEA LEVEL SUPERCHARGER provides a highly effective means of increasing the power of an engine with a minimum increase in weight.

An engine with such equipment is called a *SEA LEVEL ENGINE.*

Because of its high ratio of horsepower to weight, and because of its simplicity and compactness, the Sea Level Engine fills an important need in certain types of fighter planes.

But as will be explained in the following pages, the SEA LEVEL ENGINE is not suited to high altitude operations.



"We Live at the Bottom of a Vast Sea of AIR."

ENGINES *and* ALTITUDES

IN THE PRECEDING PAGES we have been talking in terms of operating conditions *at* or *near* the surface of the earth where the atmospheric pressure is around 14.7 pounds per square inch and the air is relatively dense.

As we climb above the surface of the earth the atmospheric pressure declines and the density of the air decreases.

This is not without its advantages:

From an aerodynamic standpoint, the "thinness" of the air offers less resistance, so it's easier to propel a plane through it—*just as it's easier to swim in water than it would be to swim in molasses!*

(See pages 51, 53; also "Pitch Control," Page 79)

Furthermore, at high altitudes, the back pressure on the engine exhaust gases is reduced and the air at the higher altitudes is colder. These conditions, taken within themselves tend to increase the power output of the engine.

But as against these ADvantages
there is a very serious DISadvantage. ★

Because the air at higher altitudes weighs less per cubic foot, coupled with the fact that there is less pressure available for pushing it into the cylinders, the power of a gas engine declines in relation to altitude.

If, for example, you have ever driven your automobile up Pikes Peak, you would have noticed a decided loss of power as you climbed toward the top. Although your engine was getting the same *volume* of air, the *weight* was considerably less and so there was not enough oxygen to provide efficient combustion.

★ Not to mention certain minor problems: The lowered atmospheric pressure reduces the boiling point of gasoline so the fuel system has to be especially designed to avoid the dangers of "vapor lock." Also, since the rarefied air is not a good insulator, provision must be made to keep the electrical current from "*leaking out*" on its way to the spark plugs.

At the top of Pikes Peak, with its altitude of 14,000 feet, your engine would develop only about 6/10 as much power as at sea level. Thus an engine capable of delivering 100 H.P. at sea level would deliver only about 60 H.P. at the top of Pikes Peak.

The automobile designer doesn't have to worry much about this because the motor car is rarely called upon to operate at such altitudes. But to the aircraft engine designer the problem is an extremely important one because he must provide engines for use in power plants that will be capable of giving satisfactory performance at altitudes varying all the way from sea level to the stratosphere.

As indicated by the accompanying chart, this means variations in air density far beyond those experienced by the motorist in climbing up Pikes Peak.

At 20,000 feet, for example, a cubic foot of air weighs only about half as much as a cubic foot of sea level air. This means that if we are to get the same *weight* of air at 20,000 feet as at sea level, we would have to use twice as big a volume of the thinner air. And at 40,000 feet we would have to use four times as big a volume.

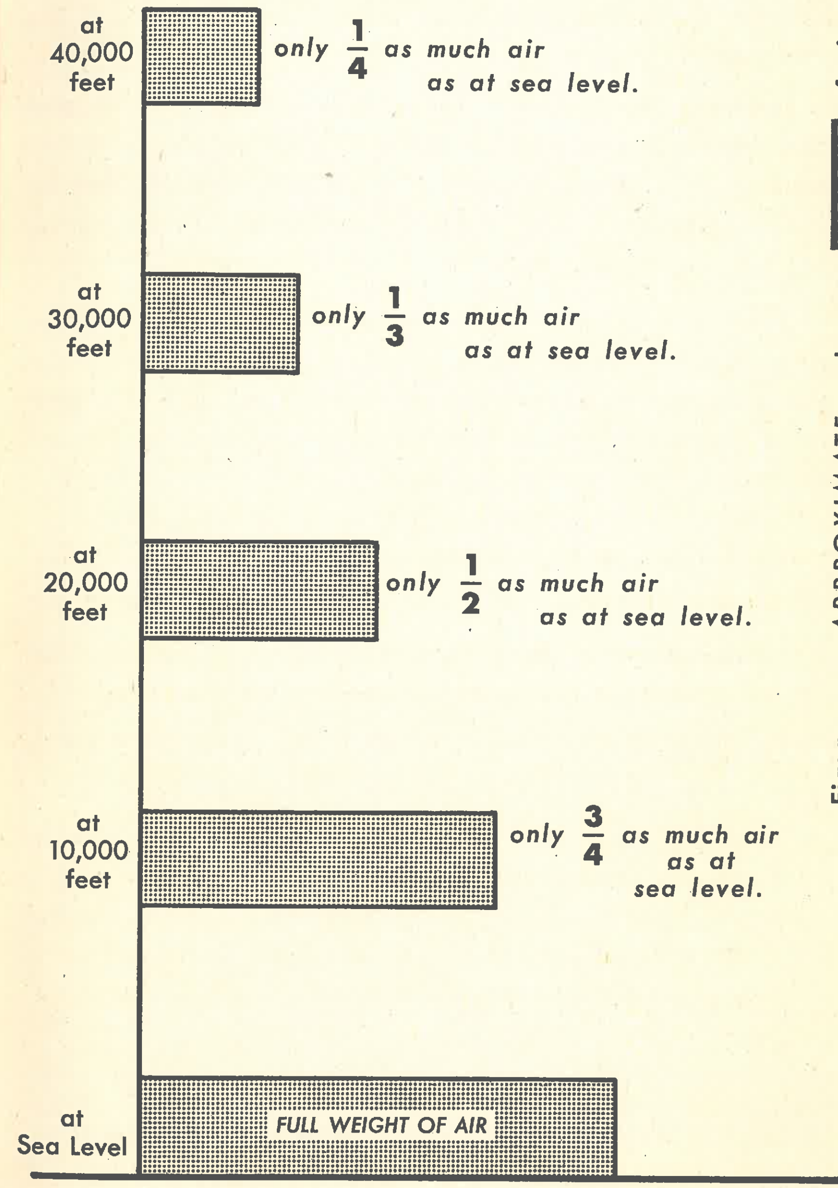
The sea level supercharger does not solve the problem for while it does provide an effective means for increasing the "*pumping capacity*" with a minimum increase in weight, an engine with such equipment is affected by changes in altitude in the same manner as an unsupercharged engine.

This is brought out in the chart on page 25.

UNLESS SOMETHING IS DONE

to offset decreasing density

ENGINE WOULD GET—



Figures are APPROXIMATE and mean WEIGHT of air.

The heavy curve shows the performance of the 1,000 H.P. sea level supercharged engine at varying altitudes and the dotted curve shows what the performance would be if the same engine were to be operated without any supercharger.

While the supercharged engine gives better performance at all altitudes, the improvement to all intents and purposes is a flat percentage.

Just as in the case of the ordinary automobile engine, each of these engines, at an altitude of 14,000 feet, will be able to deliver only about 6/10 as much power as at sea level. At 20,000 feet the power will be cut in half, and at 30,000 the engine will develop only 1/3 of its original power.★

The simple sea level supercharger enables us to get greater power from a given size engine and fills an important need in airplanes designed for low altitude fighting and ground attack operations, but such equipment is inadequate for use in planes designed for effective fighting above 10,000 feet.

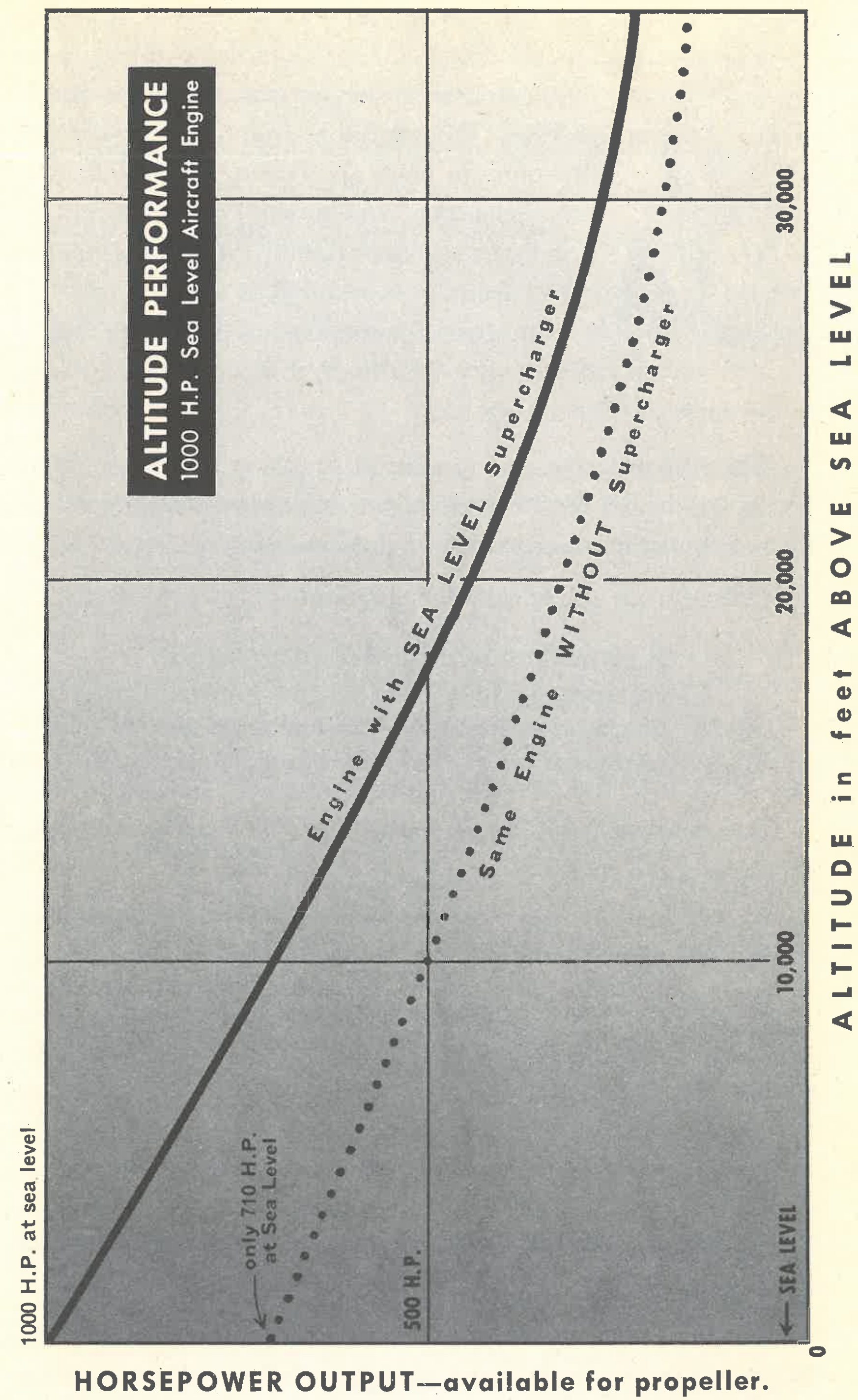
To provide sufficient power at the higher altitudes it is necessary to supply the engine with a greater volume of the lighter air.

Incidentally, it is interesting to note, by way of analogy, that what is true of a gasoline engine is also true of a human being.

The "human engine" gets its "fuel" from food. The food is "burned" or oxidized by the air taken in through the lungs.

When you drove your car to the top of Pikes Peak, not only was its engine affected by the thinness of the air, but you, as a "human engine" were similarly affected by the scarcity of oxygen. You found it necessary to breathe harder and deeper, particularly if you exerted yourself.

★ While the *total horsepower* developed within the engine declines in direct relation to the density of air the *net horsepower* output is affected to slightly greater degree. This is due to the fact that the power required to overcome internal friction remains practically constant. (See Page 77.)



The reserve capacity and flexibility of the human lungs make it possible, within certain limits, to compensate for the thinness of the air and get the necessary supply of oxygen by breathing in more air. It is nature's method of "supercharging" the human engine, enabling it to adapt itself to variations in altitude—*within certain limits.*

But since a gas engine has no such flexibility it cannot, within itself, compensate for changes in the density of the outside air.

Thus, in order to provide adequate power at higher flying levels, an aircraft engine must have special supercharging equipment designed to compensate for the thinning out of the air.

Offhand, one might raise the question:—

> ***"Why not put in a blower of sufficient capacity to take care of the highest altitudes that are to be encountered and let it go at that?"***

Unfortunately, the problem does not lend itself to any such simple solution.

It's not just a matter of providing enough power at the higher flying levels, but a matter of *avoiding too much power at the lower levels.*

If we were to compress the dense sea level air as much as we need to compress the thin air at high altitudes the engine would be dangerously overloaded. It is impossible to build an aircraft engine that could stand up and give dependable service under the high temperatures and high pressures that would result from the excessive amount of air going into the cylinders. *Furthermore, the extra power required to run such a supercharger would be a "dead load" when operating at low altitudes.*

The greater the capacity of the supercharging equipment, the better will be the performance at high altitudes, but since a plane

has got to take off from the surface of the earth and climb through low altitudes in order to reach the higher altitudes, provision must be made for slowing down the supercharger or reducing its effect in some way or another, when operating in the low altitude bands.

This, incidentally, is suggestive of the basic difference between a sea level supercharger and an altitude supercharger:

A sea level supercharger has no special controls or regulating devices—its capacity is determined on the basis of what the engine can safely stand at sea level—rather than on what it may need at higher altitudes.

But the capacity of an altitude supercharger is determined on the opposite basis—namely, on the basis of what is required at the higher altitudes, and then making some provision for protecting the engine at lower altitudes.

In theory, we might say that the ideal Altitude Supercharger would completely wipe out the variations in air density and thus provide the engine with the same weight of air—and hence full power—irrespective of altitude.

But this is true in theory only. It is almost true in the case of some superchargers. It is far from true in the case of others!

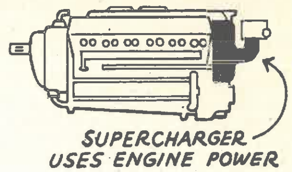
In actual practice it is necessary to compromise. The engineer is confronted with many conflicting considerations—not only as affecting the efficiency of the engine and its supercharging equipment—but as bearing on the over-all efficiency of the complete airplane and its effectiveness as a fighting tool.

This will become increasingly apparent when we begin analyzing the merits and demerits of various types of Altitude Superchargers in relation to the over-all problems of plane performance.

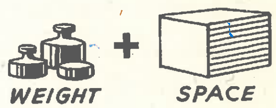
As a background for such discussions, we are summarizing some of these problems on the next page.

PROBLEMS TO BE RECKONED WITH

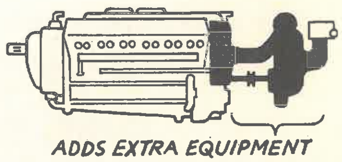
1 It takes a certain amount of power to run the supercharger and if this power is to be taken off of the engine crankshaft it is at the expense of the *net gain in horsepower.*



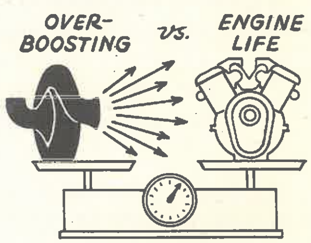
2 Since supercharging equipment adds weight and takes up space, the net gain in horsepower is not fully reflected in over-all plane performance.



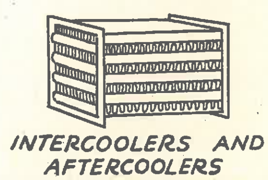
3 To be effective at different altitudes a supercharger must have speed changing devices or multiple stage compressors or both, and such things add further to weight, bulk and mechanical complication.



4 The degree of supercharging must be kept within limits to avoid the dangers of pre-ignition and detonation resulting from excessive pressures and temperatures. (See Page 17)



5 The heat resulting from the extra compression necessary at extreme altitudes is so great that special cooling apparatus must be used to reduce the temperature of the mixture which also adds to weight, bulk and complication. ★



★ **The special radiators used for this purpose are called "Intercoolers" or "Aftercoolers" depending on their location with reference to the carburetor.** ***See pages 44 and 46.***

Types of Altitude Superchargers

A PLANE EQUIPPED with only a Sea Level Supercharger is obviously unsuited for high altitude work and conversely, a plane with supercharging equipment suitable for high altitude operation will be at a distinct disadvantage in the low altitude bands because of the extra weight and size.

Thus the choice of supercharging equipment depends on the altitude "*bands*" within which the particular plane is designed to fight and that in turn depends on the needs of military strategy.

The diversified operations of our Air Forces have called for the development of a wide range of Altitude Superchargers.

Of the various types and combinations there are seven that stand out as having important differences:

1. **Single Stage with Only One Speed**
2. **Single Stage, Two Speeds with Mechanical Clutch**
3. **Single Stage with Variable Speed Hydraulic Clutch**
4. **Two Stage with Mechanical Clutch**
5. **Two Stage with Variable Speed Hydraulic Clutch**
6. **Two Stage, Variable Speed with Aftercooler**
7. **Turbo, Exhaust-Driven, with Intercooler**

In the following pages we will discuss each of these types individually and present some charts showing the variations in performance at different altitudes.

To keep our data comparable we will assume the same basic engine that was discussed on page 18. In other words, starting out with a 1,000 horsepower Sea Level Engine, we will show what happens when we equip it with the various types and combinations of altitude equipment.

The Total Horsepower developed *within the engine* will, in all cases, be kept within the safe limits for which the basic engine was designed. This means that any *extra horsepower* required to run the supercharger—*over and above that which was required to run the low*

capacity Sea Level Supercharger—will be at the expense of the *Net* horsepower output. ★

In other words, when we use more power to run the supercharger the maximum power output will be reduced by a corresponding amount—otherwise our engine would be overloaded.

Only the Net Horsepower will be shown on the charts. In other words, the curves will be plotted on the basis of the horsepower available for driving the propeller mechanism *after allowing for any extra power that may be required to run the supercharger—and always keeping within proper limits as regards mixture temperatures.*

On each curve we will indicate the "Critical Altitude" of the engine which is the point at which the power output begins to fall off in approximate relation to the decreasing density of the outside air. As will be noted from the charts, the Critical Altitudes vary widely—*depending on the type of supercharging equipment,* but in all cases we finally reach an altitude where the capacity of the supercharger will not be sufficient to provide the engine with full weight of air—*and even before that altitude is reached the extra heat resulting from the extra compression will tend to offset the full advantage.*

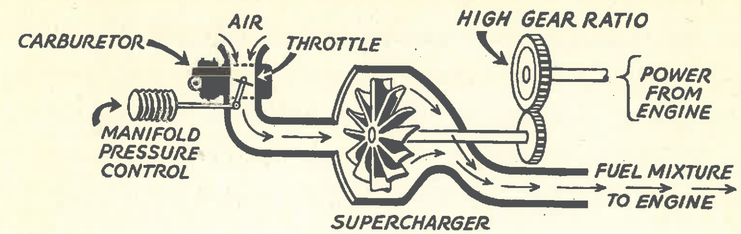
Needless to say, it has been necessary to indulge in some interpolation in the development of these curves and while the data are based on actual tests and practical experience the values are RELATIVE rather than ABSOLUTE, and the figures themselves should not be taken too literally.

For example, the Critical Altitude of an engine with a given type of supercharger might be varied considerably by using different gear ratios or speed controls.

★ An even 1,000 horsepower engine is used for reasons of simplicity. Multiply the horsepower figures by 2 and the curves will reflect the characteristics of a 2,000 H.P. engine. Or by merely eliminating the last cipher of each figure we can reduce the data to a percentage basis—applicable to engines of any horsepower.

TYPE 1 ALTITUDE SUPERCHARGER

SINGLE STAGE WITH ONLY ONE SPEED



THE SIMPLEST and easiest way to turn our SEA LEVEL ENGINE into an ALTITUDE ENGINE is to install a gear ratio that will drive the blower at a higher speed—*and then add a control device to curb the degree of supercharging at lower altitudes.*

Such a precaution is necessary in order to avoid what the engineers call "*OVERBOOSTING*" which means stressing the engine beyond its approved rating, and while a degree of "OVERBOOSTING" is sometimes indulged in to get extra power in case of emergencies, it is at the expense of dependability and long life. (*See "Rated Horsepower" page 78.*)

So in practically all altitude equipment, provision is made for protecting the engine against excessive pressures and dangerous temperatures by automatically controlling the effects of the supercharger *in relation to the density of the outside air.*

This is accomplished by means of a special control for the throttle valve in the supercharger air intake passage. When the valve is wide open the full compression capacity of the supercharger is utilized, but when the valve is partially closed the intake passage is restricted and the supercharger gets less volume of the outside air which has the effect of reducing its capacity.

The manifold pressure control is an automatic regulator which works on the principle of an Aneroid Barometer. In other words, it is actuated by changes in the pressure of the outside atmosphere. At high altitudes, where the full compression capacity is needed to

compensate for the lesser density of the outside air, the valve is kept wide open. But at lower altitudes where less compression is needed, the valve is partially closed.

The effect on the power output is shown graphically in the chart on the opposite page which shows the performance resulting from the use of a SINGLE STAGE, SINGLE SPEED ALTITUDE SUPERCHARGER in contrast to the performance of the 1,000 H.P. SEA LEVEL ENGINE discussed back on page 24.

In this example the gear ratio has been worked out to provide maximum power at an altitude of 18,000 feet where the air is only a little more than half as dense as at sea level.

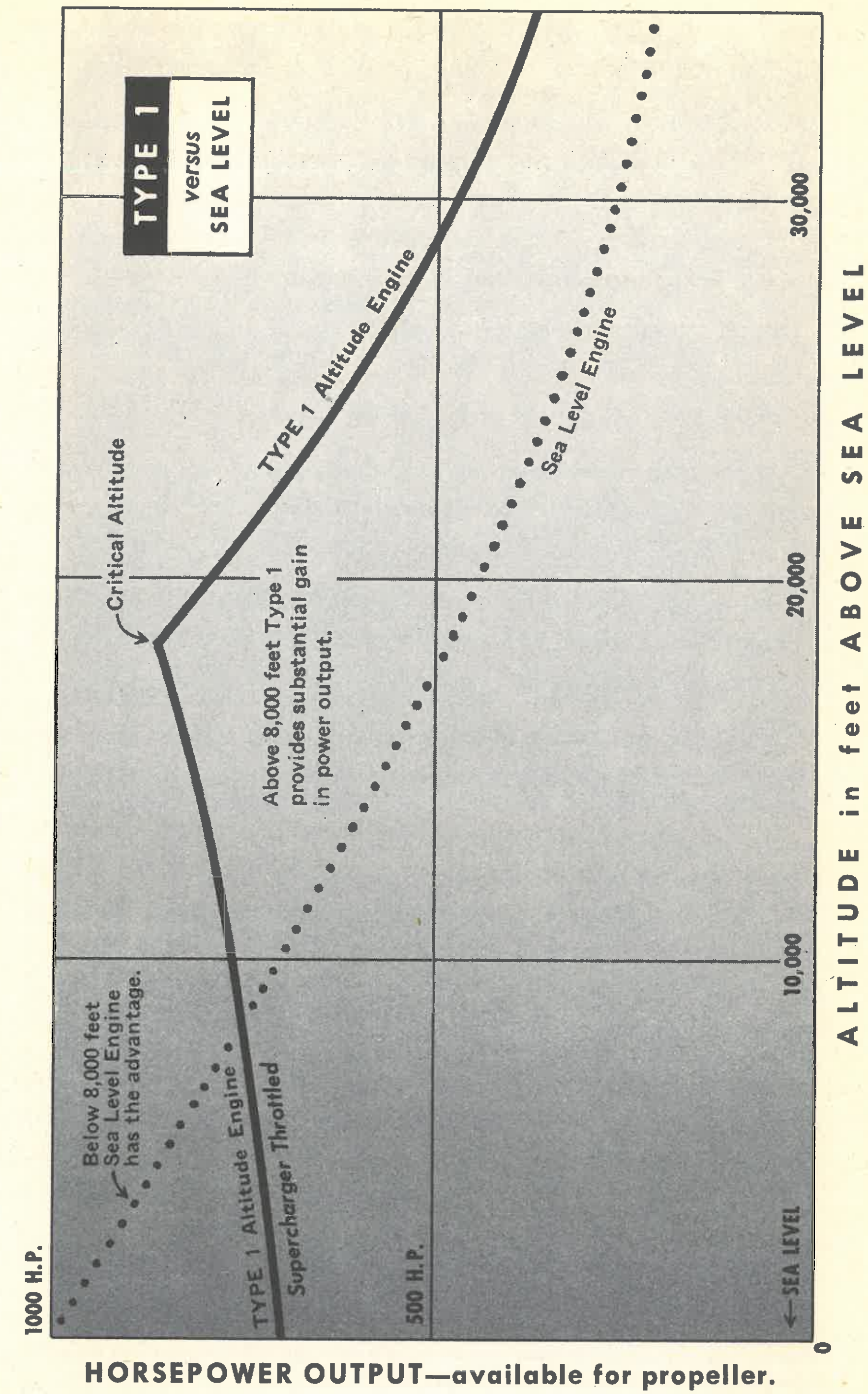
But when we increase the gear ratio of the supercharger enough to provide the full weight of air at that altitude, it requires an additional 120 horsepower to run it and this 120 H.P. is at the expense of the net horsepower output.★

Thus the power available for driving the propeller mechanism is limited to 880 H.P. which is obtained with wide open throttle at an altitude of 18,000 feet. This is the "CRITICAL ALTITUDE" of the engine and above 18,000 feet the power output falls off because the capacity of the supercharger is insufficient to compensate for the thinning out of the air beyond that point.

The power output also falls off below 18,000 feet and on down to sea level *but this is due to an entirely different reason:*

The higher speed supercharger has too much capacity for the lower altitudes and since there is no provision for changing the

★ These curves are all worked out on the basis of never allowing the engine to operate at more than its MAXIMUM RATED CAPACITY. As explained back on page 18, our basic engine was designed to deliver a maximum of 1000 H.P. net output —after taking into account the power used to drive *the low speed Sea Level Supercharger*. So when we *increase* the power required to drive the supercharger we must *decrease* the maximum power output by a corresponding amount in order to keep the engine within the safe operating limits for which it was designed.



gear ratio, it is necessary to throttle or "*choke*" the air intake and this has the effect of thinning down the air drawn into the supercharger.

The choking must not only be sufficient to keep the *weight of the charge* within proper limits but we must also allow for the higher temperatures of the air encountered at lower altitudes, in order to avoid excessive manifold pressures and temperatures.

Thus we see that at low altitudes the extra capacity is a distinct *handicap* instead of a *benefit*. We not only can't use it but we have to "*Pay a Price*" to get rid of it—*another example of compromise!*

As the plane rises above sea level, the air becomes thinner and colder and so we are able to reduce the choking and use more and more of the supercharger capacity. ★

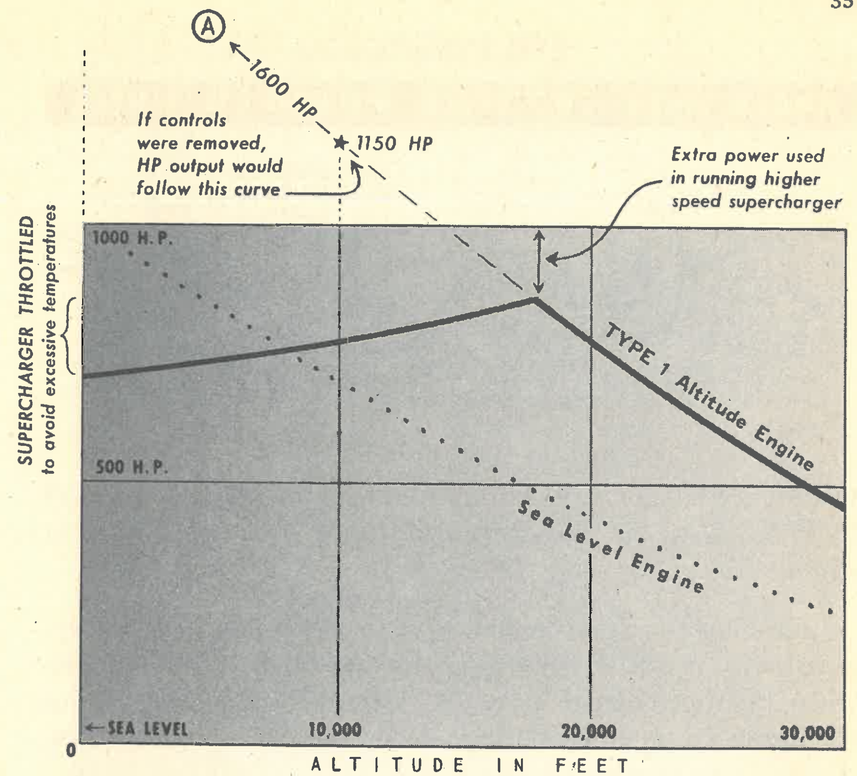
But as will be noted from the chart the power output at "take-off" and for the first few thousand feet of climb is considerably less than that provided by the Sea Level Engine.

This does not mean that it would be *IMPOSSIBLE* for the engine to deliver greater horsepower at the lower altitudes.

If we removed the controls and allowed the engine to operate with wide open throttle, the power curve would follow the broken line "A", as indicated at the top of the opposite page. Thus, at 10,000 feet, as a result of the "overboosting" we would get 1150 H.P.—and at sea level the power output, in theory at least, would approach 1600.

This might be possible in practice but only for a very short time —perhaps only a few minutes because the excessive pressures and high temperatures would ruin the engine. The point is that to keep this engine within the safe operating limits for which it was designed—*consistent with long life and dependability*—its power output must be restricted to the heavy solid line.

★ There is also less back pressure on the engine exhaust and this tends to help the power output. *See "Back Pressure" Page 75.*



At medium and higher altitudes the SINGLE STAGE SINGLE SPEED SUPERCHARGER provides much better power than the Sea Level Engine and of all the Altitude Superchargers it is the simplest, lightest and most compact.

Its shortcomings at low altitudes, however, put it at a distinct disadvantage. In fact it hardly warrants such a detailed discussion except that it provides the opportunity for establishing a very important point. . . .

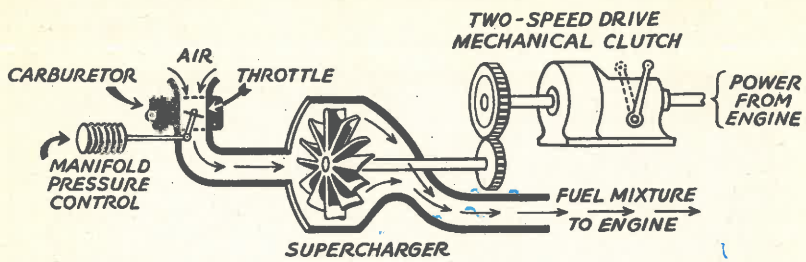
that is—

In order to get good performance at varying altitudes we must have more than one speed ratio. In fact, if we are to utilize the capacity of the supercharger to the best advantage, we would need to have *an infinite number of speed ratios!*

But that's getting ahead of the story!

TYPE 2 ALTITUDE SUPERCHARGER

SINGLE STAGE, TWO SPEED, MECHANICAL CLUTCH



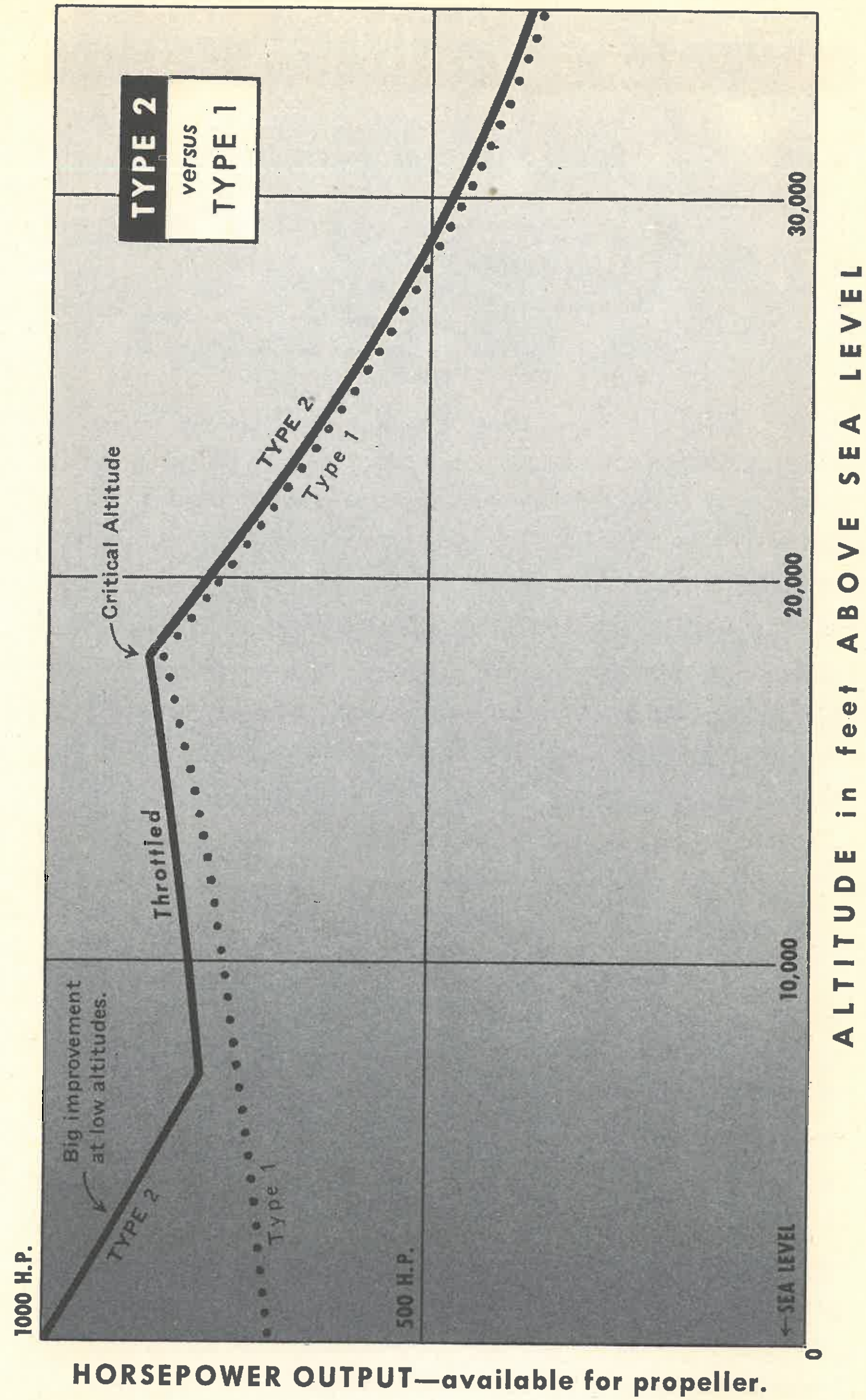
On the preceding chart we have seen that the SINGLE SPEED SUPERCHARGER penalizes performance at take-off and early climb.

This limitation may be overcome by employing two separate gear ratios: A *SLOW SPEED* gear for use at the lower altitudes where less supercharging is needed, and a *HIGH SPEED* gear for the higher altitudes where the need for supercharging increases.

This gives us the effects of the single speed supercharger at high altitudes without sacrificing power output at the lower altitudes. In other words, as indicated by the chart, it combines the performance advantages of the Sea Level Engine with the advantages of the TYPE 1 ALTITUDE ENGINE.

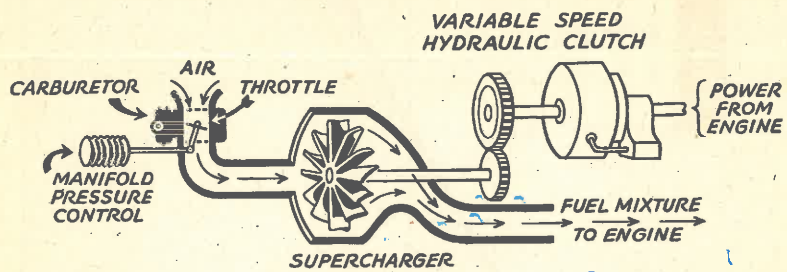
The changing of gears is done—either manually, at the discretion of the pilot—or through the use of an Aneroid Control mechanism designed to shift into the second gear automatically at some predetermined altitude. In the example shown, the gears are changed at around 7,000 feet. From that point up to the Critical Altitude the compression capacity is partially throttled so that this segment of the curve has the same peculiarity as TYPE 1.

The clutches used in this equipment must be built to carry heavy loads and withstand severe shocks. So against the gain in horsepower in the lower altitudes the designer must evaluate the somewhat greater weight and the increased mechanical complication.



TYPE 3 ALTITUDE SUPERCHARGER

SINGLE STAGE WITH VARIABLE SPEED CLUTCH



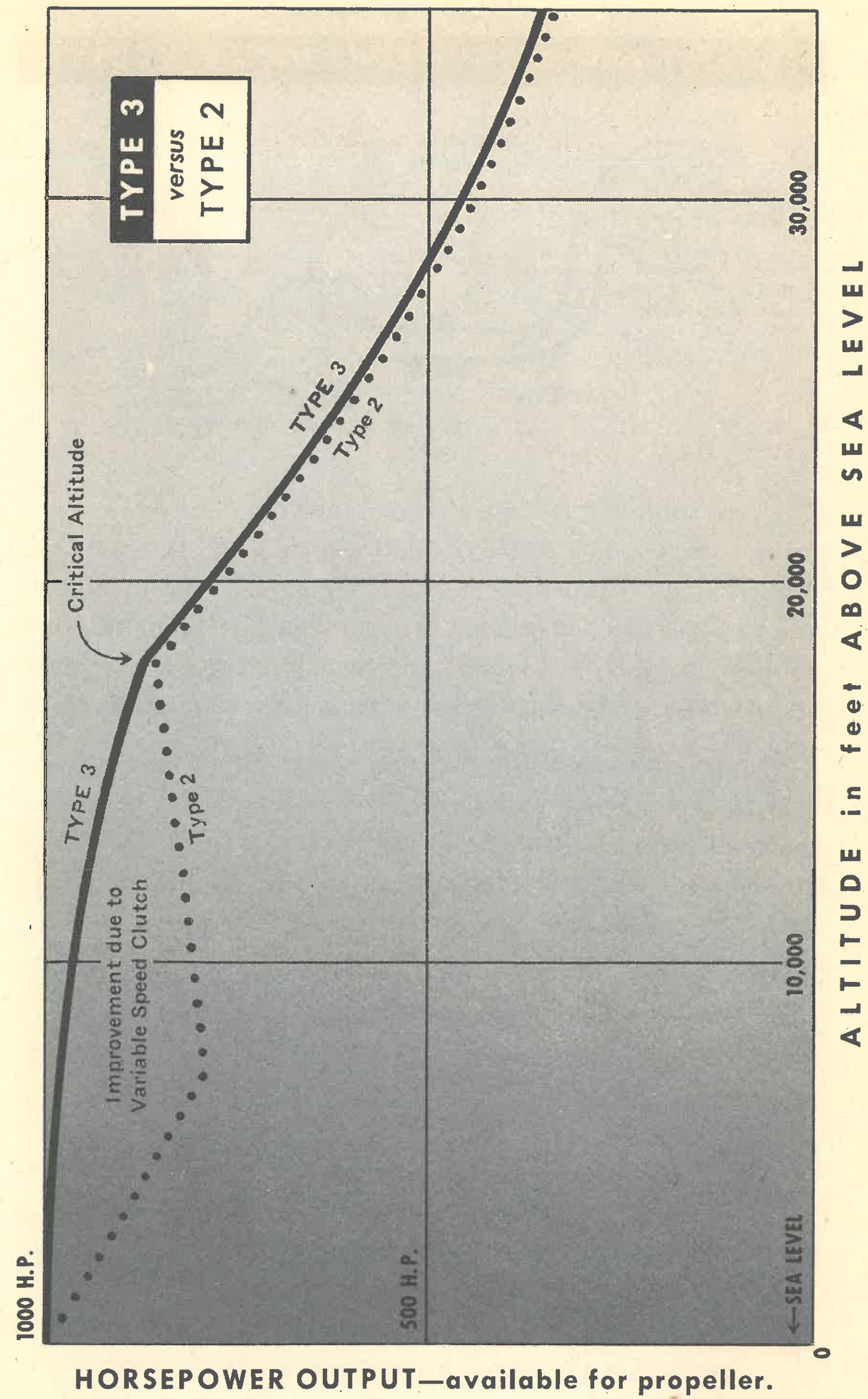
This combination represents a refinement of TYPE 2. Instead of a mechanical clutch, the supercharger is driven through a HYDRAULIC or FLUID CLUTCH somewhat similar to that used in the Hydra-Matic Drive on a motor car.

This gives the effect of an infinite number of speed ratios which makes it possible to utilize the capacity of the supercharger to the best advantage at all altitudes and since we can slow it down instead of choking it, we don't have to waste power at low altitudes.

As the plane rises above the surface of the earth an Aneroid Control causes the supercharger to run faster and faster *so as to compensate for the decreasing density of the outside air.*

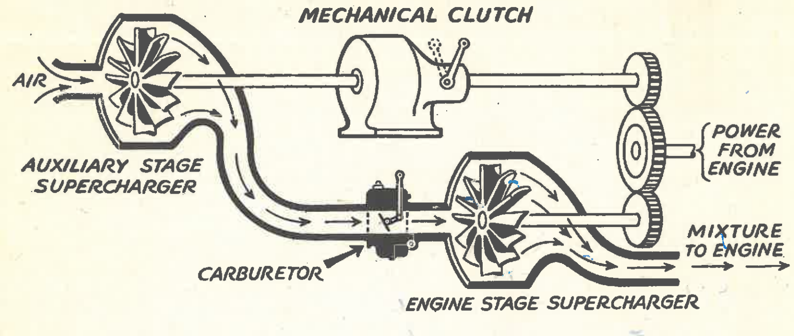
In comparison with No. 2 this combination provides a considerable improvement in horsepower between sea level and up to the Critical Altitude. Beyond that point the horsepower curve falls off at about the same rate as in the case of the two speed equipment with mechanical clutch.

The Hydraulic Clutch is somewhat more complicated, heavier and bulkier than a gear drive. Furthermore its variable speed characteristics are obtained through slippage and this generates a certain amount of heat which makes it necessary to slightly increase the capacity of the oil cooling equipment. But the advantages are considerably greater than the disadvantages.



TYPE 4 ALTITUDE SUPERCHARGER

TWO STAGE WITH MECHANICAL CLUTCH

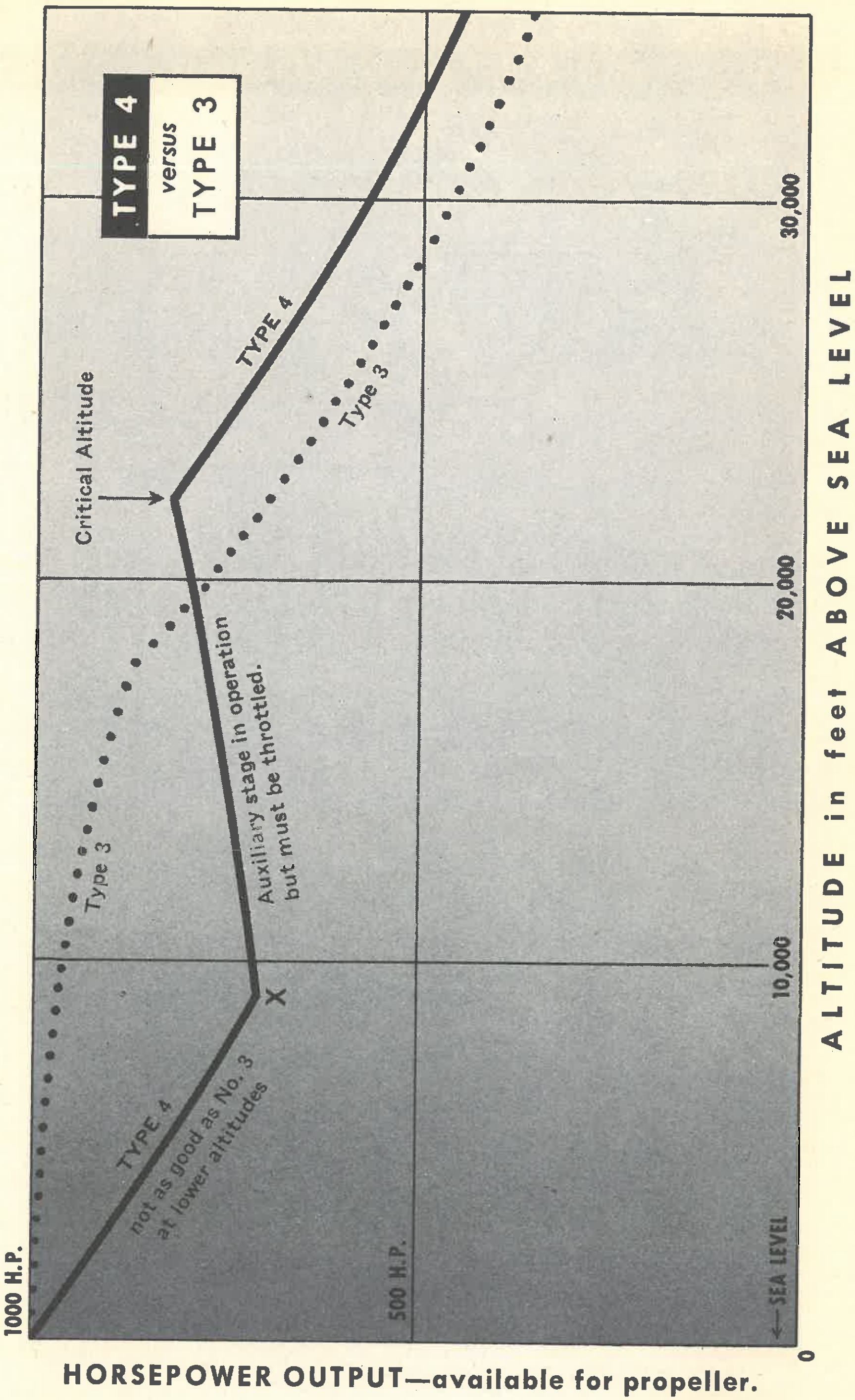


This type consists of *two separate blowers* with their airflow lines connected in series. The *ENGINE STAGE* is the same as a Sea Level Supercharger. In other words, it is driven by a fixed gear and runs at a constant speed in relation to engine speed. The *AUXILIARY STAGE* is used only at higher altitudes and is brought into operation by means of a clutch as indicated at point "X" on the curve.

At low altitudes, with only one blower running, the power curve approximates that of the SEA LEVEL ENGINE. But when the auxiliary equipment is put into operation (as shown here at around 9,000 feet) the curve takes an upturn. At altitudes above 20,000 feet the power is better than with TYPE 3 equipment.

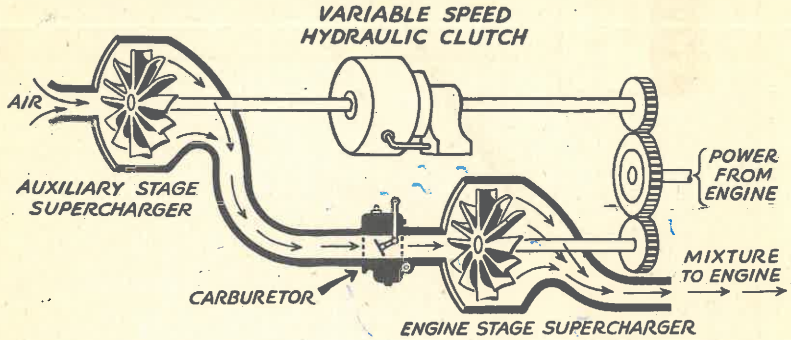
This equipment adds to bulk and is *considerably heavier than any of the preceding types*. So the plane designer is confronted with the problem of whether the advantages of greater power at certain altitudes are sufficient to offset the disadvantages of extra weight and size.

In reviewing the charts it should always be borne in mind that they reflect engine performance ONLY and when we get into heavier and bulkier equipment the improvements in engine performance will not be fully realized in the overall performance of the airplane.



TYPE 5 ALTITUDE SUPERCHARGER

TWO STAGE WITH VARIABLE SPEED CLUTCH



Here, as in the case of TYPE 4, the equipment consists of two separate superchargers with their airflow lines connected in series and here again the Engine Stage is driven through a fixed gear ratio and runs all the time.

But in contrast to TYPE 4 the *Auxiliary Stage*, instead of being driven by a mechanical clutch, is driven by a variable speed Hydraulic Clutch.

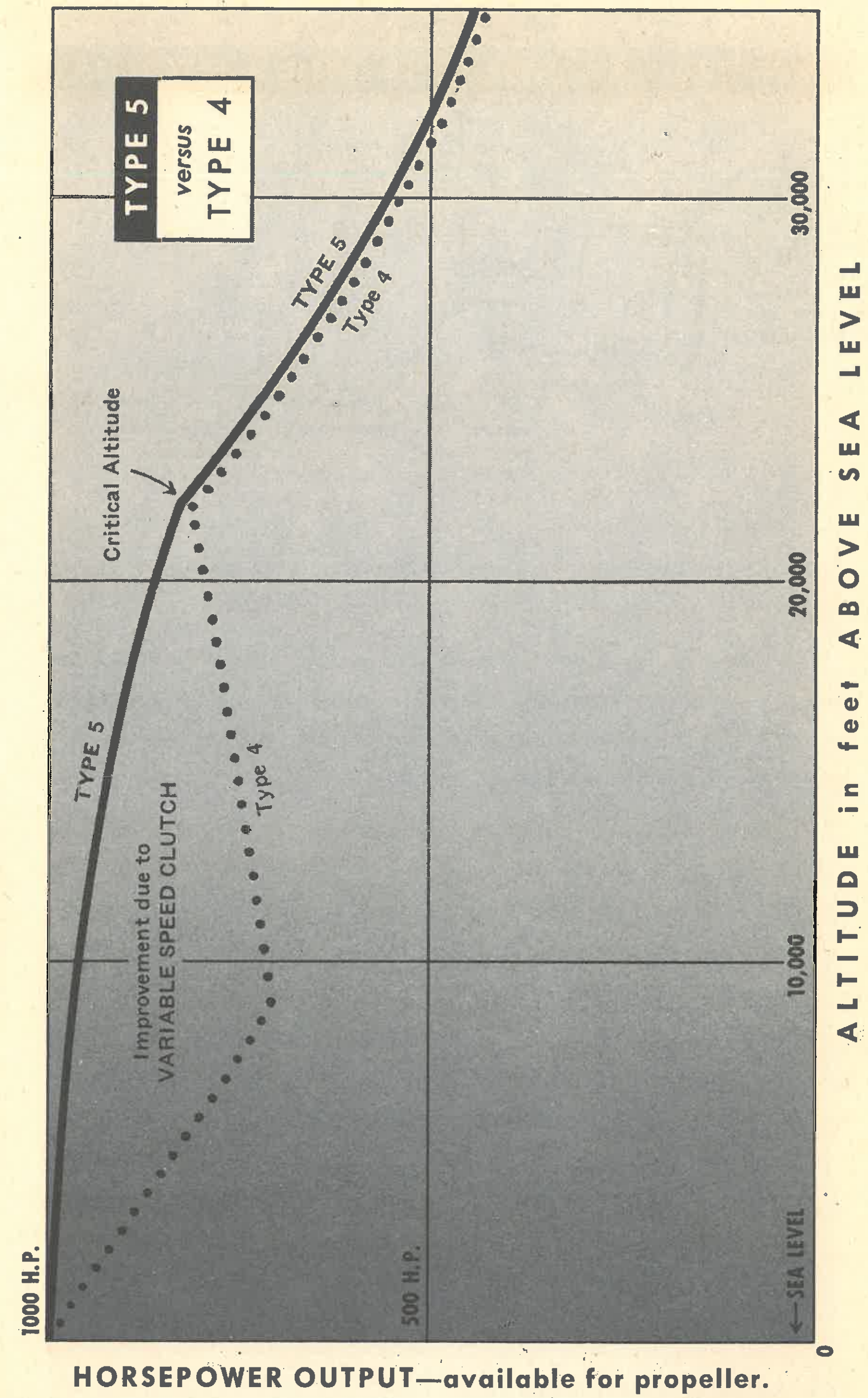
This makes it possible to take advantage of the extra capacity before reaching the higher altitudes.

Beginning at sea level, the Aneroid Control gradually cuts in the capacity of the auxiliary equipment by degrees, thus providing the desired compression consistent with *not overstressing the engine and not getting into mixture temperatures that would cause detonation.*

So, in contrast to TYPE 4, we get considerably more power for climb and on up to the Critical Altitude, as shown on the chart.

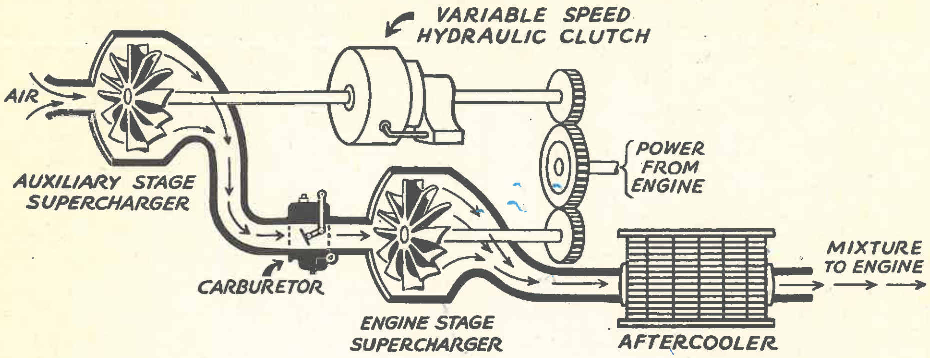
There are also certain minor factors favorably affecting the horsepower characteristics of this combination which are beyond the scope of the present discussion.

The mechanical complications and weight penalties are a combination of those mentioned in connection with TYPES 3 and 4 *but the advantages are considerably greater.*



TYPE 6 ALTITUDE SUPERCHARGER

TWO STAGE, VARIABLE SPEED WITH AFTERCOOLER



As explained on page 17, compression generates heat. *The greater the degree of compression the greater the rise in temperature.*

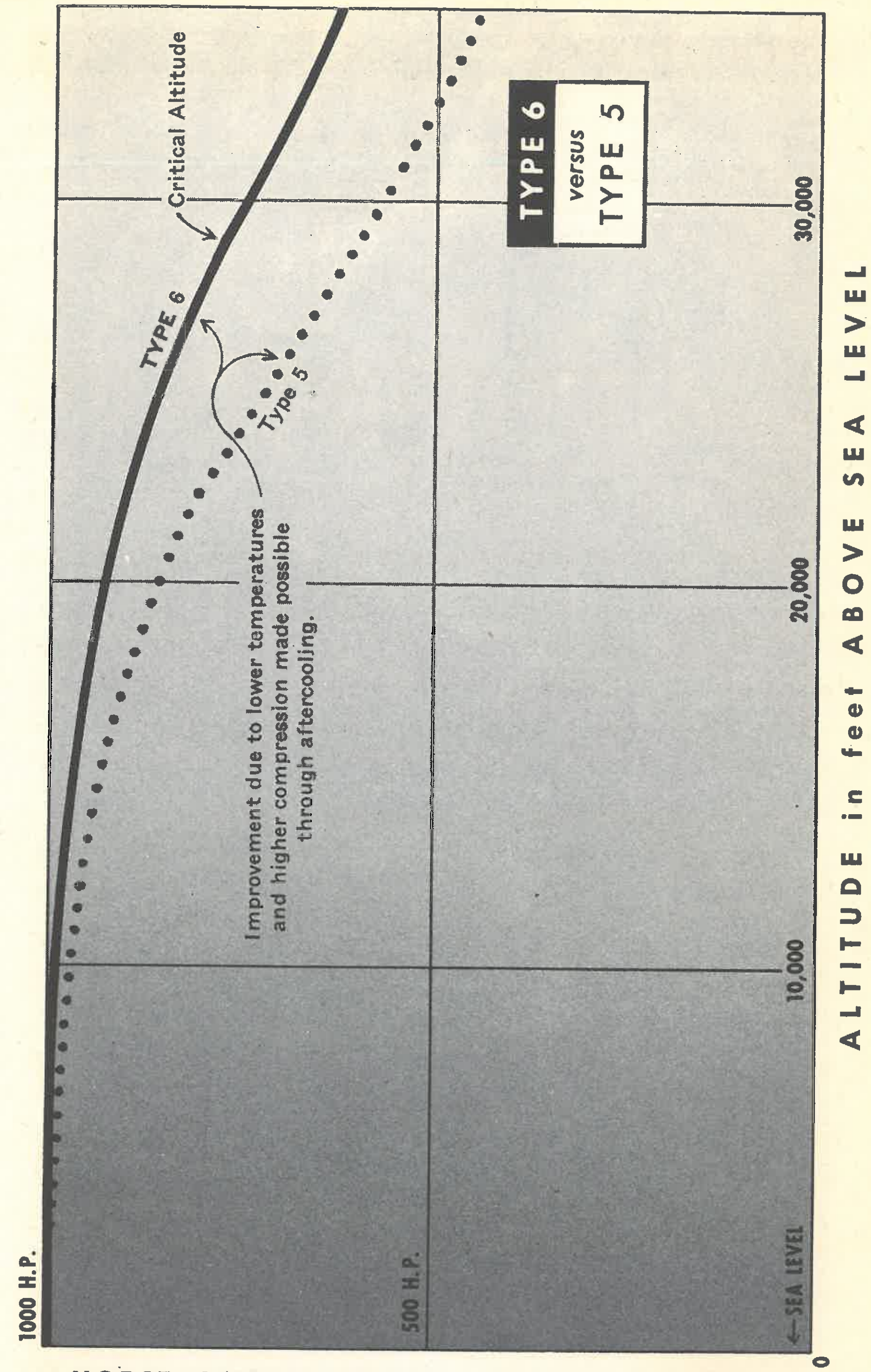
So when we use supercharging equipment with sufficient compression capacity to provide full weight of air at high altitudes it is necessary to make some provision for cooling off the air (or the mixture) after it has been compressed.

This may be done through the use of special radiators which are called "*INTERCOOLERS*" or "*AFTERCOOLERS*" depending on their location with respect to the carburetor.

The equipment illustrated at the top of this page is the same as No. 5 except that an AFTERCOOLER has been added. This cools off the mixture before it goes into the engine cylinders and permits us to operate the AUXILIARY STAGE SUPERCHARGER at higher speeds *without danger of detonation.*

Such a combination provides gains in horsepower over and above any of the previous methods and the improvement is especially marked at altitudes above 20,000 feet.

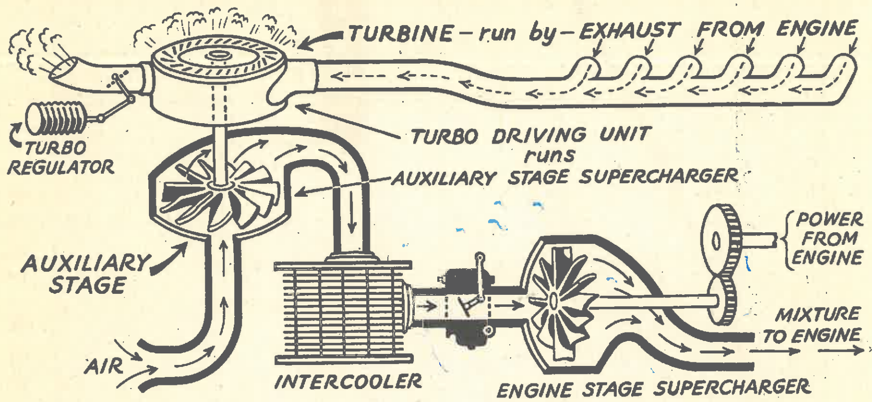
The cost of these gains is represented by the weight and space requirements plus the drag on the airplane resulting from the radiator cooling surfaces.



HORSEPOWER OUTPUT—available for propeller.

TYPE 7 ALTITUDE SUPERCHARGER

TURBO, EXHAUST-DRIVEN, WITH INTERCOOLER



This combination is similar to No. 6 in that it employs two separate superchargers, but the AUXILIARY STAGE is driven by the engine's exhaust gases instead of by power taken off the engine crankshaft.

As indicated in the sketch, this is done by piping the exhaust gases into a high speed turbine, and using the power generated by this turbine to run the auxiliary blower.

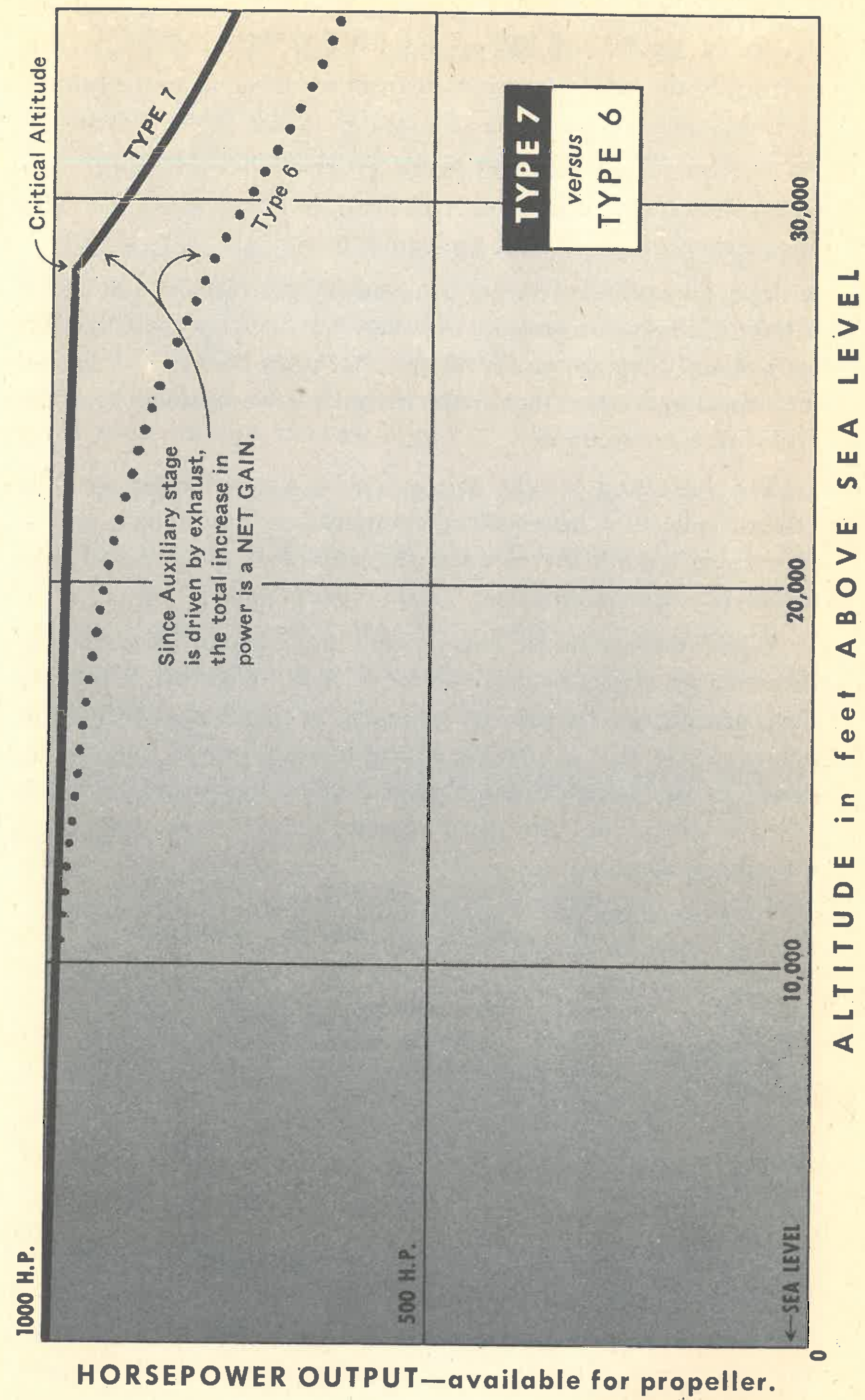
Aside from the obvious advantage of using the waste exhaust gases as a source of power, there is another important advantage:—

The TURBINE or DRIVING UNIT has a variable speed characteristic *within itself* and so it is unnecessary to use a hydraulic clutch in order to compensate for variations in altitude.

The speed of the turbine depends on the difference in pressure between the exhaust gas and the outside air. The greater the difference, the higher the speed of the turbine and hence the greater the degree of compression provided by the Auxiliary Supercharger.

So long as we are able to get sufficient mixture into the cylinders the pressure of the exhaust gases will remain the same, whereas the pressure of the outside air will steadily decline with altitude.

Discussion continued on Page 48



Thus, as the plane rises higher and higher, the auxiliary supercharger automatically picks up speed and provides the engine with practically the same weight of air from sea level up to the critical altitude.

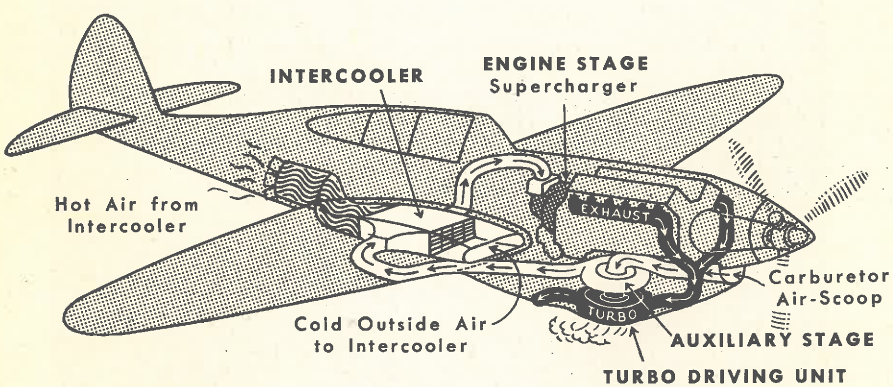
The results are reflected in the chart on the preceding page which shows what our 1,000 H.P. Sea Level Engine is capable of doing when provided with such equipment.

The Turbo Supercharger is an outstanding innovation and a tribute to American inventive genius, but it is not a "cure-all". Here again there are disadvantages that must be weighed against the advantages—here again the designer is confronted with the problems of compromise.

The bulk and weight of the Turbo Supercharger with its exhaust collectors, intercoolers, complicated "plumbing", etc. — these things greatly increase the problems of installation and limit the use of such equipment to certain types of planes.

While military restrictions prevent any adequate discussion of these factors, it may be said that for a large, high altitude bomber the Turbo Supercharger has no equal. It might also be used in fighter planes that are to escort the bomber—or in fighters designed to attack high altitude *enemy bombers.* But for medium and low altitude planes the disadvantages would more than offset the advantages.

In between the two extremes it is a matter of compromise.



THE "PROS" *and* THE "CONS"

IN THE LIGHT of the foregoing charts we begin to see why it is dangerous to make any general statements about the performance of an aircraft engine.

The engine designer develops the basic engine but the performance characteristics may be widely varied depending on the type of supercharging equipment that is used. The justification of one type as against another depends to a great extent on the requirements of the plane designer and on the specifications established by the military strategists.

A review of the charts indicates the wide range of possibilities:

Thus, as indicated on Page 32, we can transform a SEA LEVEL ENGINE into an ALTITUDE ENGINE by simply gearing its supercharger to run faster and then arbitrarily controlling the air pressure at lower flying levels so as to keep the power of the engine within the limits for which it was designed.

Or we can use a two speed gear changing mechanism with the first gear ratio suitable for sea level operation and the other for medium altitude performance.

Or we can go to the two stage type of design where the same air goes successively through two blowers—with operating controls that permit using only one of them at the lower altitudes where less supercharging is needed. And we can get better and more uniform performance by using a variable hydraulic drive which governs the speed of the supercharger instead of throttling the air intake.

We can get further gains, especially at high altitudes, by providing radiator equipment to cool the air or mixture after it has been compressed.

Last but not least we have the TURBO SUPERCHARGER, which provides practically full sea level power up to 30,000 feet but is not without its drawbacks.

With proper planning and careful attention to interchangeability, *the engine for every one of the combinations shown, can be made to come off the same production line.*

This is as it should be. Standardization not only speeds the stream of American aircraft production, but in Global Warfare it greatly simplifies the problem of making replacement parts and service "know-how" available over the wide flung battle fronts.

From this same viewpoint, it would be highly advantageous if we could have one type of fighter plane and one type of supercharging equipment that would fill the requirements for every type of service, but this is not possible. Such a plane would be at serious disadvantage when it encountered specialized enemy planes at their own best altitudes.

It must be borne in mind that the charts show engine performance—*not over-all plane performance.*

The greater the degree of supercharging, *within limits,* the better the performance of the engine but along with the increase in engine power we get increased complications and greater weight which adds to the power requirements.

With the exception of the single stage compressor, built as an integral part of the engine, supercharging involves extra equipment which must be worked into the already crowded limits of a fighter plane—with a possible reduction in the carrying capacity that might otherwise be used for additional armor, armament, ammunition, gasoline, etc.

The difficulties increase as we get into the more elaborate types of supercharging.

Intercooling or Aftercooling with its bulky radiator equipment not only increases weight and "drag" but also increases the vulnerability of the plane because it adds to the "vital organs" that may be put out of commission by enemy gun fire.

Increasing the supercharging equipment may in some instances appreciably change the center of gravity of the power plant installation and necessitate almost a complete redesign of the airplane in order to get proper weight distribution.

Some of the more complicated types of supercharging equipment are so bulky with relation to the trim outlines of small fighter planes that their installation would involve changing the shape of the fuselage, with the possibility of impairing the aerodynamic qualities.★

For high altitude flying, the advantages of high capacity superchargers more than offset the disadvantages, but the situation is reversed when we get into low altitude operations where the extra capacity is unnecessary and the superfluous equipment is a dead load. Also, it must be remembered that the extra power required to run the mechanism is at the expense of the power available to propel the plane.

In the case of the Turbo Supercharger which is driven by the exhaust gases instead of from the crankshaft, this latter point does not apply, but the excessive weight and bulky proportions of the turbo equipment make it impractical for many types of fighter planes.

The limitations imposed on the engine designer by the over-all problems of plane design must be reckoned with at every step of the way. Thus we have compromise pyramided on top of compromise and since the design of each plane presents its own special problems we can only discuss these problems in broad general terms.

In the final analysis, the choice of what kind of supercharging equipment to use—or whether to use any supercharging at all—must be determined from the standpoint of the size and type of the plane—WHAT the plane is to be used for—HOW it is to be used and WHERE it is to be used.

★ Such modifications may also involve changes in the propeller design—which is definitely influenced by the altitude at which the plane is to operate. For example, high altitude performance calls for longer, wider and heavier propeller blades.

"Service Ceiling" *vs.* "Critical Altitudes"

IN AVIATION the word "ceiling" is used a lot and is used in various ways. Its most common use is in connection with weather conditions as affecting visibility—i. e., the height of the clouds above the surface of the earth. But from a standpoint of engineering design and performance it has a different meaning—in fact two different meanings, namely "Absolute Ceiling" and "Service Ceiling".

The *ABSOLUTE CEILING* of a plane means the maximum altitude to which it can fly. It varies as between different planes depending on—

1st—*WING LOADING*—i.e., the total weight of the loaded airplane divided by the area of its wings.

2nd—*AERODYNAMIC ASPECTS.*

3rd—*POWER PLANT INSTALLATION*—i.e., the engine, the supercharging equipment, the propeller, the propeller pitch control, the cooling equipment, etc.

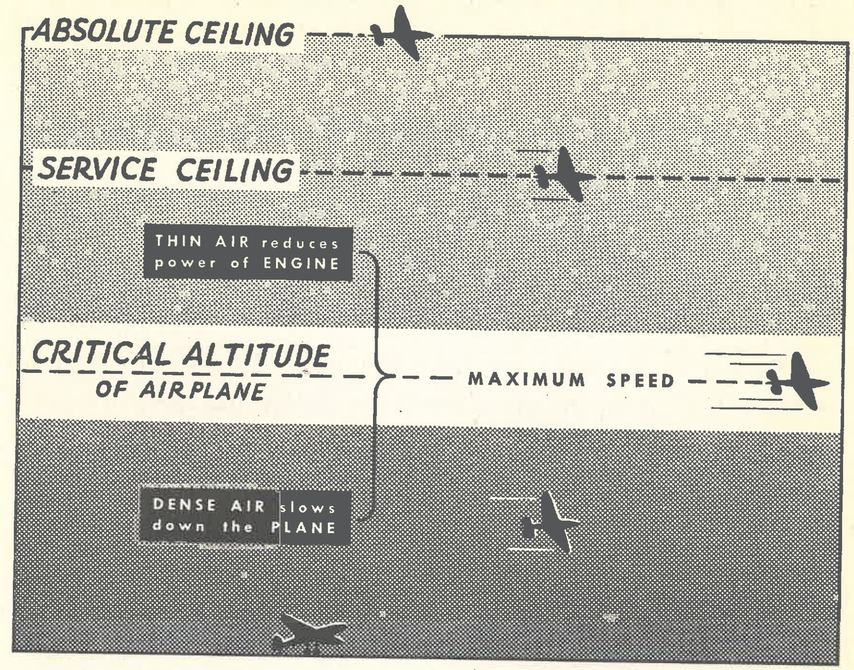
The term *Absolute Ceiling* is of no particular significance in a practical sense because when a plane reaches its *Absolute Ceiling* its climbing ability is zero.

"*SERVICE CEILING*", on the other hand, means the highest altitude at which it is *practical* to fly a given plane with a given load.

Service Ceiling, to be more specific, is the maximum altitude at which a plane will respond satisfactorily to its controls and *still be able to climb at a rate of 100 feet per minute.*

The Service Ceiling of a plane depends on the same factors as the Absolute Ceiling but, by the very nature of the definition, it is lower than the Absolute Ceiling.

In addition to the terms "Absolute Ceiling" and "Service



Ceiling" there is also the "*CRITICAL ALTITUDE*" of the PLANE which is the altitude at which *maximum speed in level flight* is attained.

Offhand, one might think that a plane would attain its maximum speed near the surface of the earth—or at an altitude where the engine provides its best power output. This, however, is not the case because the lighter the air, the less the resistance to a body moving through it. ★

In other words, while the thinner air causes the engine to lose power, it also reduces the power requirement and so the maximum speed will be attained at an altitude where these two opposing effects tend to balance out. Or to express it more accurately, maximum speed is attained when we have the best relation of *power available* to *power required.* ★

★ There's not enough room in this little book to fully discuss the various aspects of design as bearing on these points—so about all we can hope to do is to try and bring out the broad general ideas, expressed in simple every-day language—*even at the expense of scientific adequacy.*

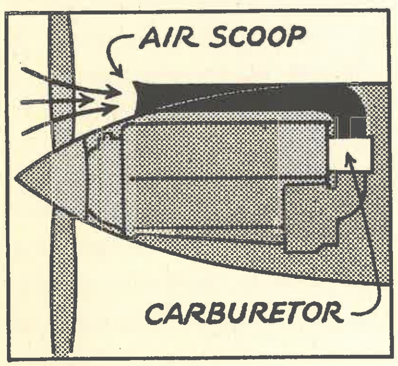
THE *CRITICAL ALTITUDE* OF THE *ENGINE* is the altitude at which the rated power output of the engine will begin to fall off with increased altitude. *See "Rated Horsepower" page 78.*

Starting out with a good basic engine, the designer can—through the installation of appropriate supercharging equipment—fix the Critical Altitude wherever he thinks it ought to be—*within reasonable limits.*

Therefore any statement to the effect that a given make of engine has a Critical Altitude of so many feet is inadequate.

To say, for example, that the "*XYZ engine has a Critical Altitude of 15,000 feet*", is meaningless, because with varying types of supercharging the same basic XYZ engine might have a dozen different Critical Altitude ratings, ranging anywhere between a thousand feet up to 30,000 feet or more. Furthermore, through the use of such combinations as two speed, mechanical clutch equipment, it is possible to have two or more Critical Altitudes in the same engine.

To state that a *particular model* of the XYZ engine has a Critical Altitude of 15,000 feet may be substantially correct. But even this type of statement would need to be qualified because the performance of an engine is affected by what aircraft engineers call "ram".★



The so-called "RAM EFFECT" has to do with the effect of the airplane's speed in forcing air into the engine. It depends, not only on the speed of the plane, but on the design and location of the engine's air intake. In other words, it depends on the *manner of installation* rather than on the design of the engine itself.★

★ The engine designer thinks of Critical Altitude in terms of laboratory tests, whereas the Critical Altitude of the engine *installed in the plane* involves factors not present under ordinary laboratory conditions.

ONE OF THE MOST COMMON ERRORS on the part of writers and commentators attempting to evaluate American and European planes has been to compare the *Critical Altitudes* of American craft with the *Service Ceilings* of allied and enemy planes.

Another common misconception is that the Critical Altitude is the highest point to which a plane can fly or at which it can effectively fight. This, of course, is simply not true. Even an unsupercharged engine of high horsepower might be able to take a plane right on up into the stratosphere—provided the plane is extremely light and has sufficient wing area. The point is that it could not take it there as fast as a supercharged engine and it wouldn't have enough power to be effective after it got there.

It is not a question of how high a plane might be able to fly but how effectively it will be able to perform in the altitude band where it is to operate—also how quickly it can get there.

In other words, the Critical Altitude and Service Ceiling of a plane are the important considerations, and while these are largely dependent on the engine and the supercharging equipment they are influenced by other aspects of design.

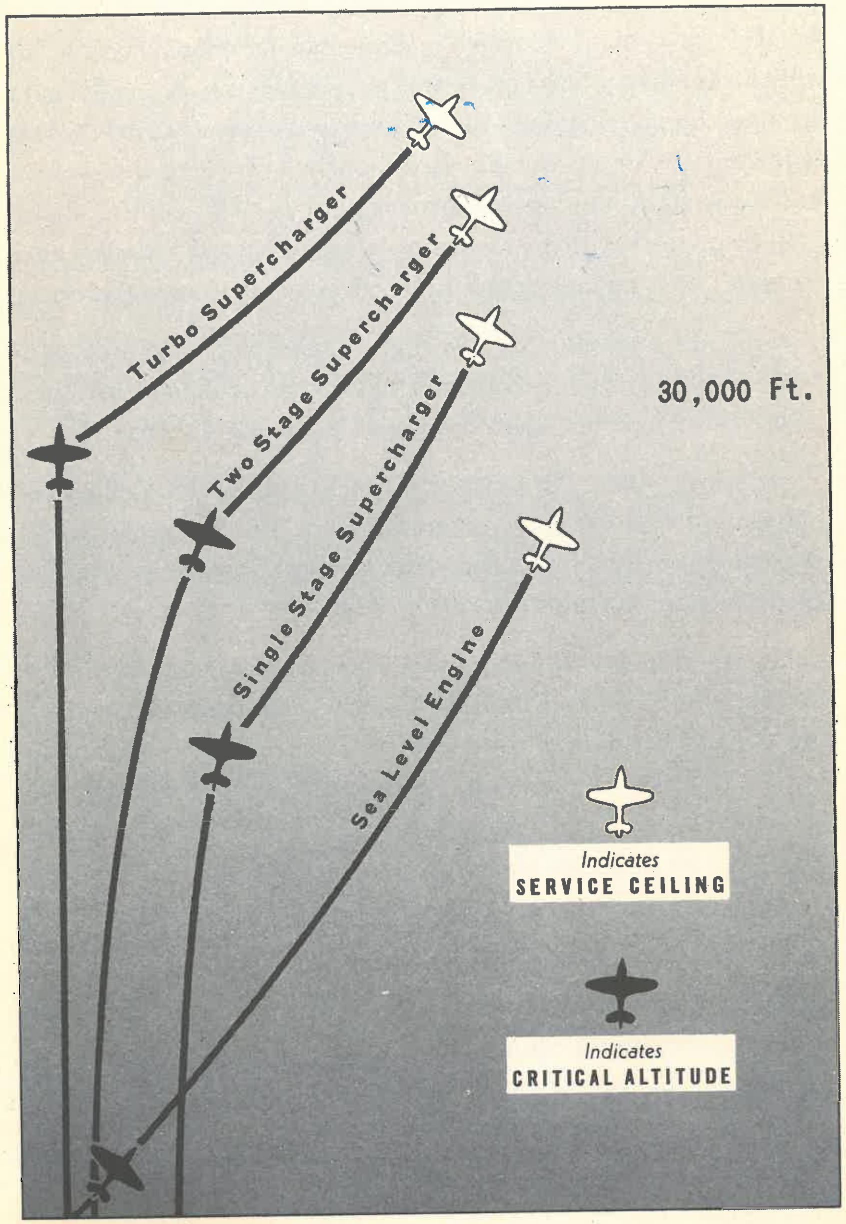
It would be possible to build a plane so heavy that its Service Ceiling would be lower than the Critical Altitude of the engine or the Critical Altitude of the complete Power Plant Installation—but a well designed plane, using the same power plant installation, would have a Service Ceiling considerably higher than its Critical Altitude—*the lighter the plane the greater the difference.*

This is illustrated by the curves on the next page which are based on planes of comparable design—*all using the same basic engine.* In other words, the variations are entirely due to difference in the supercharging equipment.

Variations in

CRITICAL ALTITUDES AND SERVICE CEILINGS

of comparable planes—all using same basic engines but with different types of supercharging equipment



The Effect of Weight

POWER PLANT EQUIPMENT must, in the final analysis, be determined by the type of service for which the plane is to be used. High altitude flying is only one aspect of performance with which the plane designer must concern himself. Other important aspects are

Take-Off, Maneuverability, Climbing Ability and SPEED.

The first three of these are seriously affected by weight. Speed is also reduced by weight although not to the same degree as the other aspects.

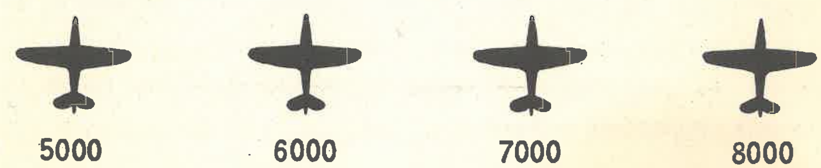
Because of the importance of weight as affecting performance characteristics it seems desirable to develop some specific examples.

So let us now consider the difference in performance characteristics of four fighter aircraft, powered by *exactly the same engine—all with the same supercharging equipment*, but differing in weight as follows:

Plane "A"	***5,000 pounds***
Plane "B"	***6,000 pounds***
Plane "C"	***7,000 pounds***
Plane "D"	***8,000 pounds***

Let us assume that in each case the weight has been properly distributed *inside of the plane*—and that outwardly, *which is to say aerodynamically*, the planes are strictly comparable.

In other words they are all exactly alike except for the difference in weight.

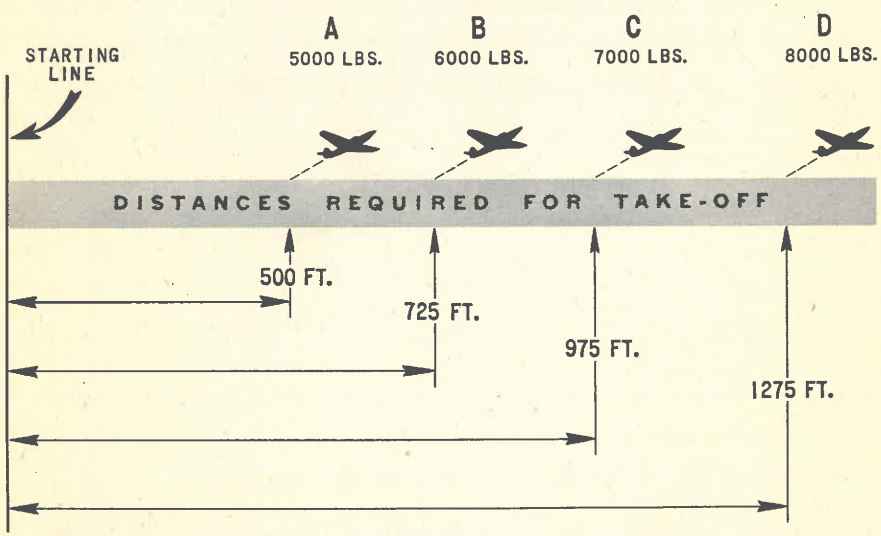


First, let us consider "*TAKE-OFF*".

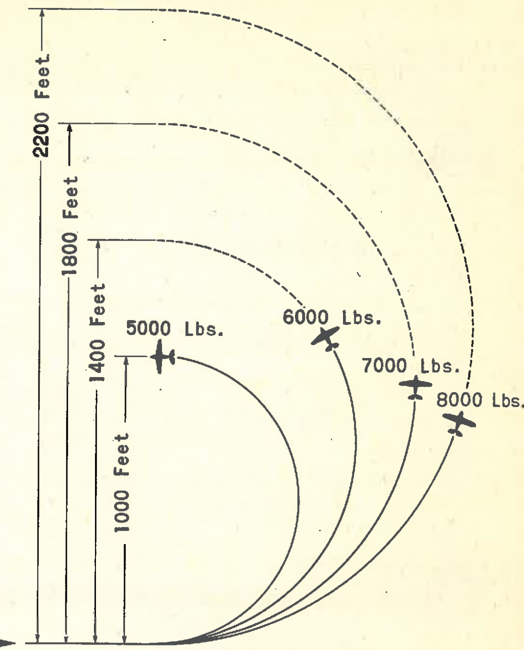
Before a plane can leave the ground, it must gain sufficient speed for the lifting effect of the air to outweigh the force of gravity. The lightest plane naturally gets into the air after the shortest run, because a relatively low speed develops all the lift that is needed to overcome its weight.

The heavier planes have to run farther along the ground before taking off, in order to pick up enough speed to compensate for their greater weight.

It should be kept in mind, of course, that the additional weights of the heavier planes may mean the installation of more guns, bigger guns, more rounds of ammunition, greater fuel capacity for longer cruising range, adequate armor to protect both the pilot and the internal mechanism of the plane itself.



MANEUVERABILITY. The diagram at the top of the next page shows the same four planes, differing only in weight. It brings out the point that their maneuverability—which is indicated by their ability to make turns sharply—also varies in inverse proportion to weight.

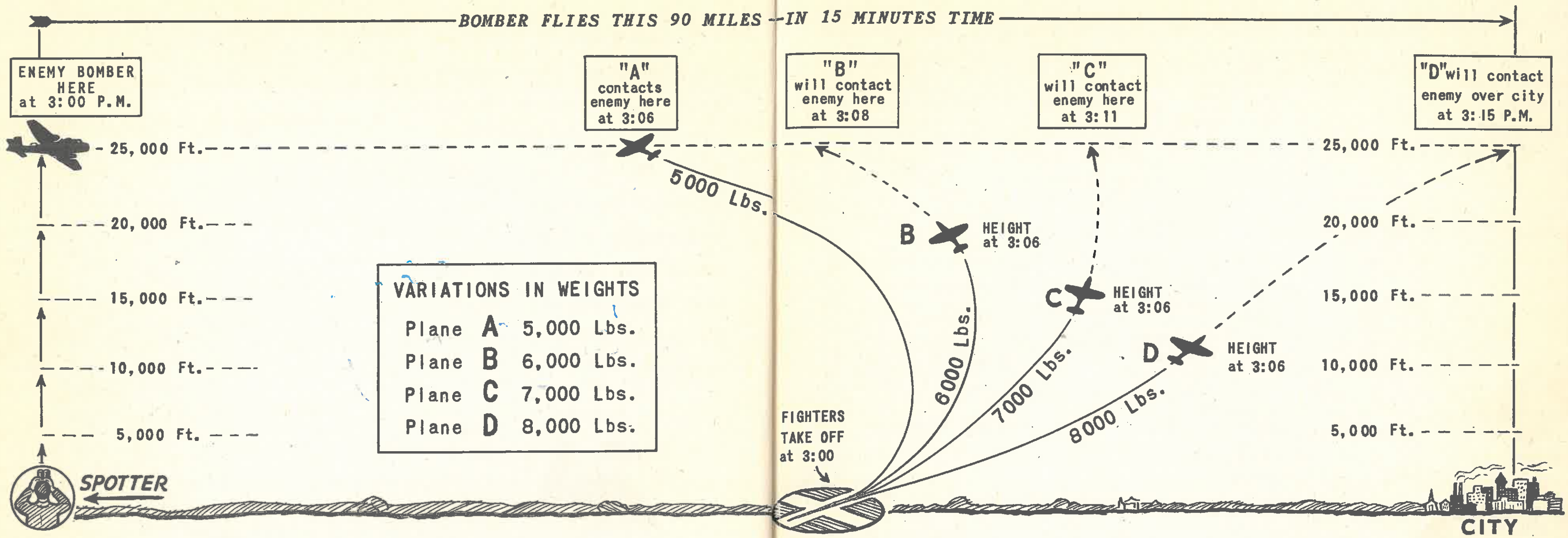


This variation is the result of the *centrifugal force* which limits the sharpness of the turn that can be made by a plane. By way of illustration, suppose you were to tie a small stone at the end of a string and swing it around over your head—you would feel a certain amount of outward pull.

Then if you were to repeat the experiment with a much heavier stone you would find the outward pull to be far greater.

Centrifugal Force is what causes your car to skid off the road if you take a curve too fast. In the case of an automobile, the friction of the wheels on the surface of the road works against the action of centrifugal force, and as long as that force is not too great, the vehicle will follow the curve determined by the steering angle.

An airplane is steered, in a somewhat similar way, by the banking of the wings and by the angle of the rudder and other control surfaces, which "bite" into the air and force the plane to follow a curved path, despite its natural tendency to go off on a straight line—or tangent. The degree of "hold" that the plane's steering or control surfaces can take on the air is limited by their size in relation to the plane's speed and weight. Centrifugal force is affected by both speed and weight: if either one is increased, the centrifugal force is also increased.



Now let us assume that the same four planes are attempting to intercept an enemy bomber. An observer spots the bomber, headed for the city, and flying at an altitude of 25,000 feet. Word is flashed to the fighter airdrome which we have assumed to be about midway between the city and the point where the bomber is reported to be.

When the bomber is 90 miles away, the four fighters immediately take off and climb to meet it.

PLANE A takes 6 minutes to climb to the 25,000 foot level. During these 6 minutes the bomber, traveling at 350 miles per hour, will have approached a point 55 miles from the city when Plane A intercepts it.

PLANE B requires 2 more minutes than Plane A, or a total of 8 minutes, to reach the bomber's level. By this time the bomber would have progressed to a point 43 miles from the city.

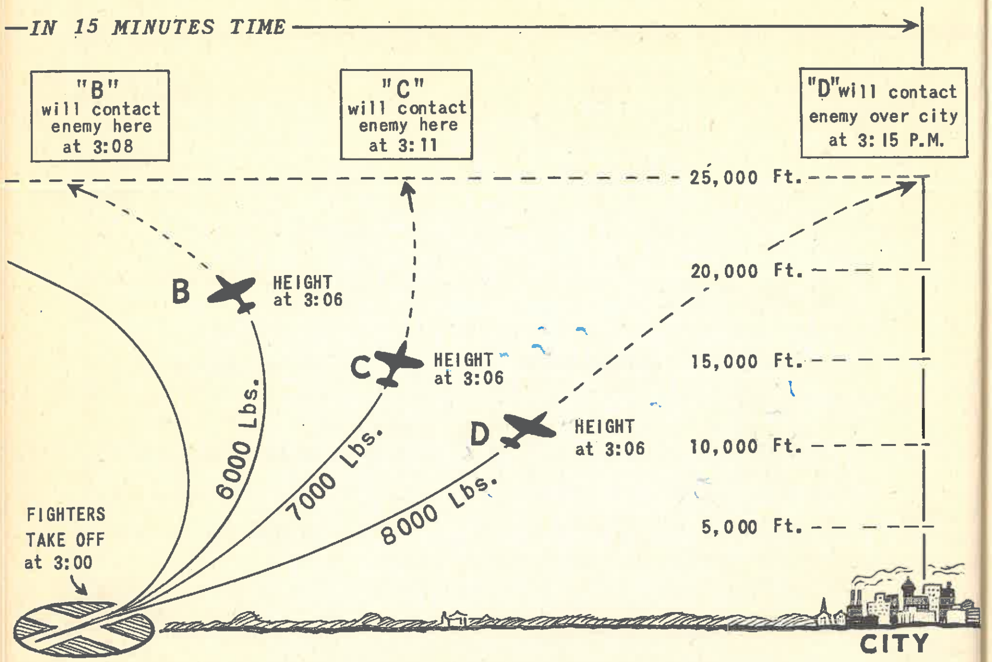
PLANE C takes 11 minutes to make the climb, so it could not be in a position to attack until the bomber had reached a point only 25 miles away from its goal.

PLANE D takes approximately 15 minutes to get up to 25,000 feet. During this time, the bomber would have covered the entire distance of 90 miles and would be above the city before Plane D would be close enough to attack.

Now, getting back to PLANE A. It rose to meet the bomber in only 6 minutes; due to the lightness of this plane it would not be able to carry very much in the way of equipment or armor. Probably it has only a few small machine guns, and a few rounds of ammunition. It can carry only a limited supply of gasoline, and will therefore not be able to stay up as long as the heavier fighters.

Will PLANE A be able to knock out the heavily armored bomber with its light machine guns? Or will a few shots from the bomber stand a good chance of blasting the light weight flier out of the sky?

PLANE B has another thousand pounds leeway which might be used for the addition of more machine guns, perhaps a small cannon, some armor, and should prove a more formidable threat to the bomber than did *PLANE A*.



Plane B's extra armament is not an unmixed advantage, however, because the added weight means that it is somewhat less maneuverable than the lighter fighter, and therefore a bit easier target for the bomber's guns. Its longer "turning radius" will also make it a little slower in circling back to the attack after each of its rushes at the bomber.

This decrease in maneuverability will be true, in successively greater degrees, in the cases of Planes C and D.

PLANE C would be even more heavily armed and armored than Plane B, and therefore might stand an even better chance of trading punches with the bomber, and would also be likely to have more gasoline capacity to stay up and chase the bomber, in case the bomber's pilot decided to turn and run for home.

PLANE D in this particular set of circumstances, might arrive too late to prevent the bomber from dropping its explosives on the appointed target. But even so, its heavier fire power and longer cruising range would make it possible to pursue the bomber and perhaps destroy it on its homeward flight.

This relatively simple example is illustrative of the problems involved in aerial warfare, and emphasizes the necessity for diversified fighting equipment.

We must have rapid climbers—highly maneuverable interceptors and heavy sluggers.

Then too we must have fighters in which *SPEED* has been accentuated above all other characteristics.

Speed is an essential requisite of the primary pursuit function —*namely the overtaking and destruction of enemy bombers* —and a fast moving pursuit plane is a difficult target.

Superior speed increases the pursuit pilot's chances of setting the terms of battle—*WHEN, WHERE and HOW.*

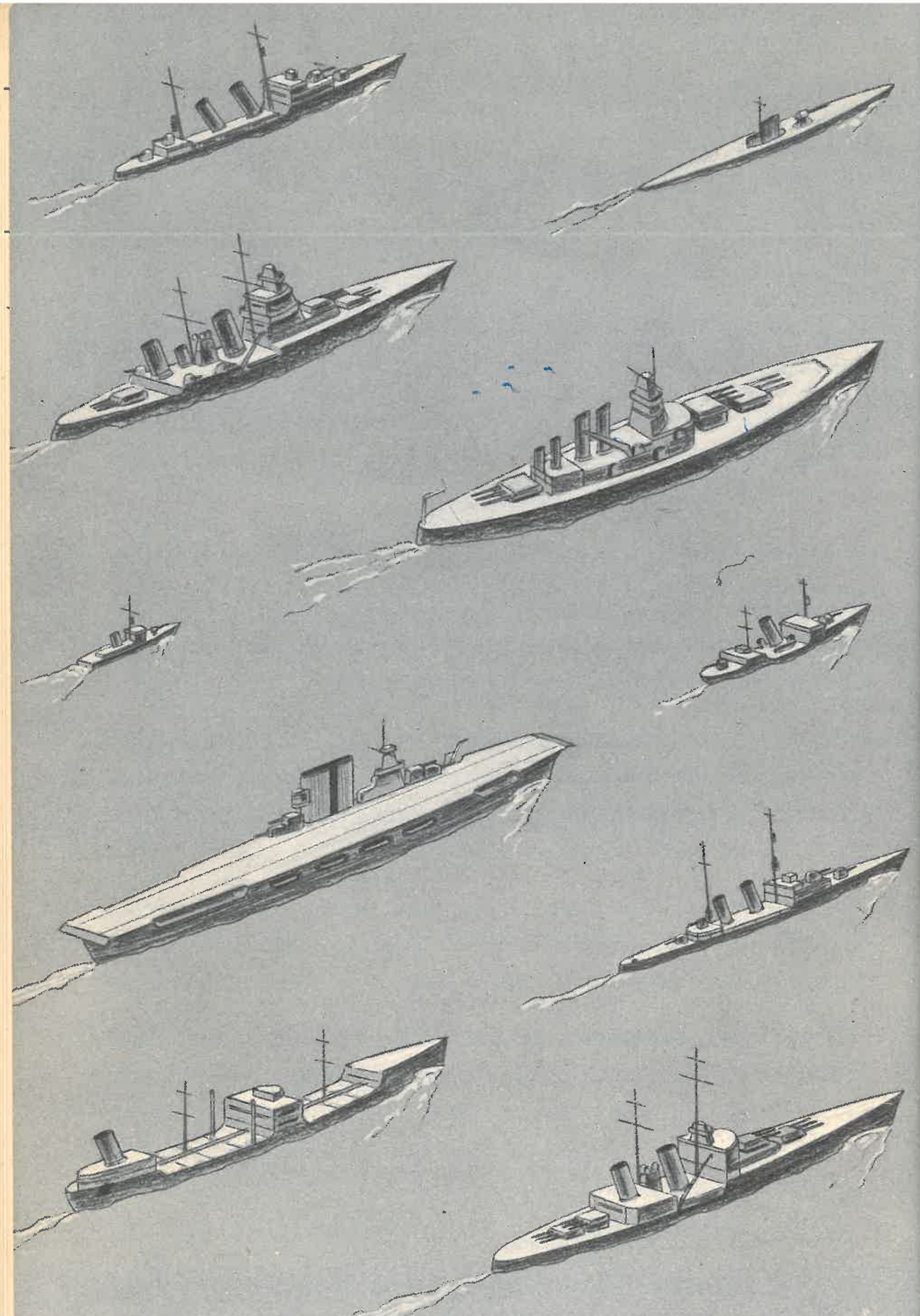
But the "*designing in*" of maximum speed involves sacrificing other qualities, to a greater or lesser degree.

A fast-moving object, no matter what its shape, cannot be diverted from its course as quickly as one moving at less speed. Therefore, a fast plane, generally speaking, is less maneuverable than a slow plane.

Furthermore, high speed flying and power diving increase the strains and stresses—so the plane must be made sturdier and this means more weight.

Weight has comparatively little effect on speed—but, other things being the same, it does limit the *rate of climb.*

Just as in the case of naval warfare, aerial combat requires a wide diversity of equipment.

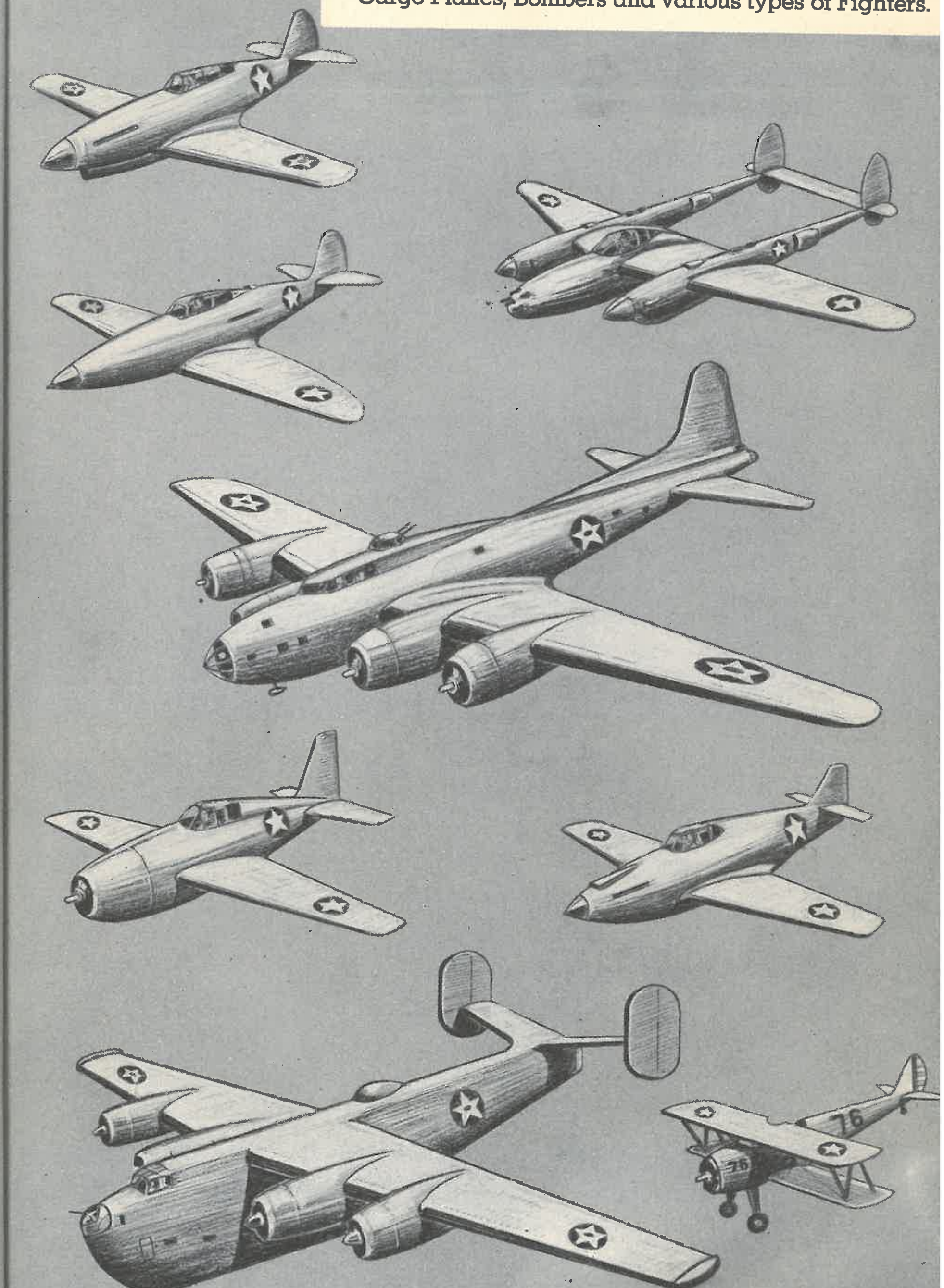


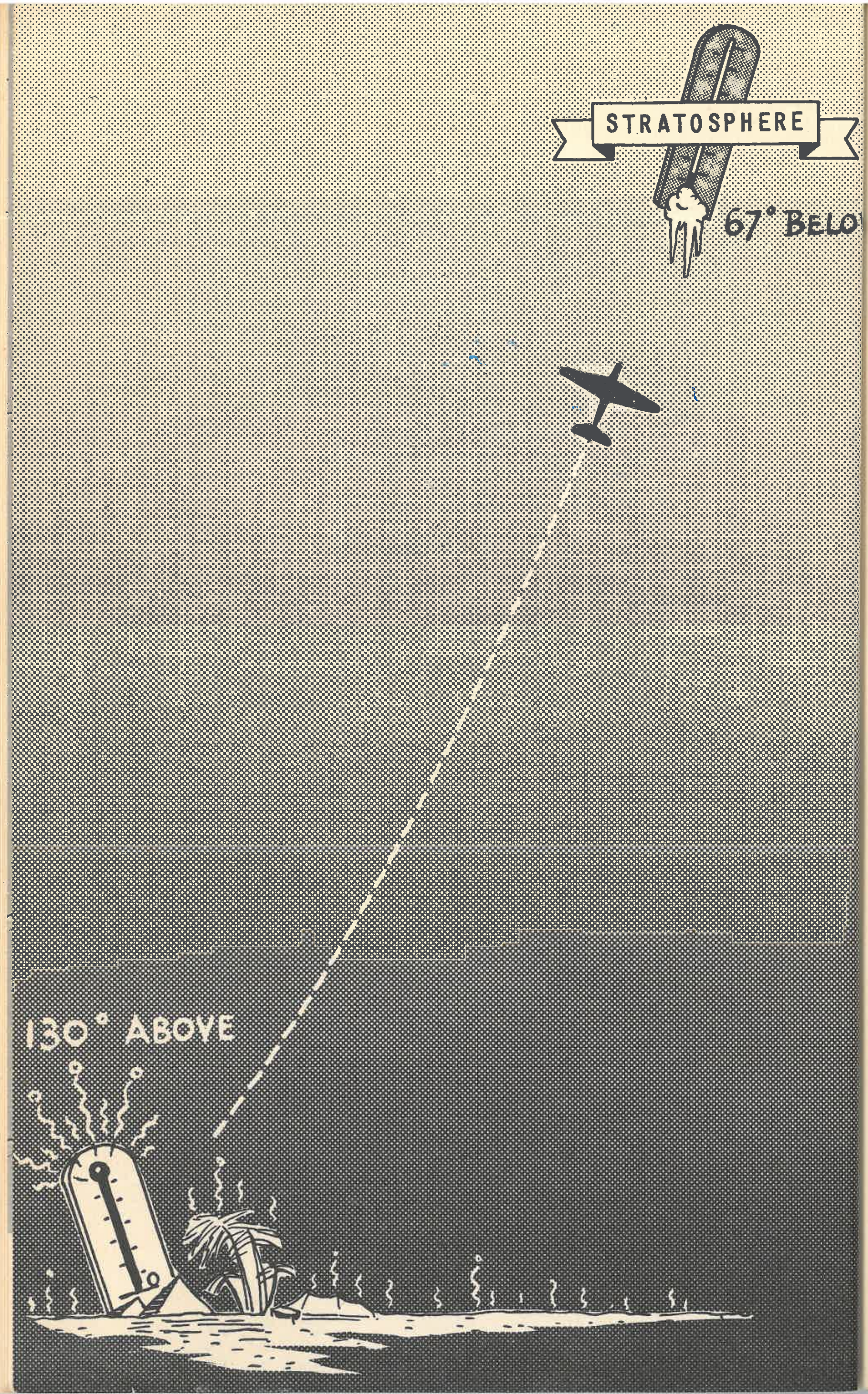
⋆ ⋆ ⋆ *Victory on the Seas* ⋆ ⋆ ⋆

—requires a wide diversity of equipment, including Battleships, Aircraft Carriers, Destroyers, Cruisers, Submarines, "Sub-Chasers", Destroyer Escorts, etc.

⋆ ⋆ ⋆ *Victory in the Air* ⋆ ⋆ ⋆

—requires a wide diversity of equipment, including Trainer Planes, Observation Planes, Transport Planes, Cargo Planes, Bombers and various types of Fighters.





★ ★ ★ THE SUMMING UP ★ ★ ★

THIS BOOKLET DRAWS TO A CLOSE. In it we have tried to bring out some of the basic factors affecting the design of engines and power plants for military aircraft—with particular reference to fighter planes.

In the light of the facts developed, it becomes increasingly evident that no one design can be best on every count.

There is no perfect all-round, all-purpose plane. Special types are best for particular and limited uses. Others, designed for a wider variety of conditions and purposes, may be preferable because of their greater adaptability to changing needs. The types we *should* have and the numbers of each depend upon the needs of strategy—as determined by military specialists who, on the basis of complete information from the fighting fronts, are constantly engaged in planning the tactics for the Allied Forces.

In the same manner, the designers of engines and planes—working in close collaboration with the Army, the Navy and the Air Forces — are continually engaged in working out the best lines of planes to meet the wide diversity and changing requirements of military needs — *with due consideration to the problems of standardization.*

While compromise will always be necessary, the physical limitations are constantly being overcome, the problems solved and the difficulties surmounted as the art continues to progress.

As a case in point, the record of American engine manufacturers, since the start of the war, is well ahead of engine makers in any other country. For example, the horsepower of one of the three standard engines now used in our Army fighting planes has been increased more than 30 per cent since 1939 without any increase in the size of the engine and with *a startling reduction in the weight-to-horsepower ratio.*

As a result, America is producing the lightest, high-horsepower, aircraft engines in the world—and this availability of greater power in a lighter "package" opens up new opportunities to the designer of the overall plane.

It is also gratifying to note that the United States is the only nation with a successful Turbo supercharger—being used on planes now produced in quantities.

In the light of the progress that is being made, it is difficult to predict what the future may bring as regards either engine design or overall plane design.

The possibilities are constantly being widened—the barriers swept aside.

Thus, it is inevitable that some of the statements in this book will need to be revised with the lapse of time.

To minimize that necessity, we have tried to keep away from mechanical details in the writing of this book—also because of censorship restrictions.

Things are happening so fast that anything that is written is likely to be out of date before it is published—*which, incidentally, accounts for much of the confusion and misunderstanding regarding the status of American Military Aircraft.*

Model for model and type for type, American built aircraft, using American built engines, will competitively meet and usually surpass the best that has been developed by either Allied or enemy nations and this is not surprising when we recall that the first successful flying machine was invented here in the United States and that our country, with its modern manufacturing techniques, has produced more airplanes than all the rest of the world.

The fastest, longest range, highest altitude fighters in the world today are being produced right here in our American factories and it is interesting to note that one of them is powered by the same basic engine used in planes designed for ground attack and troop

support at altitudes under 10,000 feet, where the higher flying types are at a disadvantage.

In contrast to Great Britain, the bulk of American production has been on planes designed for low and medium altitudes, but this is not due to any limitations in our engineering and manufacturing ability. It is because Great Britain has concentrated on the manufacture of planes best suited to the high altitude requirements of its own immediate battle front—whereas America has spread its production efforts over the wide range of equipment required to meet the diversified needs of the fighting fronts *ALL OVER THE GLOBE!*

While high altitude fighting has characterized the conflict over the English Channel and adjacent areas, the bulk of air fighting in other theaters of war has been at relatively low altitudes.

It is true that the Japanese "Zero" will attain higher altitudes than certain American planes that have engaged it in combat, but this does not mean that it is a better plane or a more effective fighter.

Let us repeat that the design of a plane is a compromise. No one aspect can be over-accentuated except at the expense of something else.

The route taken by the engineer is determined by the demands of the military authorities—which are based on the problems of strategy—*tempered to a greater or lesser degree by a consideration of the human factors.*

On the latter point the United States stands at one extreme—Japan at the other—*or, as Captain Eddie Rickenbacker has aptly expressed it:*

"The Japs regard it as an honor to fight and DIE
but we Americans think it is a greater thing
to fight and LIVE and fight again!"

Deeply embedded in the Japanese philosophy of design is the traditional low value placed on human life by the militaristic Nipponese. The pilot's life and the investment of time in his training apparently count for little in the Japanese air fighting strategy.

Witness the fact that the Zero carries no armor, is stripped of most of the protective devices with which American planes are equipped, its normal cruising radius is shorter than that of any American fighter, and its construction has been lightened to a point where it cannot stand up against American fighters. In other words, the Japs have concentrated their horsepower on high altitude performance at the sacrifice of other qualities.

The American design philosophy, on the other hand, is the opposite. It is based on the idea that the pilot is more valuable than the ship, and that the pilot will be more effective *as a fighter*, if he is given an *all around* tool to fight with—one with *more protection, better instrumentation, greater cruising radius, heavier fire power, more ammunition* than the enemy—along with *higher speed* and adequate climbing ability.

Believing as we do in our own American philosophy, it is gratifying to note that our planes have already turned back three major Japanese invasion threats and in current engagements it is not at all unusual for our Navy fighters to shoot down 10 or 12 Zeros for each American plane lost.

Thus the Japs, without regard to the broader considerations, have put their bet across the boards, on maneuverability and climb and the tide turns against them.

We might summarize by saying that there are two ways to appraise military aircraft:

One is through analysis of design, performance characteristics, fire power, etc., in relation to the specific mission or missions that the plane is designed to perform. *WHERE will it be used? HOW will it be used? WHAT altitude bands will it be called upon to cover?*

. . . and, since compromises are necessary, *have the compromises been worked out along lines that will give the best all around answer?* In other words, is it a *WELL BALANCED DESIGN?*

The other way to appraise fighting equipment is to follow the "*BOX SCORE*" on clashes with the enemy as reflected in Army and Navy communiques, and press dispatches from independent observers at the front.

Our American Fliers, using American-built equipment, have met the enemy on every front with an overall score of better than 4 to 1—in our favor.

This, of course, is only the beginning. We are just getting started and while it is beyond the prerogatives of an industrial institution to venture predictions on military matters, it is our conviction that the "score" will be increasingly favorable in the months ahead.

This conviction is based on confidence in our military strategists.

It is based on confidence in the ingenuity and resourcefulness of our designing engineers.

It is based on confidence in the skill of our American craftsmen who, down through the years, have set the pace for the world on fine workmanship combined with the techniques of large scale production.

It is based on confidence in the ability of our rapidly growing, far-flung organization of service experts to keep them flying and fighting at full effectiveness, irrespective of where they may be.

And last but not least . . .

It is based on an unbounded confidence in the men who are to use them and in the cause for which they are fighting!

"When Hitler hitched his chariot to an internal combustion engine, he ran it straight down our alley."

LT. GENERAL BREHON SOMERVELL

Interesting Facts and Technical Definitions

THE FOLLOWING APPENDIX is included in the hope that it may, to some degree, compensate for the incompleteness of the main text matter.

It is also designed to serve:

1. *—as a* **REPOSITORY** ***for miscellaneous facts and figures.***
2. *—as a* **GLOSSARY** ***of technical terms.***
3. *—as an* **INDEX** ***to the main text matter.***

While the information was developed in collaboration with General Motors engineers, here again we have taken some liberty with the phraseology in an effort to make it understandable to the non-technical reader. To some degree this may have impaired the accuracy in a strictly scientific sense and we will appreciate any criticisms and suggestions that may lead to improvements in future editions.★

★ Much has been said in this book regarding the necessity for compromise in matters of engineering design and it might be observed in passing that a similar necessity arises in the development of popularized literature on technical subjects.

Simplicity of treatment is difficult to attain within the bounds of scientific adequacy.

Interesting Facts and Definitions

AERODYNAMICS—the study of air in motion, or that branch of dynamics which treats with the behavior of air under the action of force. The development of aviation has led to intensive studies and experiments in this field with a result that the aircraft engineer is able to predict the performance of a design with remarkable accuracy.

See Drag.

AFTERCOOLER—*See Page 44.*

AIR—consists principally of Nitrogen and Oxygen. It contains small quantities of various other gases. The problems of aerodynamics and streamlining are more readily understood if we think of air as being in the nature of a liquid. *See Page 12.*

ALTITUDE—height above sea level *usually expressed in feet.*

ALTITUDE AND BOILING POINTS—The boiling point of a liquid is dependent on atmospheric pressure. At sea level water boils at 212° Fahrenheit, but at 30,000 feet it will boil at a temperature of 156°. The effect on gasoline is even more pronounced. While from a strictly scientific standpoint gasoline does not boil in the same sense as water, for purposes of comparison we might say that the corresponding figures would be 140° at sea level as against 70° at 30,000 feet. (Based on temperatures required to "boil off" 10 volumes of vapor to one volume of liquid gasoline.)

ALTITUDE ENGINE—an engine with supercharging equipment designed to compensate for the decreased density of air at altitudes higher than sea level. *See Pages 29-51.*

ALTITUDE TEMPERATURES—Under so-called standard atmospheric conditions, the temperature of the outside air drops about 3° (Fahrenheit) for each 1,000 foot increase in altitude up to the stratosphere. This taken within itself is beneficial to engine performance. But the *DECREASE* in the temperature of the outside air due to altitude, is not sufficient to offset the *INCREASE* in temperature brought about through supercharging. At extreme altitudes, for example, where the outside temperature remains fairly constant at 67° *below zero* the degree of supercharging necessary to compensate for the thinner air may result in mixture temperatures as high as 250° *above zero.* This emphasizes the necessity for using Intercoolers or Aftercoolers in connection with high altitude supercharging equipment.

See Pages 44, 46.

ANEROID CONTROL—any control mechanism actuated by an ANEROID BAROMETER. May be used to adjust the pressure in the engine intake manifold; to control the mixture ratio in the carburetor; or to maintain the proper pressure in a controlled pressure cabin.

ANTI-KNOCK FUEL—a fuel that has the ability to resist detonation—*commonly called "knock" or "ping".* Anti-knock quality is important because the permissible degree of compression in a gasoline engine is limited by it. Our research chemists have not only played an important pioneer role in the development of anti-knock fuels, but have made tremendous advances in this field in recent years. Their accomplishments, coupled with our American techniques and facilities for the large scale production of such fuels—have been important factors in raising the limits of permissible compression with corresponding gains in the power and efficiency of our aircraft engines. *See "Octane Number".*

ATMOSPHERIC PRESSURE—the pressure exerted by the weight of air enveloping the earth. Standard atmospheric pressure means the pressure at sea level at a temperature of 59° Fahrenheit. It is 14.7 pounds per square inch which corresponds to a barometric reading of 29.92 inches of mercury. *See Page 12.*

AUXILIARY STAGE SUPERCHARGER—means the blower that is used to provide extra compression at *high altitudes.* In contrast to the "Engine Stage Supercharger" the auxiliary stage does not operate at full capacity until higher altitudes are reached.

See Pages 40-46.

BACK PRESSURE—the resistance encountered by the exhaust gases upon their exit from the cylinders. The lower the atmospheric pressure, the less the back pressure and this *taken within itself* is beneficial to power output. For example, a 1,000 H.P. Sea Level Engine would develop about 1080 H.P. at an altitude of 20,000 ft., due to reduced atmospheric pressure —*provided other things remained the same.* But "other things" do not remain the same and the penalties of the lower density of the intake mixture would overshadow the minor advantages resulting from reduced back pressure.

BOILING POINTS—*See "Altitude & Boiling Points."*

BOOST—increase in manifold pressure as a result of supercharging. See Overboosting. *Also Pages 31-35.*

BOOST CONTROL—any device for regulating the pressure supplied by the supercharger. *See Manifold Pressure Control.*

CEILING—*See Page 52.*

CLIMB, RATE OF—the rate at which an airplane can gain altitude, generally expressed in terms of *feet per minute.*

COMBUSTION—In a gas engine the word "*combustion*" refers to the burning of the fuel-air mixture within the cylinder to produce power. *See Page 13.*

COMPRESSION—means increasing the density of the air or the mixture. In an ordinary gas engine this is done by the "compression stroke" of the piston, whereas in a supercharged engine the air or mixture is compressed before it goes into the engine cylinders and then compressed further (in the usual way) by the action of the pistons after it gets into the cylinders.

Other things being the same, the greater the compression the greater the power output. But compression raises the temperature of the mixture and if the temperature gets too high we get into combustion difficulties which work at cross purposes to power and economy.

These difficulties are of two kinds:

1. DETONATION—otherwise known as "knock" or "ping". When the pressures or temperatures are allowed to get too high, the fuel mixture burns too rapidly and unevenly. Instead of a smooth, steady travel of the flame in an orderly manner from the spark plug across the combustion chamber, we get harsh, fast, irregular explosions, resulting in sudden localized releases of heat and excessive pressures which cause loss of power and are injurious to the engine.

2. PRE-IGNITION—is closely related to DETONATION. In fact, it seems that Detonation progresses into Pre-ignition. When the engine gets too hot the mixture is ignited by compression *before the spark occurs* and when this happens, a part of the power resulting from combustion is wasted by trying to push the piston down too soon. Thus the engine is "*fighting against itself*" so to speak. The power impulses are uneven, the horsepower falls off and the excessive pressures and temperatures damage the engine parts and shorten the life of the engine.

So while it is true in theory that the higher the compression, the greater will be the horsepower output, beyond a certain point *the practical difficulties stand as a barrier to the theoretical gains* and the engine designer must carefully calculate the compression with a view

of making it as high as possible without getting into combustion difficulties. In the case of a supercharged engine this means the compression provided by the supercharger—*PLUS* the compression that takes place *within the engine cylinders.*

The total permissible compression depends to an important degree on the anti-knock characteristics or "Octane Rating" of the fuel that is to be used. The higher the "Octane Rating" of the fuel the greater the allowable compression.

COMPRESSION RATIO—as applied to a gas engine, means the volume of gas mixture in an engine cylinder at the *beginning* of the compression stroke *divided by* the volume at the *end* of the compression stroke.

CRITICAL ALTITUDE—*See Pages 53-56.*

CRUISING RADIUS—the radius in which a plane may operate *without refueling.*

DENSITY—means the ratio of *mass* to *volume*. If we visualize air as being composed of tiny gas particles, then its density depends on how close these particles are to one another. At low altitudes the air particles are forced close together due to the pressure exerted by the weight of the air above. At higher altitudes, where there is less pressure from above, the air particles "spread out" and a given volume of air will contain fewer particles and will weigh less than the same volume of air at sea level.
See Pages 12 and 21.

DETONATION—*See Compression.*

DISPLACEMENT—is the volume of space swept by a piston when it moves from the bottom of its stroke to the top of its stroke—*or vice versa.* The displacement of a multi-cylinder engine is the sum of the displacement of all its cylinders and is usually expressed in cubic inches. Other things being the same, the horsepower of an engine will be proportionate to its displacement.
See Page 15.

DRAG—means the resistance offered by air to a body moving through it. It depends on the *size* and *shape* of the body, the *speed* at which it moves and the density of the air *through* which it moves. At any given altitude the drag increases as the square of the speed. Drag can be greatly reduced through streamlining—and what the aircraft designers call "aerodynamic cleanliness."

ENGINE—The internal combustion prime mover and such accessories and equipment as are normally supplied with it. *See Power Plant.*

ENGINE STAGE SUPERCHARGER—means the supercharger that is built integral with the engine and which is designed primarily for sea level and medium altitude performance. See Auxiliary Stage Supercharger. *Also see Page 40.*

FIGHTER PLANES—*See Pages 7-9.*

HORSEPOWER—The word "Horsepower" is used to express the capacity of an engine for doing work. It is measured in terms of *force, distance* and *time*. One horsepower is the equivalent of the amount of work required to *lift 33,000 pounds a distance of one foot in one minute.*

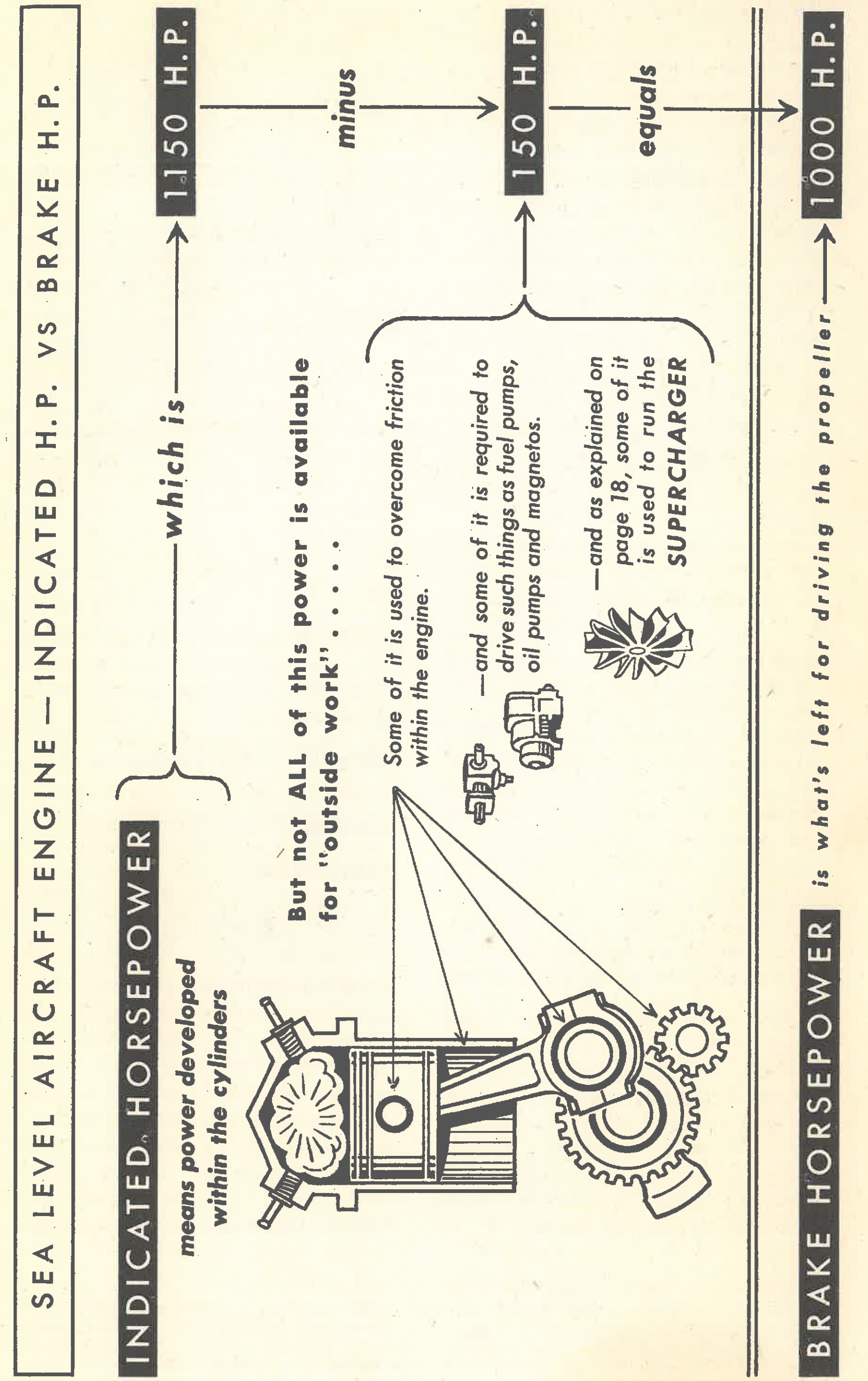
The word "*horsepower*" may be used in three different ways:

1. *Indicated Horsepower*
2. *Brake Horsepower*
3. *Rated Horsepower*

1. INDICATED HORSEPOWER—means TOTAL POWER developed *within* the engine—or what we might call the "*gross horsepower*".

As shown on the accompanying chart some of this TOTAL or "Indicated" Horsepower is used to run the engine itself—i.e. to overcome internal friction and to drive the engine equipment such as oil pumps, fuel pumps, magnetos and the supercharger.

2. BRAKE HORSEPOWER—means NET horsepower output—or the amount of USEFUL work that the engine is



HORSEPOWER—continued ★

capable of performing over and above the power required to overcome internal friction and run the engine equipment. *It is the power available at the end of the crankshaft.* ★

3. RATED HORSEPOWER is a term used to define the *safe operating limits* of an engine *under certain prescribed conditions*. It means the power output that an engine may develop under certain specified conditions of operation—*with a reasonable life expectancy.* ★

The same aircraft engine may be given two or more different "Horsepower Ratings" such as:

NORMAL RATING—which means the horsepower that an engine is considered capable of delivering *continuously*—without subjecting it to undue stress. *The Normal Rating of an engine would be lower than the maximum Brake Horsepower that it is capable of developing.* ★

CRUISING POWER RATING—which means the horsepower that an engine would be capable of delivering continuously *with economical fuel consumption*—and is considerably lower than the Normal Rating. It is the rating at which an engine would be operated on long range flights—such for example as crossing the Pacific Ocean. ★

TAKE-OFF RATING—means the maximum power output permissible incident to "take-off"—*to get the plane into the air and up to a safe flying altitude.* ★

MILITARY RATING—the maximum horsepower permissible for 5 to 15 minute periods. Such ratings are established by the Air Forces to define the limitations incident to military maneuvers. (In addition to the regular "*Military Rating*" there is also a special "*War Emergency Rating*" to meet the needs of actual combat operations.) ★

ALTITUDE RATING—While the rating of an automobile engine is always made *on the basis of sea level testing*, an aircraft engine may, in addition to its Sea Level Rating, have power ratings at one or more altitudes, depending on the type of supercharging equipment. ★

HYDRAULIC CLUTCH—a clutch which uses fluid to transmit drive or torque. *See Page 38.*

IMPELLER— a high speed multiple vane fan such as is used in superchargers to compress air or mixture through the action of centrifugal force. In a high capacity supercharger the impeller may be geared to run at speeds up to 28,000 revolutions per minute—which would mean that the tips of the blades would be travelling at *over 700 miles per hour!* As will be noted from drawing at the top of the next page a supercharger impeller is not quite so simple as was indicated in sketches used for illustrating the different types of superchargers on pages 17 and 31 to 46.

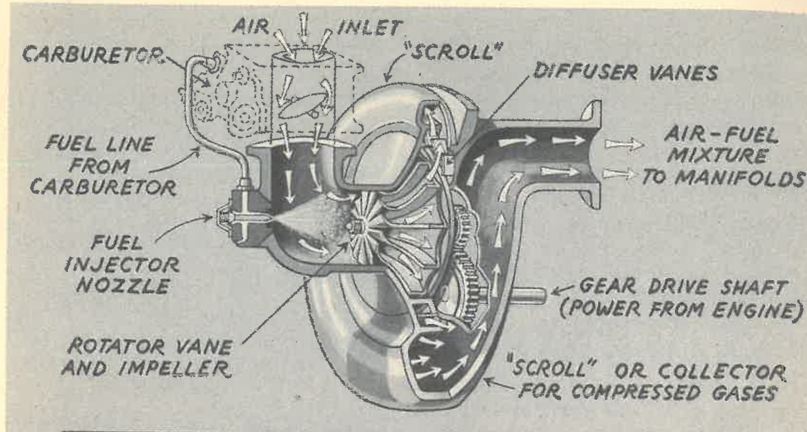
INDICATED HORSEPOWER—*See Horsepower—page 76.* ★

INTERCOOLER—*See Page 46.*

MANEUVERABILITY—as applied to an airplane, means the ability to make short turns in any direction, starting from any position. *See Pages 58-59.*

MANIFOLD PRESSURE— the pressure in the intake manifold of the engine. The weight of the mixture entering the engine cylinders varies with manifold pressure and temperature. In an ordinary automobile engine the pressure would be less than the outside atmospheric pressure because of air friction losses in the air induction system. In a supercharged engine, however, manifold pressure may be considerably higher than the pressure of the outside atmosphere.

★ **In the light of these various definitions, it is evident that any horsepower figure used in connection with an aircraft engine means very little *unless we know what KIND of horsepower, i.e. the conditions on which it is based, etc.* And when comparing two different engines it is important to use horsepower figures that *reflect the same conditions of rating.***



CUTAWAY VIEW OF A SUPERCHARGER

MANIFOLD PRESSURE REGULATION— control of the pressure in the intake manifold, sometimes called "BOOST CONTROL" or "SUPERCHARGER CONTROL". Regulation may be obtained either by throttling the air intake, or by varying the speed of the supercharger impeller, or by using only one stage of the equipment. *See Pages 31, 34, 38, 40.*

MECHANICAL CLUTCH— a device for connecting or disconnecting a power supply. A mechanical clutch used to drive a supercharger is essentially the same as the clutch used in an ordinary automobile except that it is smaller and more heavily loaded. See Hydraulic Clutch. *Also see Page 36.*

OCTANE NUMBER— a standard or "scale" for rating the *anti-knock* qualities of gasolines. The higher the Octane Number of a gasoline, the less its tendency to knock, and the higher the permissible compression. As a result of the High Octane fuels available to the American Air Forces, our aircraft engine designers are able to provide a higher ratio of horsepower to weight than would otherwise be possible. *The conquest of the air depends on the conquest of fuel "knock".*

OIL COOLER— equipment for cooling engine lubricating oil to keep it within the proper temperature range.

OVERBOOSTING—supercharging to a pressure higher than is safe for continuous operation. Although overboosting is dangerous when carried to extremes, it is frequently indulged in to increase the power for take-off, or under emergency combat conditions. *See Rated Horsepower, Page 78.*

PITCH CONTROL— a mechanism through which the angle or "*pitch*" of the propeller blades may be changed during flight in order to maintain maximum propulsion efficiency. Serves a somewhat similar function to the gear shift mechanism in an automobile and is usually automatic in its operation.

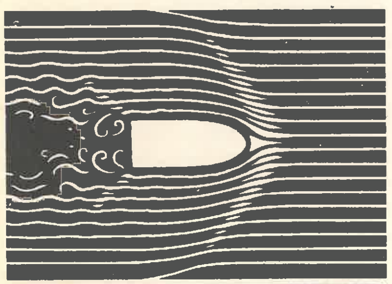
POWER LOADING—the *total weight* of the loaded plane *divided by the Rated Horsepower.*

POWER PLANT—In aviation the correct technical term is "*Power Plant Unit*" or "*Power Plant Installation*" which, as explained on Page 6, includes the

complete equipment used to convert heat energy into propeller thrust. Also includes starting equipment, electrical generator to supply current for miscellaneous uses, gun synchronizers, etc. *See Page 6.*

PRE-IGNITION—*See Compression.*

PROPELLER SPEED—As mentioned on Page 16, the tip speed of an airplane propeller must be kept below the speed of sound. When any object approaches the speed of sound—*about 750 miles per hour*—there is an enormous and sudden increase in drag. The air no longer follows the usual laws that govern its behavior. The pressure generated at the forward point cannot get out of the way and so must be carried bodily along by the power of the moving object. Furthermore, the air will no longer close in at the rear end of the object—*which incidentally accounts for the fact that an ordinary bullet does not need a streamline tail!*



Above speed of sound

A certain rough similarity exists in the "bow wave" of a steamship. Water which cannot get out of the way is thrown upward from the surface. In air, however, there is no such upper surface, and no place for the "bow wave" to go. Hence, it must be dragged along by brute force. (Based on explanation by John G. Lee in his excellent book "*Fighter Facts and Fallacies*". Wm. Morrow and Company, 1942.)

PROPELLER THRUST—the driving force exerted by the plane's propeller.

RAM—increased manifold pressure resulting from the impact on the air intake of the engine's air induction system due to the plane's velocity through the air. With effective design of the air intake the "*ram effect*" may appreciably boost the pressure of air going to supercharger. *See Page 54.*

RATED HORSEPOWER—*See Page 78.*

SEA LEVEL ENGINE—one which develops its maximum horsepower at sea level, the power falling off in approximate relation to altitude increases. *See Pages 17 and 25.*

SERVICE CEILING—*See Pages 52-56.*

STRATOSPHERE—the upper region or external layer of the atmosphere beginning at approximately 36,000 feet, where the air is very thin and the temperature remains practically constant at 67° below zero Fahrenheit irrespective of further increases in altitude. The stratosphere is free from clouds and in contrast to the lower atmosphere there are no strong vertical air currents.

SUPERCHARGING—means compressing the air or the intake mixture to increase the weight of charge going into the engine. Frequently called "*boosting*". *See Pages 17 to 51.*

TEMPERATURE—*See Altitude Temperatures.*

TURBO SUPERCHARGER—*See Page 46.*

VAPOR LOCK—If the gasoline in the fuel lines gets too hot, or if the atmospheric pressure is greatly reduced, bubbles form in the fuel lines, interrupting the flow of gasoline to the carburetor. This results in uneven fuel supply to the engine and may cause missing or misfiring.

WING LOADING—the weight carried by the wings expressed in pounds per square foot, *i. e. the total weight of the loaded airplane divided by the total projected area of the wings.*

See Marked Paragraphs - Page 68

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