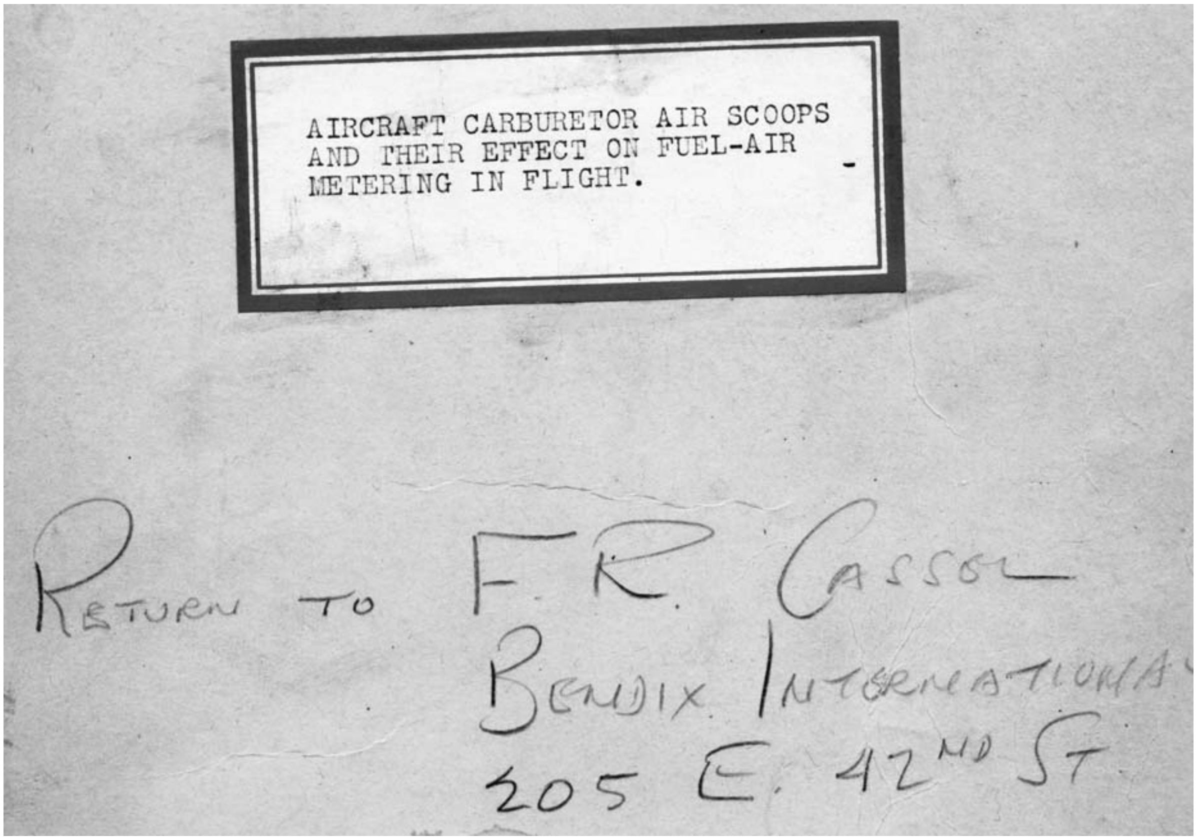

AIRCRAFT CARBURETOR AIR SCOOPS
AND THEIR EFFECT ON FUEL-AIR
METERING IN FLIGHT.

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AIRCRAFT CARBURETOR AIR SCOOPS AND THEIR EFFECT ON FUEL-AIR METERING IN FLIGHT.

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INTRODUCTION

In our recent intensive efforts to carry airplane performance to higher speeds and altitudes, we have encountered many complex problems in apparently simple development of previously satisfactory practice. Ignition, cooling, and fuel vapor control are only a few instances. Similarly, the design of an aircraft carburetor air scoop would appear to offer only elementary questions of design. How to locate the opening where it will receive full air speed ram, and how to fair it in with the cowling structure, would seem to lie well within current knowledge; actually there are indications that many present designs could be improved. Likewise, many of our ideas as to the effect of air scoops upon carburetion have been derived from the past, when carburetors were non-automatic, requiring continuous readjustment by the pilot as soon as the airplane left the ground for changes of air pressure, temperature, and ram; and any accompanying disturbances in the scoop duct system could usually, though not always, be taken care of by the same manual adjustment.

The automatic carburetor has now become indispensable for military use and has also proved its worth in commercial service. Rather peculiarly, however, the precedent set with the older non-automatic carburetors of making all tests and carburetor settings on the engine test stand on the ground, has up to this time been maintained with the automatic carburetors. We now have experience to indicate that the maximum airplane performance cannot certainly be obtained when the carburetor setting is derived from ground tests alone and that we will hare to gain some further knowledge and develop new instrumentation and equipment before we can fully reproduce flight conditions on the ground so far as the carburetor is concerned. Until that time, we must be prepared to occasionally modify our ground test conclusions and settings by flight check.

This paper deals particularly with some of these flight conditions, which have not heretofore been taken into consideration in ground test. Some of our work is incomplete, particularly the instrumentation reports, and on such account this presentation is perhaps premature. It is given now, however, in the hope that it may secure immediate attention, and perhaps more effective attack, upon problems, which definitely affect the performance of our airplanes.

CONTINUITY OF WHOLE AIR INTAKE SYSTEM

Originally the aircraft carburetor air scoop was merely a frontal air intake to help accelerate the air from flight speed up to its velocity through the carburetor. Now the airplane speed and slipstream speed have risen far above the velocities we dare use in the carburetor and manifolding; and they represent a source of energy that can have profound effect upon the whole intake function. It therefore seems worthwhile to begin by considering the whole intake system as one unit, of which the different sections are actually interdependent. In such treatment the main considerations should perhaps be --

(a) to obtain greatest possible ram and maximum Critical altitude with least addition to the airplane head resistance (which is definitely in the domain of airplane research and design), and

(b) to obtain this objective with the least possible interference with the fuel and air metering functions (which brings together the airplane engineer and the carburetor engineer).

Figure 1 is a sort of composite sketch of late practice in air intakes, and illustrates the varied and sometimes conflicting considerations of design. To indicate relative areas we have given at different points the air velocities of average practice, <u>at rated power at sea level.</u> At Critical altitudes some of these velocities may be nearly doubled, and at light cruising powers they may be much decreased. Considerations of supercharger design make it desirable that the entrance diameter "A" be kept as small as possible. It is therefore necessary that the approach "B" to the impeller entrance be made free and direct: but as this tends to add appreciably to the overall length and weight of the engine, a generally accepted compromise is to change at "B" to a rectangular section of enlarged area, and to slant the passage at the angle "C", less than a right angle, to decrease bend losses. We regard the transition shape from "B" to "A" as one of the most important and difficult elements of the intake system first, to insure uniform and normal air flow into the impeller disk; second, to obtain similarly uniform delivery of fuel spray (when the fuel has been released anterior to this point). To avoid flow energy loss, it has now become accepted practice to maintain the generally rectangular proportions of "B" up through the carburetor, scoop elbow, and scoop duct.

Reverting now to the scoop entrance "H", this is preferably located where it will receive full air speed ram, but far enough from the propeller that it does not feel the "spat" of air from each passing blade. Apparently the opening should be raised above the cowl somewhat to clear the boundary layer, and to maintain ram during climbing attitude. The area, of opening should be such as to maintain during climb a ram value only a few inches below the indicated air speed impact pressure across the full section "F" of the carburetor entrance, which of course requires a well-designed scoop elbow.

Because of the difficulty of knowing the distribution of flow rate when it is not uniform across a given section, and the similar uncertainty as to local air density, we have adopted the practice of using a "nominal velocity", obtained by dividing the air volume flowing in a unit time, assumed at external air density, by the area of the passage section.

The considerations governing design of the scoop elbow will be discussed in later paragraphs. It will be noted that decreasing the angle "C" (Figure 1) to favor the air entrance to the supercharger, has made the scoop elbow "G" angle more acute and less favorable to air flow.

As to the carburetor air passage, the important elements are the throttle, venturi throat, the air speed metering elements therein, and the density compensator or aneroid. The way in which these are affected by <u>scoop phenomena in flight</u> is a major subject of this paper. As previously suggested, one of our main objectives is to achieve a practice whereby the metering of the carburetor as installed in the airplane in flight will be as nearly as possible the same as on the engine test stand.

ELBOW EFFECTS UPON FLOW RESISTANCE AND CARBURETOR METERING

These have received major attention in past discussions of scoop design and one fallacy in such treatment has lain in the assumption that what happened in the elbow on ground test, under steady inflow of air, was exactly what happened in flight. Actually, flight conditions sometimes seem to superimpose new effects upon those of steady flow. However, we will first discuss a few of the basic forms as to their steady flow characteristics.

Figure 2 shows a "round" elbow and a chart of the velocity distribution across it under suction-induced flow. The actual model was constructed of wood spacers with sheet Lucite walls. A detail of the velocity-measuring element is shown in the corner view. Figure 3 is a still taken from a moving picture film of kerosene smoke flowing through this elbow, from which it will be seen that the stream followed the elements of curvature fairly closely. In air box test this type of elbow disturbed the carburetor metering very little. Pressure measurements in flight on one airplane with this type of scoop showed a quite even pattern at the carburetor deck, and we had no evidence of appreciable departure from ground test metering: this was with a short over-cowl scoop. On another airplane with this same general shape of elbow, but with an extension forward of some three or four feet, there was some metering disturbance, and not quite as even a pressure pattern on the carburetor top deck as with the previously mentioned airplane. We suspect that if turbulence is excited in the scoop duct by constriction at the entrance, or by oblique or turbulent flow induced by the propeller, that the air stream can oscillate rather easily in passing around this type of bend: but we have nothing to prove this point.

Figure 4 shows a transparent model of "sharp corner" elbow with velocity vectors at three different levels, while Figure 5 shows the smoke flow through it. It is difficult to appraise the velocity distribution when the stream lines are irregularly oblique, as they are in this case, but the vector curves check with the smoke figures in indicating that the flow goes toward the back of the scoop just beyond the elbow. Presumably if the scoop had had about two diameters more of straight run, the flow would have nearly equalized across the section.

Figure 6 shows a similar, though not identical, scoop tested in flight by one of our engine companies, and the pressure distribution observed across it, which is generally similar to that observed in the air box. In this particular flight test there was negligible disturbance of carburetor metering at the lower air velocities, but quite a bit at the higher ones, as will be discussed later. We have other installations with this shape of scoop and metering disturbance has sometimes been reported.

Figure 7 shows the previous scoop elbow of Figure 4 with straightening vanes and the corresponding pressure curves. Figure 8 shows the smoke flow through this scoop. It will be noted that there is a pronounced pressure, irregularity immediately under the vanes, which emphasizes the need for vertical rise of preferably about six vane space widths between the lowermost vane and the carburetor metering elements. With this there was negligible metering disturbance in the air box. We have but one report of flight test with this shape and in this no metering disturbance was reported. It will perhaps be of interest to compare Figures 7 and 8 with Figure 30 in later pages.

Figures 9 and 10 show what we have called for obvious reasons an "island" scoop. The conception here was to create a central and symmetrical flow of air down to the carburetor by opposing the two halves of the entering air stream to each other as they enter the vertical down sweep. As the graphs show, there is a tendency for the flow to be strong down the center so that a considerable length of riser is necessary. Also it is difficult to balance the front and rear flows accurately against each other; so that air box trials are necessary for successful design of this type of elbow. As shown in later Figure 36, this scoop has given quite satisfactory performance in flight, with no reported metering disturbance. We are inclined to believe that a scoop of this sort, that compels division and remixing of the air stream at the scoop elbow, is less affected by propeller-induced turbulence than the single passage types: but again we have no definite proof of this.

Figures 11, 12, 13, and 14 show characteristics of the "acute angle" scoop elbow such as is illustrated in Figure 1. These pictures illustrate the point of carrying the entrance end of the vanes forward across the warm air opening so as to equalize the pressure at the carburetor deck; as is well known, most warm air valve constructions are sadly deficient in this respect. We have no reports of flight tests with this shape of scoop with vanes in it; however we did find in air box test that use of the vanes regained at the carburetor top deck one inch of mercury of pressure that was lost by the acute angle without the vanes. Since this pressure loss would be magnified by the supercharger there is reason to believe that, other things being normal, use of the vanes should give at least one thousand feet gain in Critical altitude and possibly considerably more, with an acute angle elbow like this.

HOW UNEVEN AIR FLOW DISTURBS AIR METERING. We have seen that the different elbow shapes result in uneven velocity distribution across the face of the air stream: and we have also found that these irregularities continue down into the carburetor. The manner in which they affect metering is of some interest.

In essence, present day carburetors meter by *measuring the velocity* of flow *in an air stream of known area,* with correction for the density of the source of flow. The carburetor structure thus involves a constriction, or venturi tube, to determine the area of the air stream: and one or more elements which respond to the air stream velocity and transmit to a fuel metering mechanism some measure of the pressure differential between the air stream *impact,* or *total pressure,* on the one hand, and its *velocity* depression, on the other.

Through a large range of airflow such a differential varies with the air velocity squared, times the initial air density. The fuel flow follows a similar relation to its metering head, so that if air and fuel differentials are either equal or proportional through the above-mentioned range, the following will be true:

(1) $(\text{AIR VELOCITY})^2 \text{ x } (\text{AIR DENSITY}) \text{ varies as } (\text{FUEL VELOCITY})^2 \text{ x } (\text{FUEL DENSITY})$

(2) $(\text{WEIGHT FLOWING}) = (\text{VELOCITY}) \text{ x } (\text{AREA OF STREAM}) \text{ x } (\text{DENSITY})$

(3) $$\frac{\text{FUEL WEIGHT FLOWING}}{\text{AIR WEIGHT FLOWING}} = K \text{ x } \frac{\text{FUEL STREAM AREA}}{\text{AIR STREAM, AREA"}} \text{ x } \frac{\text{FUEL DENSITY}}{\text{AIR DENSITY}}$$

That is, at constant densities, a constant fuel-air ratio may be obtained from fixed site air and fuel orifices; and any desired regulation of the fuel-air ratio may be obtained by corresponding change of the fuel orifice size. Also, the correction for varying air density is as the square root of such density change, and under any density remains constant for different air velocities (until the Critical range is reached, as will be discussed later).

Figure 15 shows a number of different constructions for obtaining air velocity differential. It is not generally known that the impact or total pressure reading remains almost constant at different positions along the venturi tube from entrance to outlet, and is equal to the static pressure at an infinitely large entrance area; while the down stream pressure is but little different from the static at any given point along the stream. Thus, in Figure 15, "B" gives a little greater metering differential than "A". The "boost venturi" constructions of "C" and "D" give a higher metering differential for the same loss as the others, and also possess important advantages in the Critical range, as will be discussed in detail later.

When we come to examine the effect of the mildly uneven air flows of the elbows upon the elements of Figure 15, (mild as compared to some disturbances to be described later) we see that if either the pressure or depression elements, or both together, are located other than in a point of average of mean square air velocity, the metering differential will vary from that generated by the same air weight flowing in a. uniform stream. Actually, we do not find much difference between all the forms shown in Figure 15 so far as scoop sensitivity is concerned, some are slightly better with one elbow, some with another. However, this steady flow bend effect is not a serious drawback in our effort to give the airplane best performance because we can reproduce it on the ground, on the engine test stand or in carburetor air box test, and modify either elbow shape or carburetor setting as needed. Of the two it is preferable to modify the elbow so as to keep the carburetor setting uniform with that of the same engine on another airplane.

It should be noted that in ground test without a ram duct, an elbow should have a funnel placed upon its entrance to reduce entrance constriction and give the same flow lines as would exist with ideal air speed ram.

It has also been found that the sensitivity to elbow shape can be reduced by multiplying the number of air speed elements. Obviously there is a limit to the number of these that can be employed without obstructing the airflow: also, more multiplication does not correct completely, because of the velocity square relation. Figure 16 shows a variety of scoop elbows that give negligible variation on the metering with the two ranks of air speed elements of the type shown in "D" of Figure 15.

Figure 17 shows two sources of disturbance that should be avoided. "A" shows the air stream constricted but still including the air speed members, which makes the carburetor meter rich. "B" shows an obstruction such as an alcohol tube creating a "lee", or dead area over the velocity-metering member, which makes the fuel-air ratio lean.

DISTURBANCE FROM PROPELLER SLIP STREAM

We come now to one of a series of phenomena which have been bothersome in carburetor work because the action in flight did not reproduce in ground test, namely, the propeller slip stream effect. After much work we found that under certain conditions the propeller slip stream did not expand to lower velocities in the scoop duct as shown in Figure 1, but instead continued at its original high velocity as a turbulent and discontinuous flow, which resulted in an irregularly shaped air stream to and through the carburetor, which disturbed the metering considerably.

This particular trouble appears to be confined to scoops having their inlet close to the propeller. It is more marked when the slipstream velocity is high with reference to the airplane air speed: as for instance "reving up" on the ground, and during take off. If it occurs at all in steady level flight, it will probably be in high blower, and with high propeller pitch. Thus far we have found no means of overcoming this effect with anything we can do to the carburetor alone. Apparently we must either tolerate it, or remove the scoop entrance from the direct attack of the propeller blade impulses.

When we first began to surmise that the slipstream was affecting the carburetor metering we made the rather simple check illustrated in Figure 18. On a Cyclone engine mounted on a rigid stand with a fixed pitch club and no cowling we mounted a round corner air scoop, turned forward toward the propeller, with extensions of different lengths. With this we tried the three different types of carburetors, which have been used on this engine in air line service. The three charts show the pounds of fuel per hour versus engine R.P.M, with the different scoop lengths, each carburetor's mixture; adjustment being kept constant throughout its test. It will be noted that <u>with this same elbow bend,</u> change of distance from the scoop entrance to the propeller blades made a pronounced difference in the fuel flow rate with all three carburetors.

We next tried to analyze the airflow through the scoop to find what there was about it that so greatly affected the carburetor metering. For this we used the setup shown in Figures 19 and 20, which show respectively the longest and shortest scoop extensions, out of several lengths which were tried on three different elbows: the right, or sharp, angle one shown: a round bend scoop; and another form shown in Figure 9. On both the entrance and outlet of the elbow unit we placed grids of impact, or total pressure, tubes as shown in Figure 21.

With the sharp angle elbow, the impact pressure distribution with different scoop extensions it shown in Figure 21. With the short stub entrance, 19.5 inches from the rear propeller edge, the impact pressure distribution was relatively uniform, not varying more than from two inches plus to one inch minus of water at different points on both grids. With the next longer extension, 13.5 inches from the rear propeller edge, the variation in pressure distribution was more marked, amounting to six inches of water. With the next longer extension, 7.5 inches from the propeller, the variation was more sharply localized and reached eight inches of water. With the scoop extended to 1.5 inches from the propeller, the pressure was a little higher, but the distribution about the same. Further study and observation with tufts seamed to indicate that the slip stream just off the propeller blades had a pronounced spiral direction, which piled up pressure in the far side of the entrance of the longer scoops: and that there was also developed a spiral curl down the two opposite corners, which condition sometimes was maintained symmetrically at the scoop base flange and sometimes was reversed.

Figure 23 shows the pressure distribution obtained with the three different scoop elbows with extensions 7.5 inches back of the propeller edge. It will be noted that with all these shapes there was very little difference in pressure pattern.

<u>PRESSURE PULSATIONS CAUSED BY THE PROPELLER.</u> In addition to the

turbulence and disturbance of air stream pattern just noted, we have had repeated evidence that the propeller blades created a pressure-time pulsation in the scoop duct, most marked when the scoop opening was close behind the propeller rear edge. With one airplane a definitely audible, very low pitch note was reported by the pilots, which disappeared when the scoop was shortened some ten inches. In the effort to find out more about this phenomenon we have been developing a pressure indicator especially adapted to study of these delicate and rapid pulsations. The equipment is illustrated in Figure 24 and its scale size may be judged from the accompanying batteries shown. The special equipment consists of a power unit, an amplifier unit, special pressure pickup gauges, an oscillograph, a recording camera, and remote control for operation from the pilot’s cockpit. It is constructed to operate either in the laboratory on 115 volt, sixty cycle alternating current, or in an airplane on 12 volt direct current. The pressure pickup element was developed for us by the General Electric Company laboratories at Schenectady and has proven remarkably stable and consistent. As would be expected with so delicate an instrument, a major problem has been that of interpreting all the disturbances recorded.

So far our work with this device has been confined to checking and calibrating in our laboratory and on an engine on a ground test stand. Figure 25 is a typical record as suggesting the characteristic and scale of the indications. The lowest line was obtained from a contact breaker driven off the gun synchronizer on the engine, and timed to show a break each time a propeller blade passed the front of the air scoop. The second line is a timing wave fed directly from the power unit with 1/100 second frequency. The scoop pressure pulsations are clearly marked and in this test quite regular: it will be noted that they time exactly with the propeller blade passage. Their total amplitude is about 14 inches of water pressure. Apparently in this case the propeller was the chief source of pressure oscillation.

Figure 26 shows another record at 1800 R.P.M. ground propeller load. (The previous one was 1200 R.P.M.) In this the pressure phenomena are more complex and there is evidence that some other frequency, possibly the engine suction strokes or the natural frequency of the scoop as an organ pipe, was striving for ascendancy with the propeller beats. However, the propeller impulses were clearly dominant. It is too early to say just how much information we may hope to gain from this sort of test. In the past we have gone through a few experiences where we are quite sure it would have been valuable, particularly some of those to be described in the following section.

As regards this propeller blade effect on our test stand, we did a great deal of work with the carburetors, changing their metering elements, etc., in the effort to find a cure or offset to this high turbulence in affecting the carburetor metering, and nothing we tried reduced the maximum disturbance to less than ten percent change in air-fuel metering between the long and short extensions. We have therefore more or less given up hope of ever taking care of this sort of disturbance by anything we can do to the carburetor. We believe, however, that this effect is confined to takeoff and "reving up" since we did not find a similar pressure variation in any of our flight tests, some of which were made with the identical grid units used in these experiments.

If there is good reason to bring the scoop entrance up close behind the propeller, we would suggest that the opening be flat radially from the propeller center and long in its circumferential direction, as shown in "A" and "B" of Figure 27: so that the propeller blade width does not close off or trap a pressure impulse in the scoop as it goes by. In the average of our experience we have had less change of carburetor metering between flight and ground test with these than with type "C". To date we have not been able to fully identify any given metering disturbance in flight as solely due to a scoop opening close to the propeller. But we are rather afraid of these and we hope that future aerodynamic research will develop adequate ram characteristics without the necessity of bringing the carburetor scoop opening so close.

ENRICHMENT AT HIGH ALTITUDE AND HIGH POWER

The "scoop effects" thus far noted have boon relatively insignificant. We now come to a disturbance, which has been more annoying because of its consistently refusing to appear at all in any sort of ground test, although occurring fairly often in flight. This has made it particularly difficult to deal with under our present habits of procurement, which prescribe elaborate details of ground test with little provision for check or development work in flight. This disturbance manifests itself as an increase of air speed metering differential at high altitudes, high powers, and high speeds, and is superposed upon the normal enrichment due to decreasing air density. It appears to have some of the characteristics of <u>Critical velocity flow</u> and to be in some measure due to the elbow and propeller disturbances previously enumerated. Because it occurs only in flight, and because modern airplanes hare not been available for a systematic research program, our knowledge on this it at present fragmentary.

Referring first to basic air speed metering characteristics <u>under steady flow</u>, well known and repeatedly checked in air box test, Figure 28 shows on the upper left hand chart the velocity metering depression and also the lost or flow resistance obtained with different air flows at sea level with both a single venturi and boost venturi of standard proportions. In each metering curve its lower part is a true parabola. (The continuation of this true parabola has been marked at a dotted line.)

In the range of the true parabola, the fuel-air ratio tends to have a constant characteristic, at previously explained, but at the metering depression rises above the velocity square ratio, the fuel-air ratio increases, and we call this the <u>velocity enrichment.</u>

For this experiment the two venturii were selected to have about the same "loss" at sea level. The "single" has a lower metering suction than the "double", or boost form, which objection could have been helped by making its throat smaller, and carrying its expansion zone to the same diameter as before. But this change would have given a higher throat velocity and increased the <u>velocity enrichment,</u> which is already higher than that of the boost venturi.

The right upper chart shows similar values at 20.000 feet -- <u>under steady flow.</u> It will be noted <u>first</u>, that the depressions have increased inversely as the air density, per given weight air flow; <u>next</u>, with each venturi form the departure from a parabola is greater at a given weight air flow than at sea level; and <u>finally,</u> the <u>Critical point</u> of the tingle venturi, where the metering force and loss rise rapidly, is clearly shown to occur at about 7,800 pounds of air per hour.

If, instead of plotting the airflow of these two curves in weight units, we use velocity, and correct for the density, we find the different altitudes coincide, and we obtain the characteristic velocity enrichment relation of the lower chart, which brings to light a little known characteristic of the boost venturi construction. The boost, or smaller member, is really a channel in parallel with the conical entrance of the larger member, and as we see in the case of the single venturi in the upper right hand chart, any increase in enrichment is accompanied by an increase in "loss", or flow resistance. The result is that an automatic compensation takes place, under steady flow at least, and the depression in the small or boost venturi bears a constant relation to that in the larger one until the critical condition is reached in the boost venturi throat; after which its depression stays constant under increasing air flow so that the fuel-air ratio starts down. The point of starting down depends somewhat upon the proportions of the boost venturi; in this case it comes at about 500 feet per second nominal velocity in the main venturi -- i.e. the velocity that would exist in the main venturi throat if the air were at entrance density.

The curve here given has been repeatedly checked by different authorities and may be regarded as a basic characteristic. It should move slightly to the left inversely as the square root of the absolute temperature if the abscissa is velocity; but if the base line is air weight units, the curve should move to the right with lower temperatures. All this, of course, is under steady flow conditions. On this basis, we have selected for our carburetor practice a maximum air velocity of 400 feet per second for boost venturi constructions, and 300 feet per second limit when single venturii are used.

VELOCITY ENRICHMENT IN FLIGHT. The foregoing is preliminary to consideration of velocity enrichment in flight. Figure 29 in the upper left shows curves of metering suction, each at a constant altitude, plotted against indicated horsepower. By using a known factor of reasonable accuracy we can compute the airflow itself: and if we assume this factor constant we can apply the parabola characteristic to these curves as was done with Figure 28. Then, if we plot the departure from the parabola as ordinate against nominal main venturi air velocity as abscissa, we have a picture of the departure from normal air metering. Note that this method eliminates all other carburetor characteristics and variables from the picture. It does require that --

a. The temperature and pressure of the air be accurately measured.

b. The fuel-air ratio should be within the range of maximum power; otherwise our air consumption per horsepower factor will change.

c. The altitude compensation must remain constant throughout each fixed altitude run.

The scale of accuracy, of course, depends upon the torquemeter, and the correction from brake to indicated horsepower.

Nevertheless, the conclusions indicated by these curves have been borne out by exhaust analyzer and fuel consumption measurements, and may be regarded as clear indications of a trend. They show rather clearly that there is a tendency toward enrichment with increasing air intake rate; of which the functional significance might be in the venturi system, the scoop duct, or (rather unlikely) in the supercharger entrance.

Though the curves do not show it, the record of the test reports that the enrichment sometimes seemed greater with the ship in climb attitude (when the propeller disturbance referred to in the previous chapter might possibly have been more active.)

The lower left hand curve shows the enrichment versus air intake velocity, as reported in flight} also that of the carburetor alone under steady flow in ground test. The right hand charts show a similar pair of indications after we made a change in the carburetor to throw it leaner at the higher velocities. It will be noted that the change in steady flow characteristics is reflected, and if anything augmented, in the airplane.

Figure 30 shows another type of flight test in which the horsepower was left fairly constant while the chip climbed. This test involves the same scale of uncertainty as the one previously described; and in addition, rests upon the promptness and accuracy of the aneroid in passing from one altitude to the next. Yet these readings were also borne out by those of exhaust analyzer and flow meter.

They also show the general characteristic of velocity enrichment to a much greater degree than the carburetor alone. Again a minor change in the steady flow ground metering of the carburetor shows a major change in the) characteristics in flight. Incidentally, the pressure pattern in the air scoop, though taken at only a few points, is better and more even than that of Figures 4 and 5. This seems to be generally true with all the scoops of which we have taken patterns in flight.

Perhaps the most serious element of the difficulty shown in the foregoing tests is the fact that the larger scale of disturbance occurs only on the airplane. Thus far we have been unable to reproduce it in the laboratory. We have put the ram from a blower on the entrance of the air scoop and graduated it to give the same pressure pattern on the face of the carburetor as was measured in flight, yet we did not get the enrichment. We have tried in various ways to augment the entrance effect at the scoop opening without appreciable effect. It was our hope that we might record in flight the scoop duct pressure pulsations with the indicating device previously described, and then reproduce these in a laboratory: but we have not yet achieved this.

From general experience it seems that the disturbance is associated somewhat with displacement of the air stream reaching the carburetor. It seems to be also associated somewhat with propeller disturbance. I do not recall that we have had any disturbance of this sort in turbo installations. As a matter of fact, in the present extent of our knowledge it seems that there could only be two reasons for this change of air metering characteristics.

(a) Periodic variation of flow rate: since the depression varies as the momentary velocity squared, the integrated depression will be greater in pulsating than in steady flow for the same average mass flow per unit time.

(b) Diminution of the air stream to fill only part of the main venturi throat. This could result if the air stream should continue through the scoop duct and carburetor at the initial slip stream velocity or plane air speed velocity, provided this latter is higher than the normal venturi throat air speed required for that horsepower and altitude. This has been the case in nearly all the circumstances under which enrichment was reported. We have not had an opportunity to make flight tests comparing single and boost venturii, but by reference to Figure 26 it will be noted that the enrichment has the characteristic of the main venturi depressions, rather than those of the boost venturi.

Whatever the cause of this peculiar disturbance, its cure will probably prove simple, once we learn the characteristics of the actions involved.

It is believed that to develop the nature and basic causes of this phenomenon will require some weeks of test in an airplane especially set aside for this purpose, using the methods and equipment already referred to. The work should be done under the direction of carburetor research engineers and should be accompanied by ground check on various points as the need develops. It is suggested that this is a very suitable and proper occasion for aid from the Military services or the Government research organizations.

PRESSURE WAVE EFFECTS.

Nearly every airplane builder has evidence at one time or another of the existence of pressure waves in the intake air system. We have already referred to periodic disturbances excited by the propeller, but we have had others occurring only at high air speed and independent of engine speed. We have had others arising from supercharger surge, and in one case from turbo supercharger surge.

We have already mentioned the case where the pulsations in the scoop gave a definite low pitch note which disappeared when the scoop was shortened. Another interesting instance occurred when a spacer between the scoop elbow and carburetor blew out, and the engine ran much smoother afterwards at altitude: I believe thereafter a 2.5 inch hole was regularly put in the scoop at the elbow to "untune" the scoop pulsations. In one recent case a metering disturbance occurred at nearly closed throttle in the carburetor, and the frequency was definitely that of an organ pipe, closed at one end and having a length equal to that from the scoop entrance to the throttle valves of the carburetor. This frequency, about 70 to 80 per second, happened to coincide with the natural response rate of our aneroid which had been previously damped to withstand mechanical engine vibration of very much higher rate. We prepared to install .the oscillograph device previously described but meanwhile it was fortunately found that this trouble could be mitigated --

(a) by changing the scoop duct length,

(b) by making the scoop entrance project definitely forward out of the somewhat conical cowling contour, and

(c) by putting a "dash pot" in the aneroid (though this alone did not cure one minor detail of metering disturbance).

As haste was urgent, no pressure records were taken.

There is reason to believe, however, that resonance pressure waves in the scoop can upset carburetor metering if they happen to coincide with the resonance frequency of metering air chambers in the carburetor; in fact we have had a definite experience like this in a float type carburetor, details of which I am not at liberty to reveal here. The basic laws of pressure waves in pipes are fairly well known, but an ocular demonstration of their magnitude was shown in the test illustrated in Figures 31, 32 and 33. As part of the previously mentioned investigation, we set up a tube about 5.5 feet long with manometer pressure heads at regular intervals. A blast of air was directed toward the mouth of the tube and interrupted by a routing disk driven by an electric motor. Figure 31 shows the setup and Figure 32 the shift of the manometers under the steady jet of air uninterrupted: while Figure 33 shows the variation in pressure distribution with the interrupter disk in rotation. I might note that we found it rather difficult to excite definite waves of fundamental frequency in the pipe by this method, a fact which has been reported by other experimenters.

As stated in the foregoing, this difficulty has been cured by relatively simple means, which are available in the future. We are inclined to believe, however, that formation of pressure waves due to air speed probably depends a good bit upon the exact formation of the air opening with reference to cowl curvature, and direction of airflow. It is common observation that to excite a definite frequency note in a bottle, tube, or musical wind instrument without a reed, requires that the air blast be directed in just a certain way with reference to the orifice. Apparently the exciting blast must be relatively neutral with reference to the air surge in and out so that it can reinforce either one, once the vibration is set up. It is conceivable that a slight change in the air opening, say for instance an overhanging top extension forward, might prevent excitation under steady air flow over the cowling. This again is a subject for wind tunnel or other aerodynamic investigation.

In general, it is difficult to conceive of a ready method of detecting pressure waves of characteristics that will disturb air metering, without the use of some such indicator as the one previously described. An analogy suggested by Figures 32 and 33 would be to place the several pressure connections along the scoop duct, connect them to respective air speed gauges, balanced on plane speed static, and look for a change in their gradation of readings. Fortunately, cases of disturbance from this cause have been recorded rather seldom.

WARM AIR VALVE SYSTEMS

At the present time it is current practice to fit to the scoop an alternative warm air passage, with selecting valve, for use when there it heavy atmospheric precipitation or when atmospheric conditions favor formation of ice in the intake system. It is well known that many of these warn air controls are generally unsatisfactory, but the reasons therefore are less generally understood. The current types are particularly bad when, as recently, a large heating muff is supplied so that a graduation or mixture of warn and cold air is necessary to protect against ice on the one hand and to avoid overheating on the other. The usual valve construction is objectionable for the following reasons:

1. Due to the fact that the cold air is under a variable degree of ram according to the ship attitude, while the warn air is not, for a given intermediate position of the heat valve, a greater proportion of cold air will come in in level flight or in a dive than during climb when most needed. (See Figure 34.) It is common experience to have a thermocouple located at "X" read cold air at level flight.

2. Similarly, for a given percentage opening of the valve, more warm air will be drawn through in proportion to the cold air at large throttle openings than at small throttle openings: at small throttle openings enough cold air comes through under the ram differential to satisfy the carburetor demand. This, like (1), is exactly opposite to what the engine requires. These two faults are inherent

in any type of scoop where the cold air is under ram and the warm air is not.

3. It is impossible to shut off entrance of heavy rain or thick wet snow without getting full hot air, which may bring the intake temperature too high for engine safety.
4. With such a construction the cold and warm air do not mix well, but pursue separate paths down through the carburetor and adapter. This does not give good protection against ice formation and makes it necessary to use a hotter air intake charge than would otherwise be necessary. In addition, it is impossible to locate a thermometer bulb in the system and have it give consistent readings that will indicate the minimum temperature that is safe from ice formation.

In addition, the ordinary shape of warm air valve is objectionable in the full hot air position in that the air passage entrance is abrupt across the carburetor and does not give good airflow entrance. Figure 35 shows the pressure distribution of a common type of scoop in the full warm air position.

All the deficiencies just enumerated disappear with the construction shown in Figure 36 in which there are two valve systems and three air supplies: cold outside air; warm "protected" air; and hot air. The warm and hot air supplies are subject to the same ram or lack of ram. As shown in sequence, first position is full cold air; second is with outside air fully shut off and protected air from back of the cylinder baffles, usually at a temperature of about 40° F. above outside air; third is part warm and part hot air, as required by weather conditions and the pilot's judgment; and fourth is full hot air.

Attention is directed to the relation of the forward extension of the island member to above the center of the warm air entrance. This insures a balanced flow of warm air down the front and rear halves of the scoop to the carburetor and a considerable degree of mixing. The particular shape of scoop shown is not perfect as giving an entirely even pattern of pressure across the carburetor entrance, but it is very good and this type of scoop in service has proven quite satisfactory. The scoop structure shown in Figure 1 has similar air flow characteristics to this and probably would be as satisfactory.

There is one point that should not be overlooked, namely our definition of "protected" air. All the rain and precipitation that hit the front cowl opening around the propeller must eventually go back past the engine baffles and it can easily happen that one of the streams so created should flow into the warm or "protected" air opening unless special means are employed to prevent this. The same could conceivably happen with reference to the intake air entrance on the hot air muff. Such a wash is improbable and would no doubt be apt to leave evidence of its passage over the otherwise dust covered surfaces: but anyway it is not altogether safe to assume that air from behind the baffles is entirely free from precipitation.

CONCLUSIONS

1. Scoop difficulties occur less frequently than is generally believed. The air scoop has repeatedly been blamed for such diverse ailments as supercharger surge, poor manifold distribution, vapor lock, and many other deficiencies for which it is similarly not guilty. Nevertheless there remain certain problems, which, though we can diagnose them we do not fully understand.
2. The most important disturbance of metering in flight is enrichment at altitude and high power. This may be connected with scoop form and propeller slipstream effect. While the difficulty may be partly cured by change of carburetor setting, it is preferable to try to restore normal air metering conditions in the carburetor by flight research to find the cause. In this work, measurement of airflow (as closely as possible) and of carburetor metering suction are of most direct guidance.
3. There are occasional cases of disturbance from pressure pulsations in the intake duct. We believe these can always be dealt with as here outlined.
4. Since many of these difficulties occur only in flight and at present cannot be reproduced in ground laboratories, they must be studied in flight. Such work is obviously the combined function of the external airflow expert, or aircraft engineer, and the internal airflow expert, or carburetor engineer.
5. It is quite important for the time being that we abandon the conception that carburetor settings must be determined only by ground stand test, and amend our procedure accordingly. What is important is that the engine should have its required fuel-air ratio in flight; not that it should have the same jet size as will produce this ratio on the ground, but a different ratio in flight. Eventually, however, we should increase our collective knowledge to a point where we can regularly determine a flight setting from ground test, and where check flights will be necessary only to confirm that the ground fuel-air ratios are reproduced.
6. In both Military and commercial procurement of new planes, procedure provision should regularly be made for prototype test of all engine accessories whose performance may be affected by vibration, temperature, or air impact conditions: provided these are different in the new installation from previous practice.
7. In the carburetor it would seem that --
    - (a) multiple air speed elements are preferable.
    - (b) the impact and velocity members should be as close together as possible in order to have the same position with reference to

"nodes" of pulsation in the scoop. Also the opening area should be small with reference to the volume of any air pressure chambers in the carburetor, so that their resonance frequency will be lower than any frequency in the scoop.

(c) elastic pneumatic members, such as aneroids, should be damped for both low and high frequency vibration.

8. As to air scoops: --

(a) It now seems that an elbow shape that gives a uniform pressure pattern at the carburetor face will give less metering disturbance, and is likely to give greater "ram" to the engine. For new designs this should be experimentally checked in prototype flight.

(b) If, for basic design reasons, the scoop entrance must be brought close to the propeller, it is probably safer to give the opening a wide "circumferential aspect", about four times the width of the propeller blades at that radius.

9. As to warm air supply, since vanes may definitely be needed in the scoop elbow, warm (protected) air and hot air should be supplied between the vanes and the scoop entrance, to avoid icing trouble. Proper air temperature control involves that

(a) the proportion of cold and warm air should not be affected by ram differential.

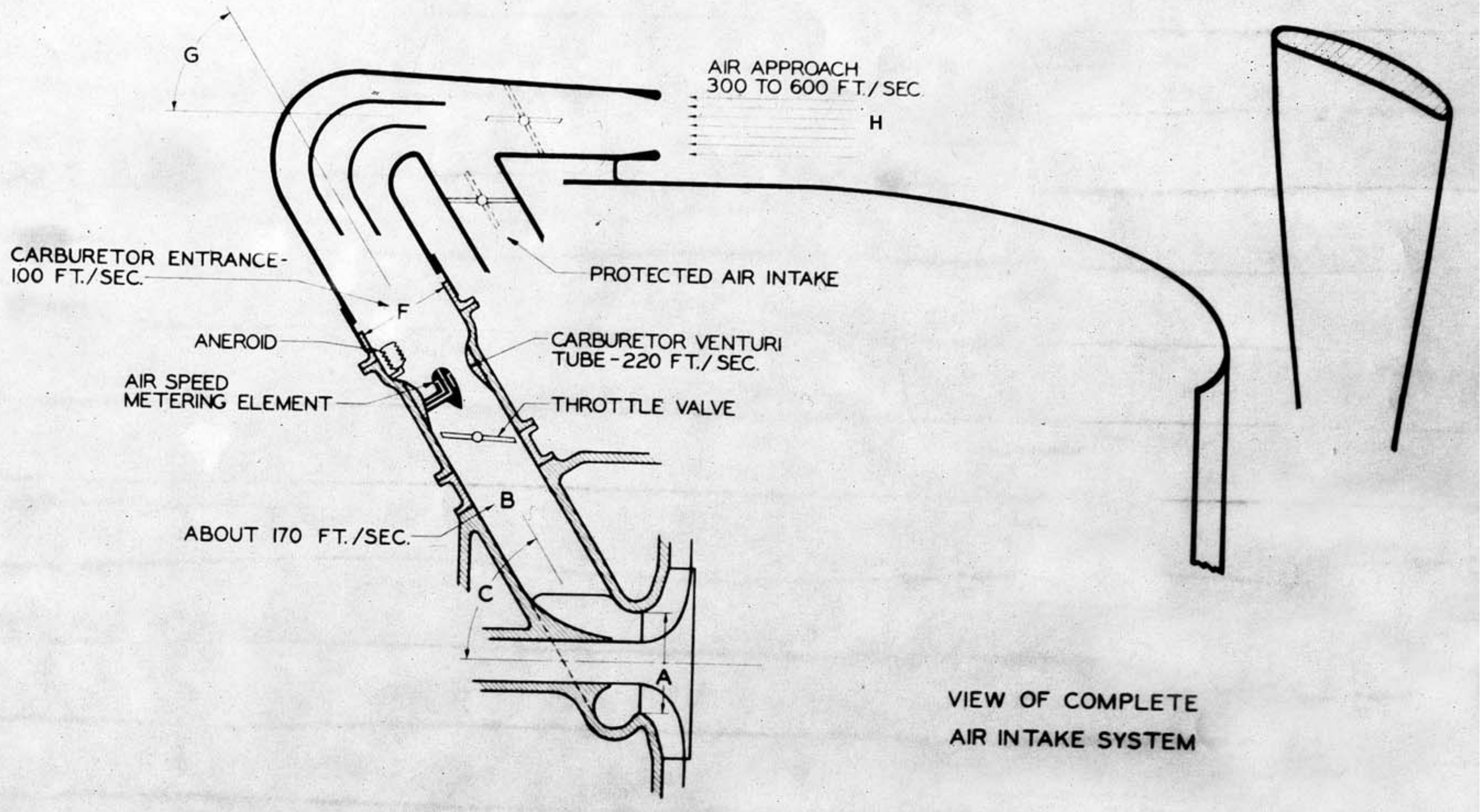
(b) the control valve should not affect the carburetor metering.

(c) the warm and hot air should be mixed; and the hot air stream should not localize on the aneroid.

(d) it should be possible to completely close the cold air entrance without getting "full hot" air.

****

In the work here reported we wish to acknowledge the help of Pratt & Whitney Aircraft, of Wright Aeronautical Corporation, of North American Aviation, and of other aircraft companies. Much of our own work should be credited to Mr. M. R. Balis, Mr. E. J. Partington, and Mr. S. B. Smith of our experimental departments.



VIEW OF COMPLETE
AIR INTAKE SYSTEM

VIEW OF COMPLETE AIR INTAKE SYSTEM, SHOWING DISCREPANCIES BETWEEN INTERNAL AND EXTERNAL AIR VELOCITIES AT RATED POWER AT SEA LEVEL.

FIG. I.

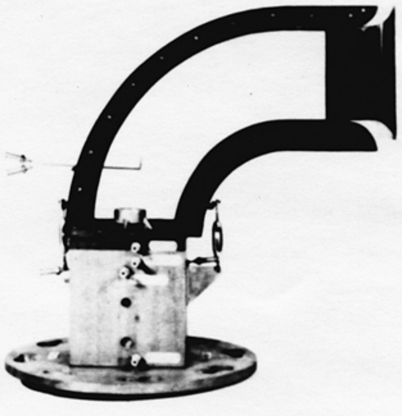


FIGURE 2.

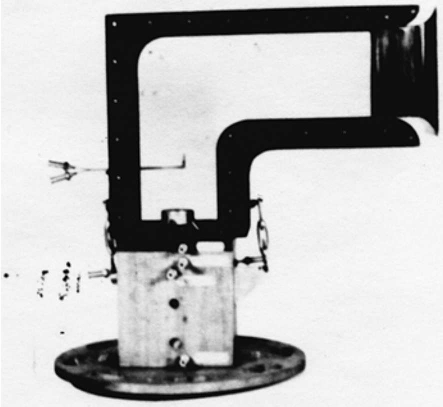


FIGURE 4.

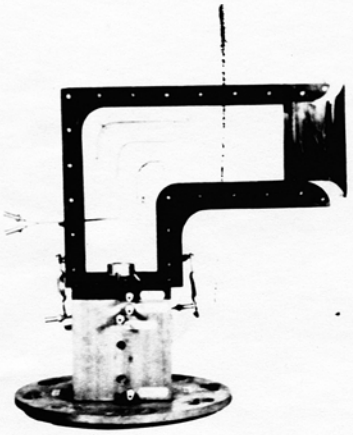


FIGURE 7.

FIGURE 9.

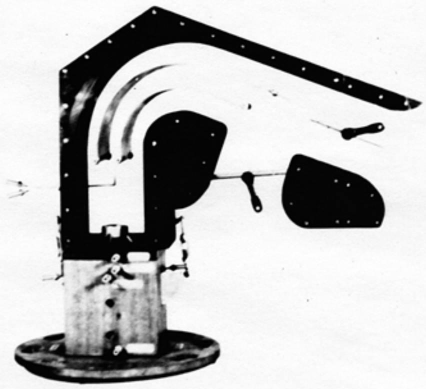


FIGURE 11.

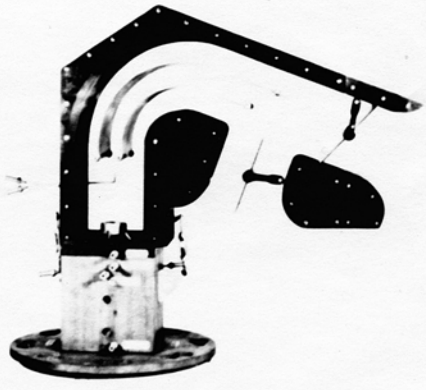


FIGURE 13.

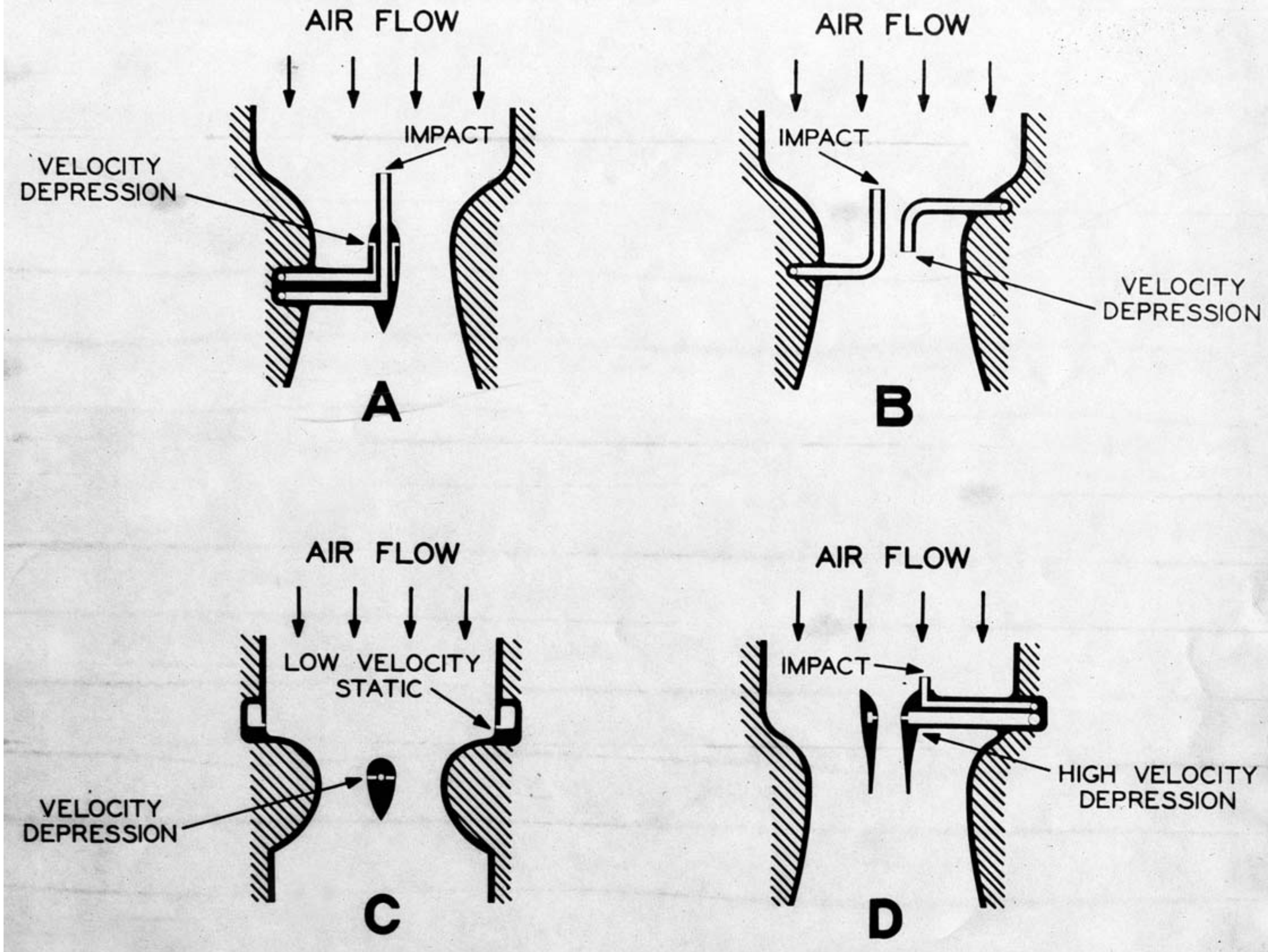
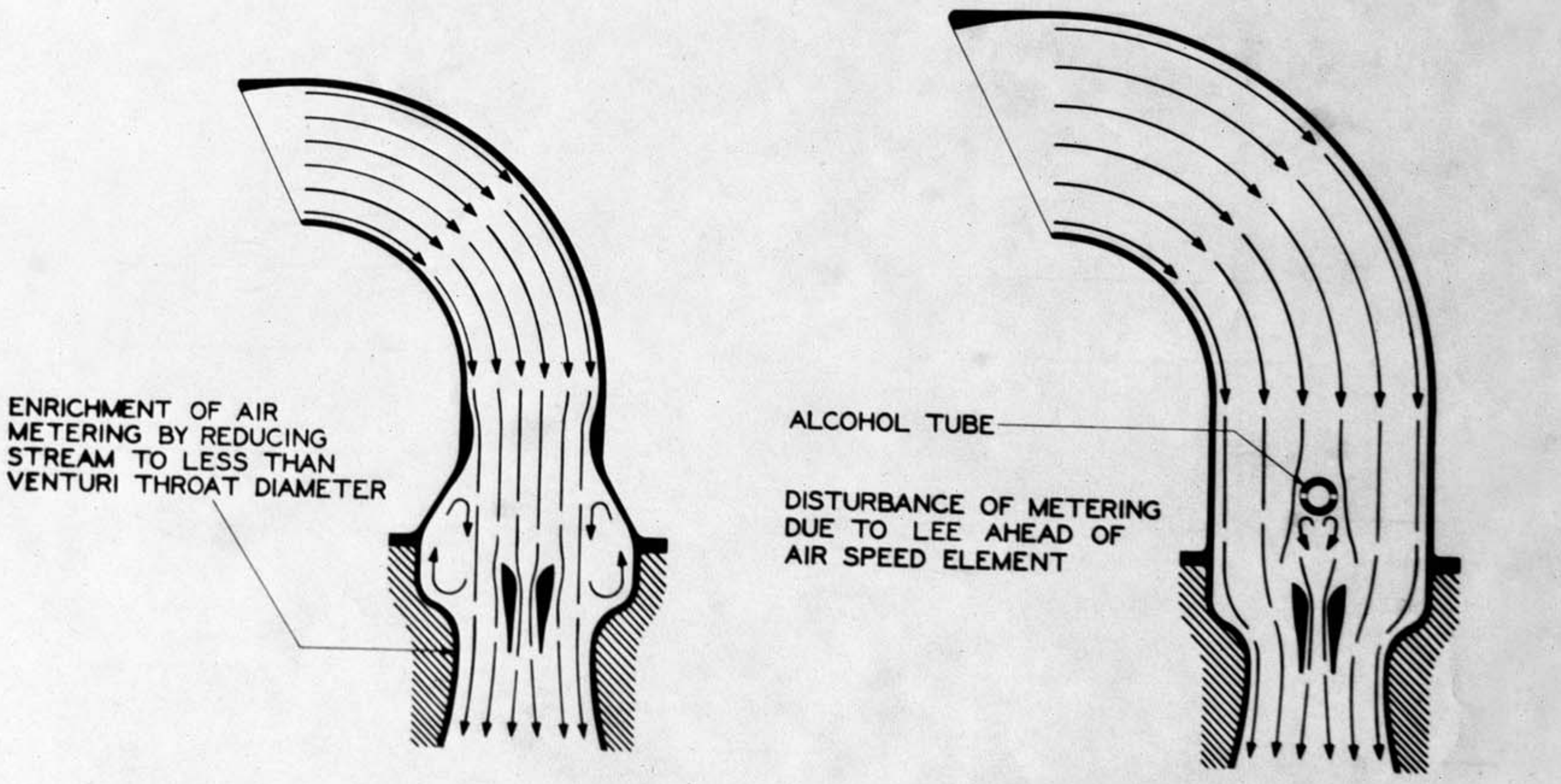


FIG 15

DIFFERENT ARRANGEMENTS OF CARBURETOR ELEMENTS FOR MEASURING VELOCITY DIFFERENTIAL THROUGH VENTURI TUBE THROAT.

FIGURE 16.

VARIETY OF SCOOP ELBOW SHAPES WHICH DO NOT AFFECT CARBURETOR METERING, WHEN MULTIPLE AIR SPEED ELEMENTS ARE USED. THIS, UNDER AIR BOX STEADY FLOW AND MAY BE DIFFERENT IN FLIGHT.



DETAILS OF SCOOP CONSTRUCTION NEAR CARBURETOR WHICH DISTURB AIR VELOCITY METERING.

FIG. 17

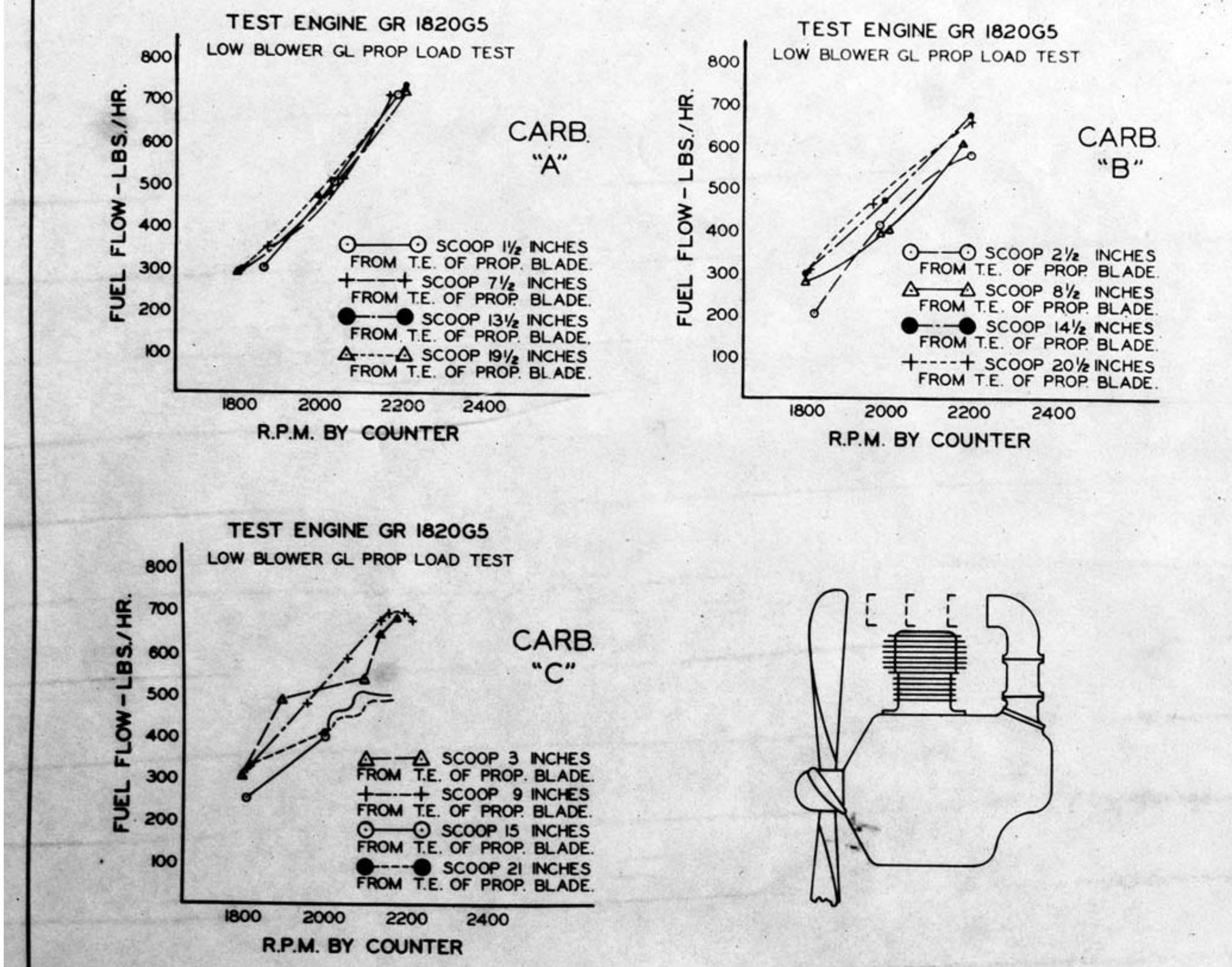


FIG. 18

DISTURBANCE OF METERING DUE TO PROPELLER SLIP STREAM. THREE DIFFERENT TYPES OF CARBURETORS WITH SAME SCOOP ELBOW. SCOOP ENTRANCE DIFFERENT DISTANCES FROM FIXED PITCH PROPELLER TRAILING EDGE.

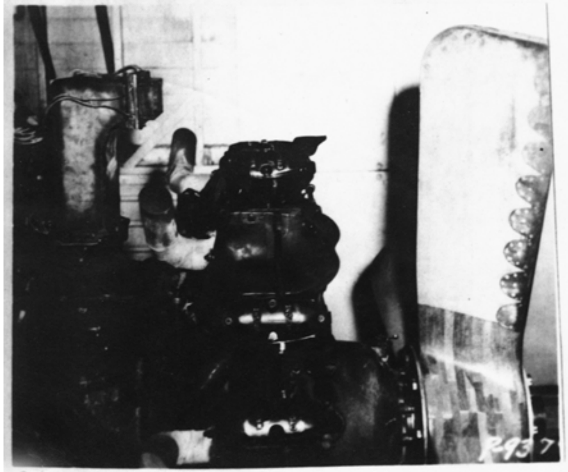


FIGURE 19.

SHARP CORNER SCOOP ELBOW WITH SHORT EXTENSION AS SHOWN IN FIGURE 22.

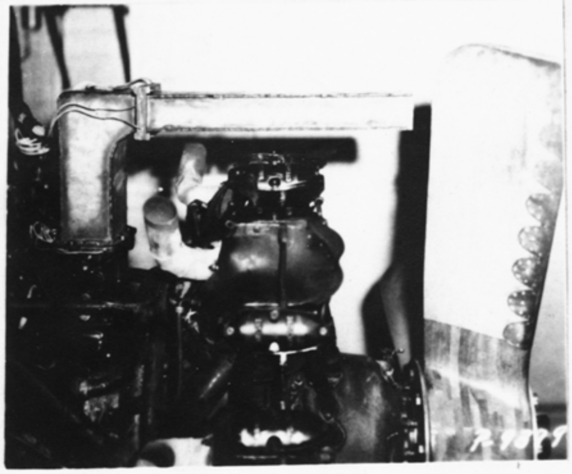
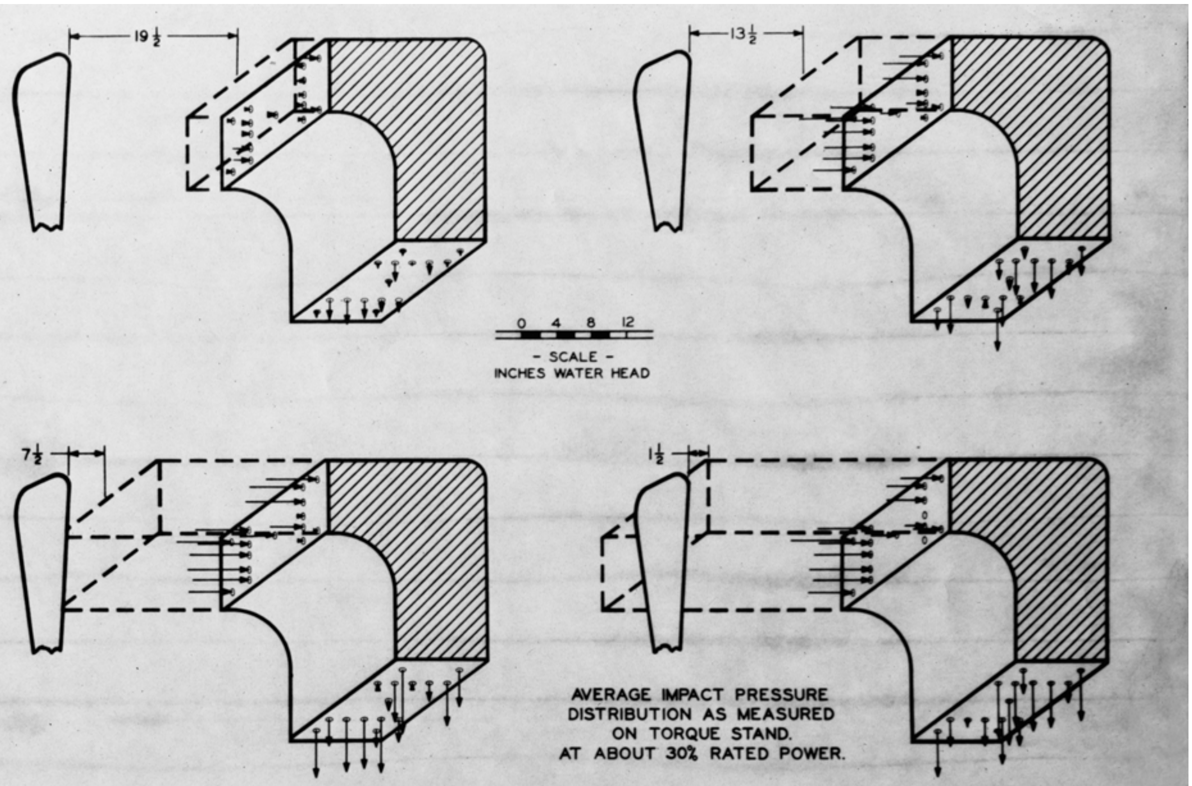


FIGURE 20.

SHARP CORNER SCOOP ELBOW WITH LONG EXTENSION AS SHOWN IN FIGURE 22.

FIGURE 21.

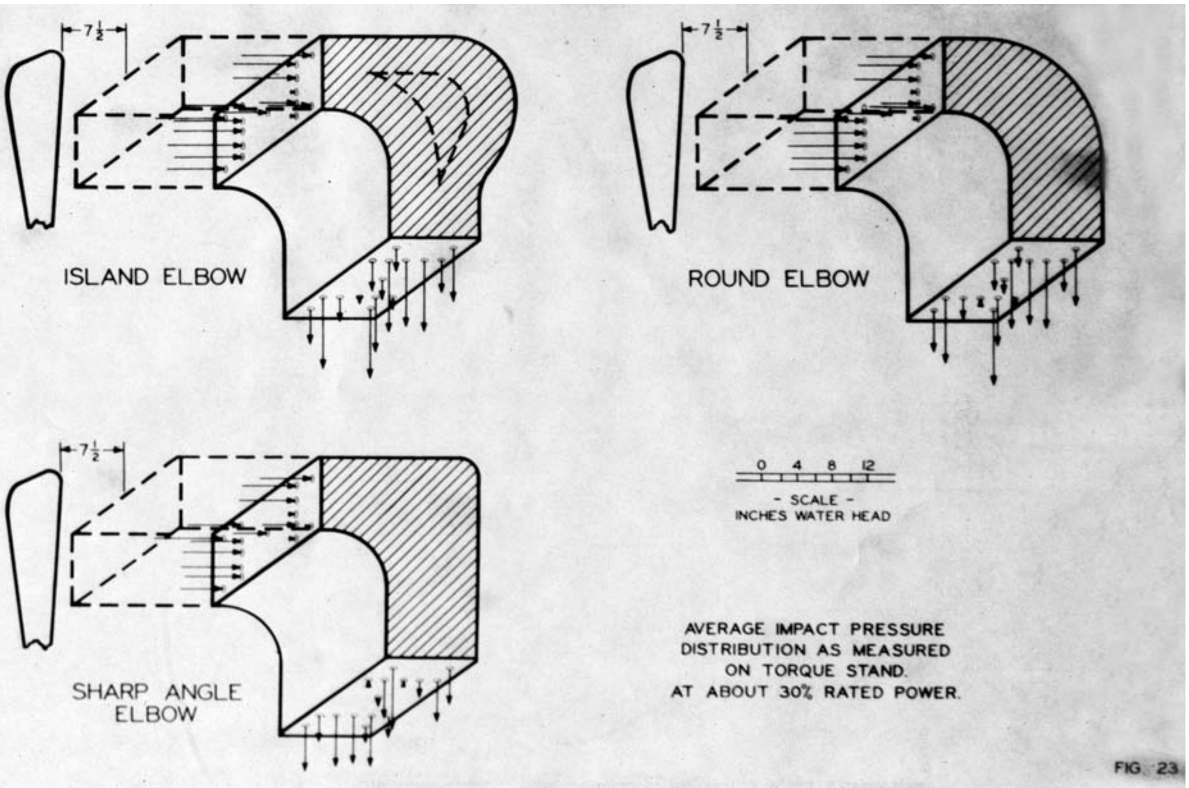
IMPACT GRID USED IN TESTS OF FIGURES 22 & 23.



AVERAGE IMPACT PRESSURE DISTRIBUTION AS MEASURED ON TORQUE STAND. AT ABOUT 30% RATED POWER.

FIG. 22

SHOWING INCREASE OF IRREGULARITY OF PRESSURE DISTRIBUTION ON AIR SCOOP AND CARBURETOR ENTRANCE AS SCOOP OPENING IS BROUGHT TOWARD PROPELLER.



AVERAGE IMPACT PRESSURE DISTRIBUTION AS MEASURED ON TORQUE STAND. AT ABOUT 30% RATED POWER.

FIG. 23

SHOWING PRESSURE DISTRIBUTION ON CARBURETOR ENTRANCE WITH DIFFERENT SCOOP ELBOW SHAPES WITH SCOOP ENTRANCE NEAR PROPELLER.

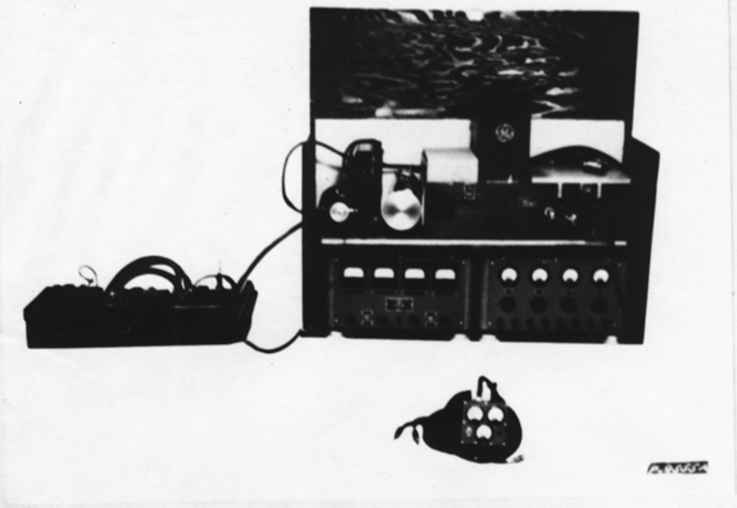


FIGURE 24.

OSCILLOGRAPH APPARATUS FOR INDICATING AND RECORDING PRESSURE PULSATIONS IN AIR SCOOP, CARBURETOR, AND INTAKE MANIFOLD. SEE RECORDS ON FIGURES 25 & 26.

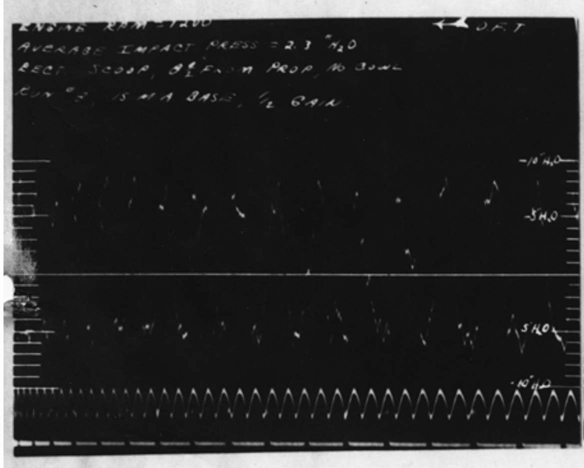


FIGURE 25.

FIGURE 26.

RECORDS OF IMPACT PRESSURE PULSATIONS IN SCOOP WITH AIR ENTRANCE 8½" FROM PROPELLER TRAILING EDGE. FIXED PITCH CLUB ON RIGID TORQUE STAND AT 1200 & 1800 R.P.M. IN FIGURES 25 & 26 RESPECTIVELY. BREAKS IN BOTTOM LINE INDICATE TIME WHEN PROPELLER BLADE IS PASSING SCOOP ENTRANCE. MIDDLE LINE IS TIME TRACK, FREQUENCY 100 PER SECOND. NOTE AMPLITUED OF 15" H_2O PRESSURE IN FIGURE 25.

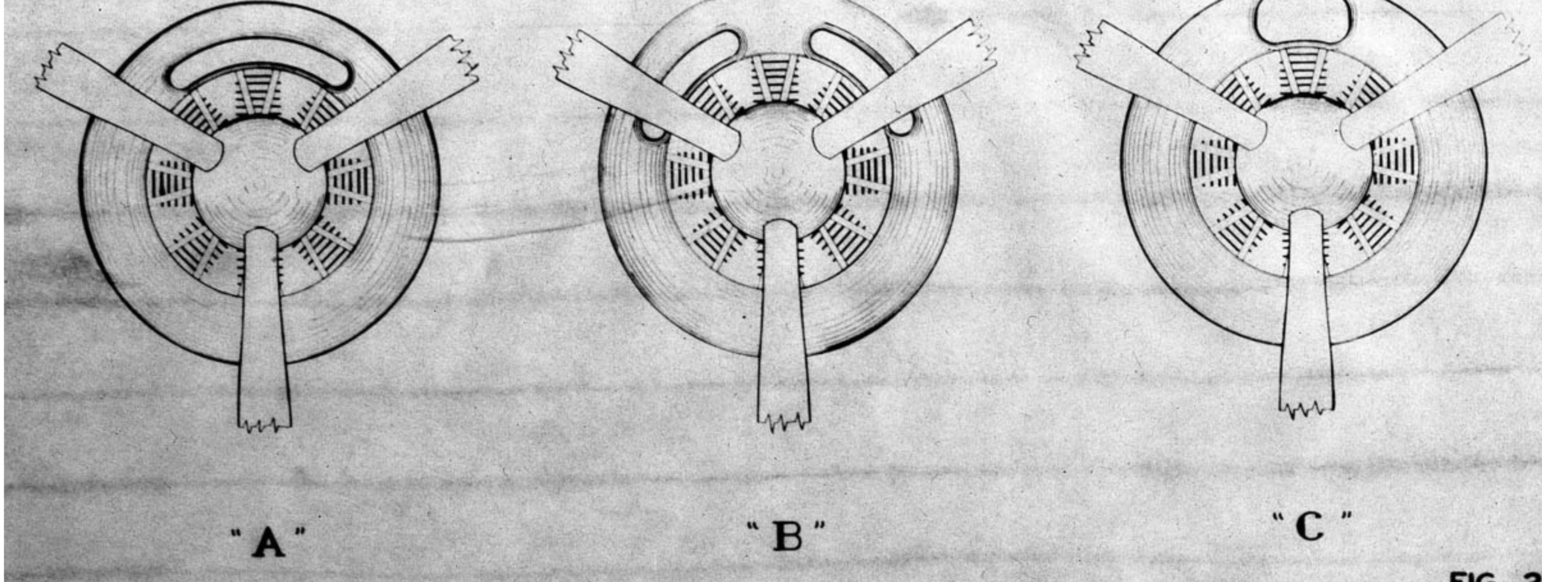


FIG. 27

FRONT COWL AIR INTAKES WITH VARYING
DEGREES OF PROPELLER BLADE INTERFERENCE.

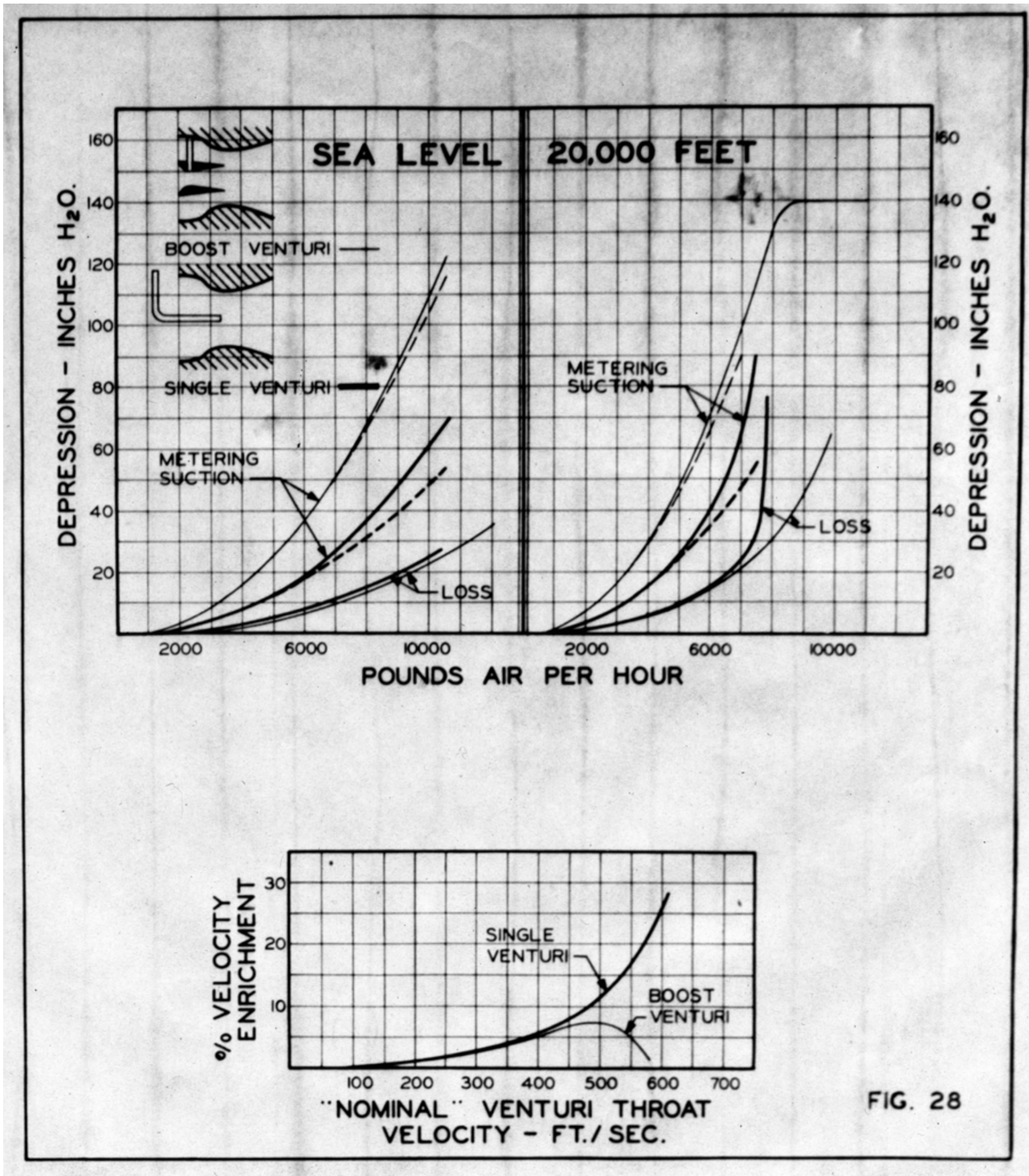
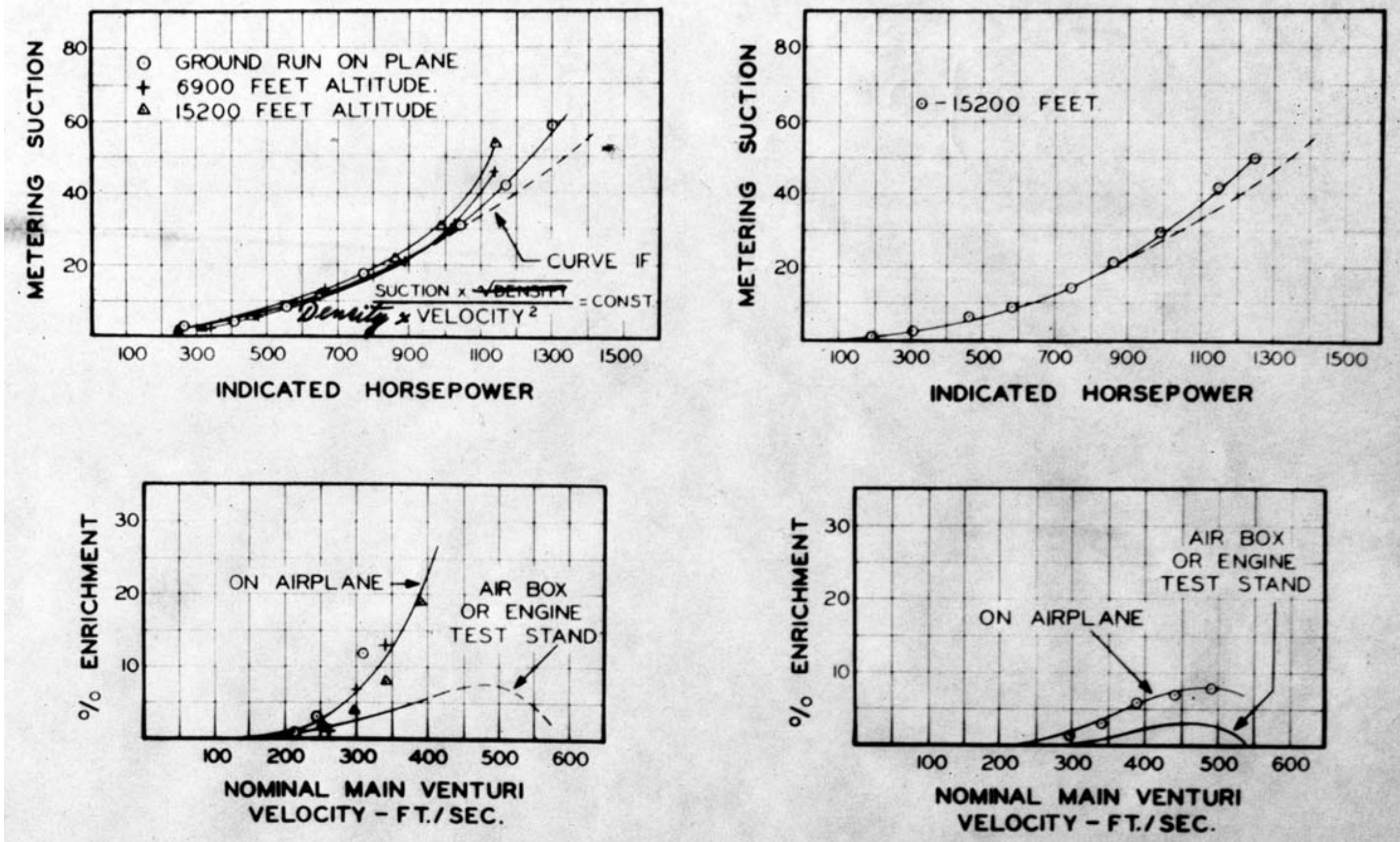


FIG. 28

THE TOW UPPER CHARTS SHOW METERING SUCTION AND LOSS CHARACTERISTICS WITH BOOST VENTURI (LIGHT LINE) AND SINGLE VENTURI(HEAVY LINE), RESPECTIVELY, AT SEA LEVEL AND 20,000 FEET. DOTTED LINE SHOWS RANGE OF TRUE VELOCITY METERING. NOTE RAPID INCREASE OF BOTH METERING SUCTION AND LOSS WITH SINGLE VENTURI, REACHING CRITICAL VELOCITY AT ABOUT 7,800 POUNDS OF AIR PER HOUR. LOWER CURVE SHOWS PERCENT ENRICHMENT IN TERMS OF NOMINAL VENTURI THROAT VELOCITY: THIS IS INDEPENDENT OF ALTITUDE.

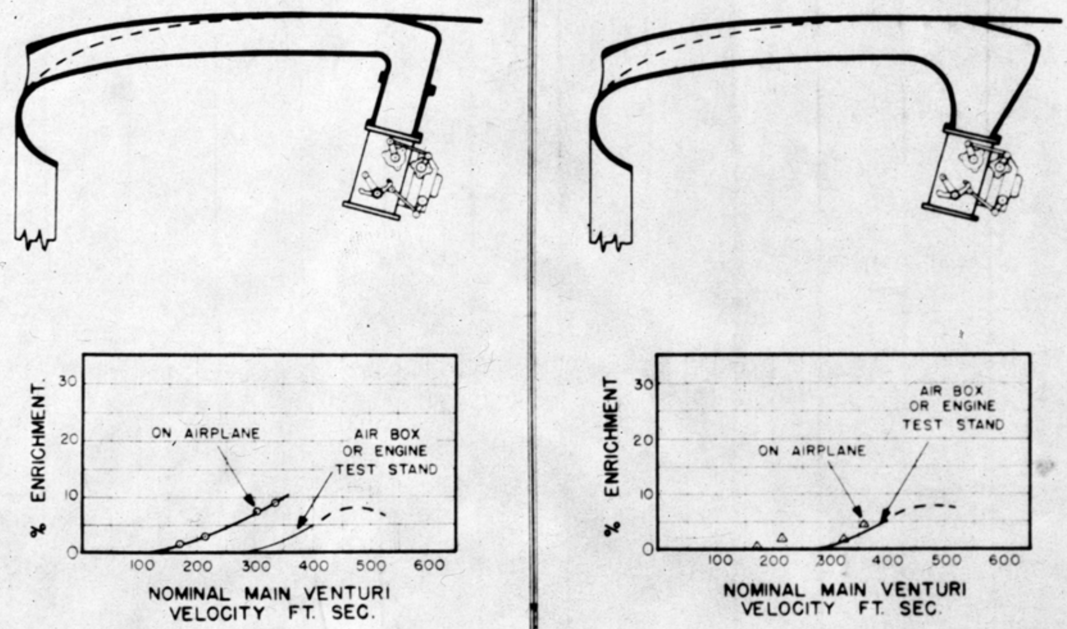


CARBURETOR SETTING NO. I

CARBURETOR SETTING NO. II

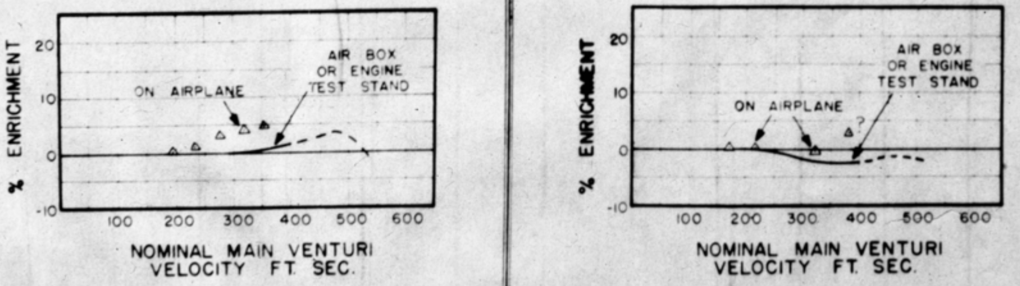
SHOWING DIFFERENCE IN CARBURETOR METERING BETWEEN FLIGHT AND GROUND TEST, WITH TWO DIFFERENT CARBURETOR SETTINGS. NOTE IN EACH CASE THE INCREASED ENRICHMENT IN FLIGHT, APPARENTLY INCREASING WITH AIR INTAKE VELOCITY.

FIG. 29



BY DIRECT AIR METERING PRESSURES WITH COMPUTED DENSITY CORRECTION (NO ANEROID CORRECTION)

BY DIRECT AIR METERING PRESSURES WITH COMPUTED DENSITY CORRECTION (NO ANEROID CORRECTION)



AFTER ANEROID CORRECTION - ANEROID VENTED TO MAIN VENTURI.

AFTER ANEROID CORRECTION - ANEROID VENTED TO BOOST VENTURI.

FIG. 30.

VELOCITY ENRICHMENT IN FLIGHT WITH TWO DIFFERENT AIR SCOOPS. UPPER ENRICHMENT CURVES ARE DERIVED FROM DIRECT OBSERVED VELOCITY DEPRESSIONS, BY VARIATION FROM

$$\frac{\sqrt{\text{SUCTION}}}{(\text{NOMINAL AIR VELOCITY}) \times \sqrt{\text{AIR DENSITY}}} = \text{CONSTANT}$$

LOWER ENRICHMENT CURVES ARE DERIVED FROM OBSERVED METERING SUCTION, AFTER ANEROID CORRECTION, BY VARIATION FROM

$$\frac{\sqrt{\text{METERING SUCTION}}}{\text{LBS. AIR / HR.}} = \text{CONSTANT}$$

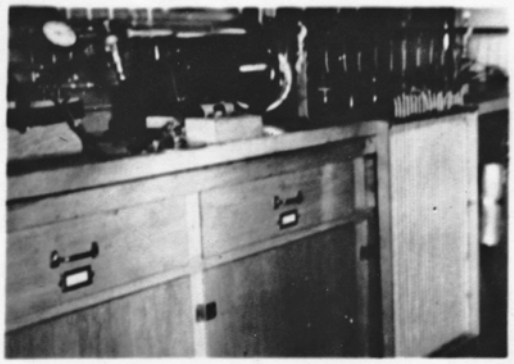


FIGURE 31.

DEMONSTRATION OF RESONANCE WAVES WITH INTERMITTENT AIR BLAST DIRECTED SQUARELY AGAINST LONG AIR TUBE.

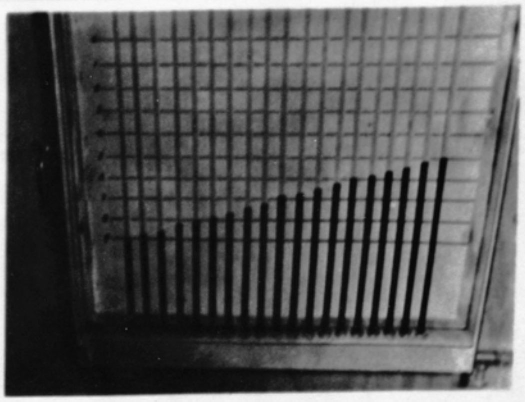


FIGURE 32.

DISTRIBUTION OF PRESSURES ALONG TUBE IN FIGURE 31 WITH UNINTERRUPTED BLAST INTO TUBE.

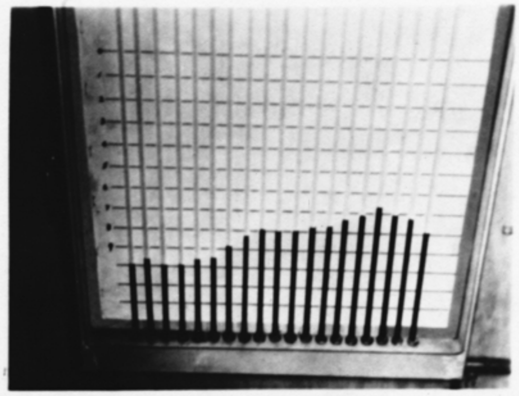
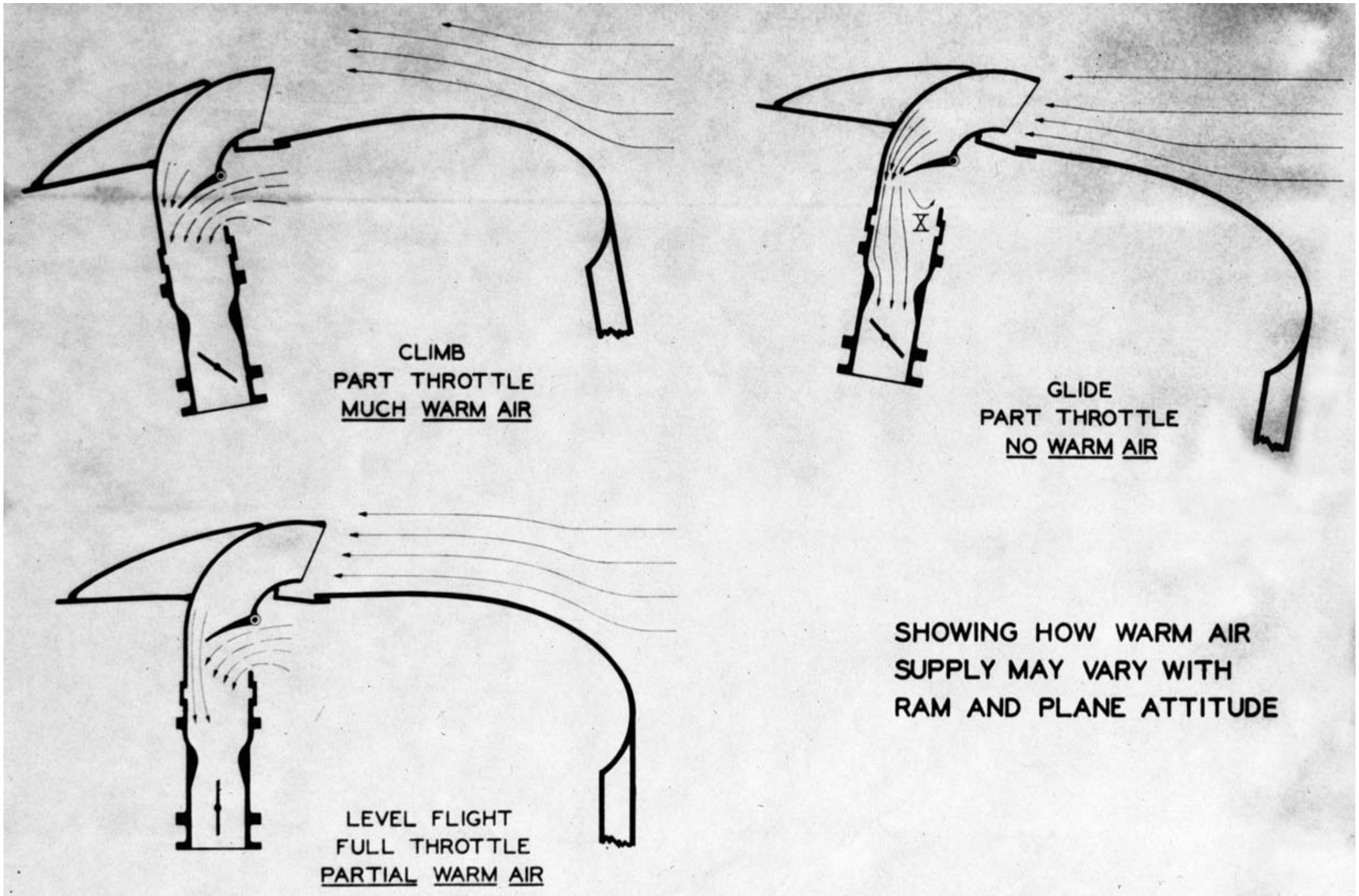


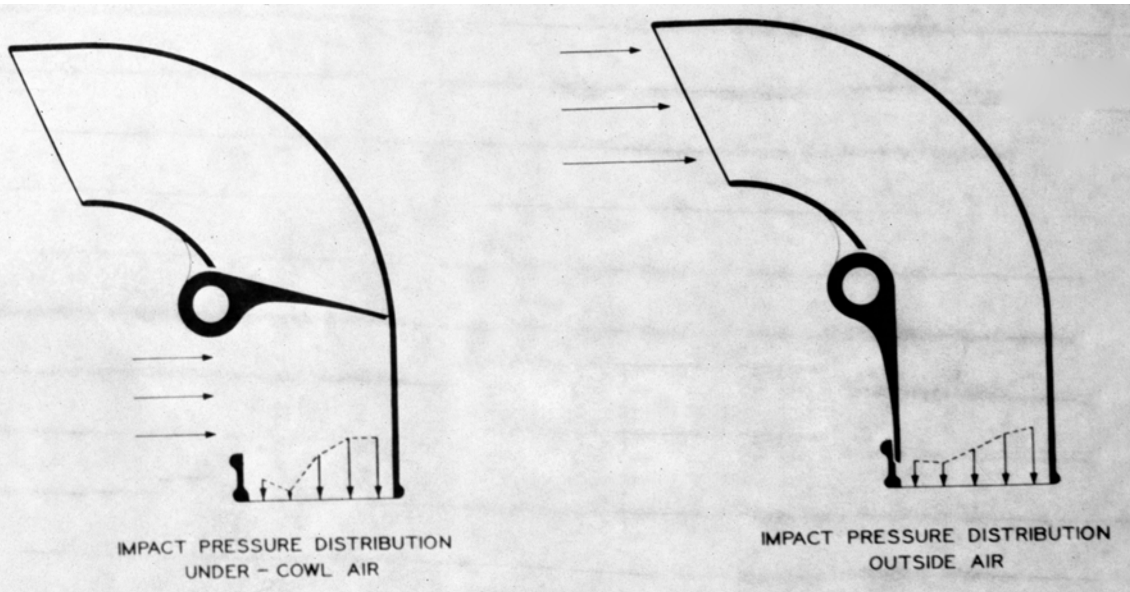
FIGURE 33.

DISTRIBUTION OF PRESSURES ALONG TUBE IN FIGURE 31 WITH BLAST INTERRUPTED IN RESONANCE FREQUENCY OF TUBE.



DISTURBANCE OF WARM AIR REGULATION BY PLANE ATTITUDE AND THROTTLE POSITION, WITH USUAL ARRANGEMENT OF WARM AND COLD AIR INTAKES.

FIG. 34

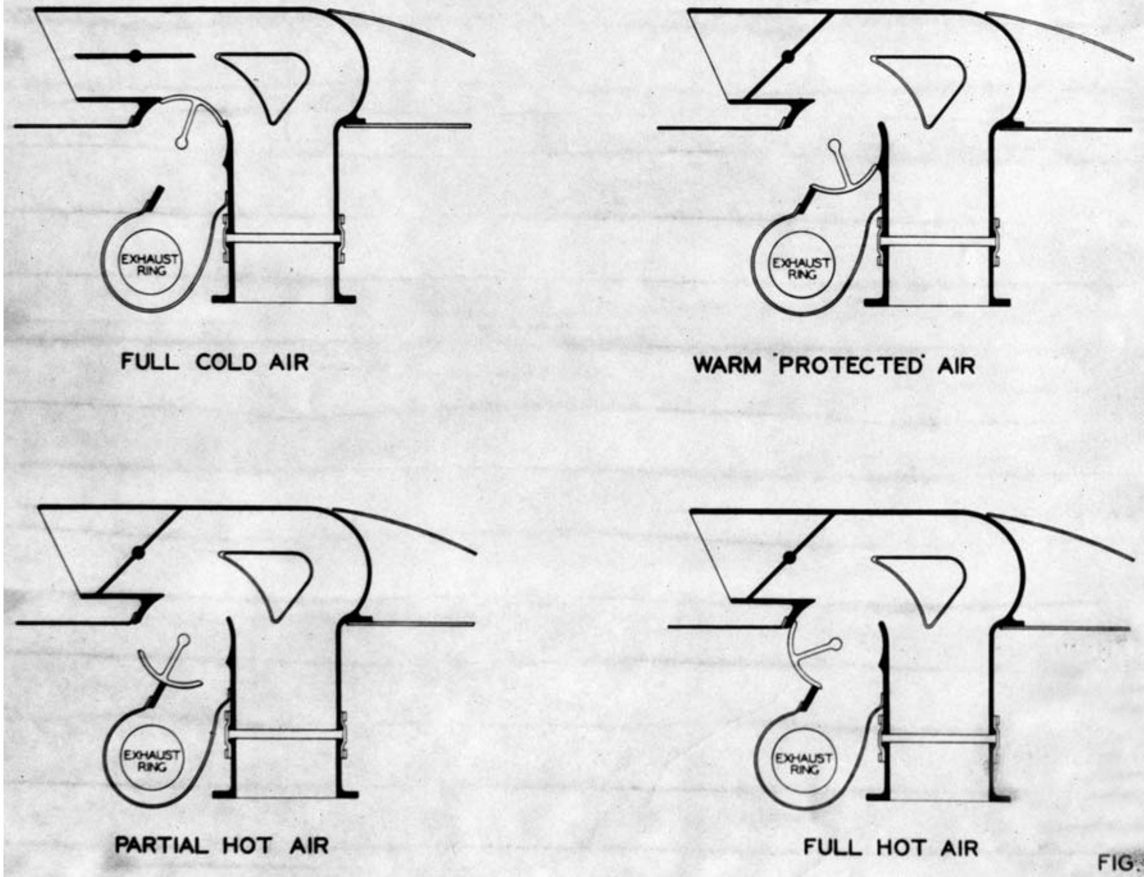


IMPACT PRESSURE DISTRIBUTION
UNDER - COWL AIR

IMPACT PRESSURE DISTRIBUTION
OUTSIDE AIR

IRREGULARITY OF PRESSURE DISTRIBUTION WITH COLD AIR INTAKE CLOSE TO CARBURETOR ENTRANCE.

FIG. 35



FULL COLD AIR

WARM "PROTECTED" AIR

PARTIAL HOT AIR

FULL HOT AIR

IMPROVED FORM OF AIR SCOOP, WITH THREE POSITION VALVE SYSTEM.

FIG. 36