# A SURVEY OF THE PROBLEMS AND ADVANTAGES OF METERING FUEL TO AN AIRCRAFT ENGINE AS A FUNCTION OF THE MAJOR VARIABLES WHICH INDICATE AIR CONSUMPTION, AND A DESCRIPTION OF A DEVICE WHICH PERFORMS THIS FUNCTION

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This is to certify that the

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# OUTLINE OF PAPER

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## ABSTRACT

1. The Speed-Density carburetion system is a new variety of a long-known method of fuel feed control for internal combustion engines, which meters fuel according to engine R.P.M., intake manifold pressure, intake manifold temperature, and exhaust back pressure. Since these engine variables are easily and accurately read in flight, on the engine test stand, and on the flow bench, it is a particular advantage of this system for aircraft that carburetor settings can be both directly derived and directly checked in flight.

2. Another advantage is that a separate fuel feed control is provided for the two major factors affecting engine detonation: namely, intake manifold temperature and pressure. It is possible, therefore, to obtain a setting which will exercise maximum control of detonation for any given engine and fuel.

3. Since the throttle valve is the only air flow restriction, this system may permit some gain in power at critical altitude, provided an efficient intake air duct is used which has its inlet located where it will receive nearly full ram pressure. For safety in heavy rain and snow an alternative air inlet should be provided from some protected region.

4. In the choice of locality for fuel spray delivery it must be remembered that ice can accumulate beyond the point of spray delivery

wherever the wall temperature drops below 32°F. Care must therefore be taken to discharge the spray where the adjacent walls are protected by conducted engine heat. The single exception to this rule is the method of fuel discharge from the supercharger impeller, known as "spinner injection", where no special precaution against refrigeration icing seems necessary.

5. This Speed-Density principle may be applied to the control of fuel metering with direct or timed injection of fuel on reciprocating engines. In a modified form it also presents special advantages on jet propulsion engine controls.

6. In this system the fuel flow is dependent upon a group of variables instead of upon air flow. Therefore, the fuel flow requirement expressed in terms of the operating engine variables will be more complex than an air flow carburetor requirement curve of fuel/air ratio vs. air flow.

7. The author believes that progress with this system will be more rapid if fuel/air ratio is eliminated as the principal parameter. Instead, it is recommended that fuel flow be directly expressed as a function of the pertinent engine variables. Only in this way will it be possible for the manufacturer of the fuel metering equipment to guarantee the characteristic flow of the metering device.

8. The device described is currently in production for use on large liquid-cooled reciprocating engines. Whether or not it is a practical device for poppet valve air-cooled engines is unknown to the author at this time.

## INTRODUCTION

It is the purpose of this discussion to examine the problems and desirability of metering fuel to an engine as a function of the major variables which indirectly indicate engine air consumption, and to describe a device which performs this function. This system has been applied to aircraft engines with continuous induction system injection, to engines with timed cylinder injection, and to gas turbine jet engines.

In this system the engine itself is being used as an air meter in place of the standard carburetor venturii system.

To help understand why fuel metering equipment of this type has been developed, some of the problems existing with the present mass air flow fuel metering devices are listed below:

1. Increased airplane speeds and the desire to reduce airplane drag and improve pilot visibility have sometimes resulted in placing the air scoop entrance so close to the nacelle that it receives varying area of ram and of boundary layer air flow, according to the attitude of the airplane. These items combine to produce pressure irregularities at the carburetor inlet which can exceed the normal carburetor metering suction differential and thus disturb the metering function.

2. It is difficult to obtain sufficient metering forces for precise minimum cruise operation, and still maintain sufficient air capacity at the engine critical altitude.

3. It is difficult to provide exact compensation for the large range of air pressure and temperature encountered on high performance installations, regardless of whether the carburetor is before or after the first stage supercharger.

When the Speed-Density system is employed the above problems are neatly disposed of, but the problem must be carefully examined to see whether we would, as Hamlet said: "Rather bear those ills we have, than fly to others that we know not of". The following factors will be considered:

1. Whether the engine air consumption bears a simple relation to a minimum number of engine variables, since this will determine the complexity of the metering device.

2. Whether the air consumption is consistent in relation to these variables among production engines and throughout the life of one engine. Obviously, the accuracy of the mixture ratio cannot exceed the accuracy with which the air consumption can be defined by the operating variables or the consistency of air consumption in accordance with them.

3. Whether the desired fuel flow under the various power conditions can in fact be obtained in terms of the operating variables.

## HISTORICAL SUMMARY

The early applications of the Speed-Density principle to automotive engines apparently occurred with direct or cylinder injection supply systems. Since the injection pumps were positively driven, the pump could supply the speed metering function (provided the curve of volumetric efficiency vs. speed of the pump and of the engine were quite similar). It remained only to relate the fuel pump stroke control to the intake manifold pressure by some means which could be suitably calibrated.

The first clear recognition of this is probably shown in a series of four patents filed in the period from 1921 to 1926 by Davol, who shows two forms:

1. That in which the intake manifold pressure is controlled from a manually operated throttle valve and the fuel stroke is controlled by cam means in proportion to the resulting intake manifold pressure.

2. That in which the fuel pump stroke is manually operated, along with a cam and "boost control" system which operates the throttle to select a corresponding manifold pressure.

The nature and application of correction for exhaust pressure is shown in United States Patent 2008143 of Mock.

During the period from 1930 to 1936 the Air Corps was greatly interested in a Speed-Density type of control for use with timed injection systems. They constructed a unit which responded to manifold density and controlled the injection pump. The control system was partially developed and engine tested in combination with the injection pump which was designed and supplied by the Marvel Carburetor Co.[1] This system provided timed injection of the fuel into the induction manifold near the inlet valves.

During 1933-1935 the Air Corps equipped about 25 Boeing P-26 ships with these manifold injection pumps. They were manually controlled and were calibrated to give a correct mixture at ground level on the propeller load curve by proper cam relation between the throttle and pump control lever. Load and altitude compensation were accomplished by the pilot's manual operation. After some experience with this system the Air Corps decided that full automatic control of an injection pump was essential.

Work was started on manifold pressure fuel regulating devices in connection with timed cylinder injection in 1930 by the Bendix Corporation. The first known American flight of a manifold pressure metering control was in 1934 on a ship powered by a nine cylinder Pratt & Whitney air cooled engine. In this system forward motion of the cockpit throttle simultaneously increased the fuel pump stroke and established a corresponding manifold pressure datum (modified for manifold temperature and exhaust back pressure). This system gave remarkably good acceleration and deceleration. Later a test airplane operated by T.W.A. and powered with a nine cylinder Wright engine was equipped with a similar system and was flown on several projects during the period from 1936 to 1939. Figure 1 shows this assembly on a Pratt & Whitney engine. However, general interest in manifold pressure metering and direct injection was postponed in this country by the introduction of the Bendix

Injection Carburetor which gave great improvement over previous suction carburetors. Nevertheless, the manifold pressure control and direct injection were contined and engines were kept operating intermittently on this equipment at the Wright Aeronautical Corporation from 1939 to 1942.

It is interesting to note that the principal aircraft engine manufacturers in Germany changed all of their spark ignition aircraft engines from carburetor fuel feed to timed cylinder injection during the period from 1935 to 1938. The output of these pumps is controlled by manifold density responsive regulators. All of these designs which have been discussed in the technical literature[2 & 3] are quite complex, most of them involving oil servos to move the pump control racks. Several incorporate a boost control as an integral part of the fuel metering system. Those which we have examined show well refined design and excellent workmanship. It is significant that the Germans fought the recent war with liquid and air-cooled engines equipped with the manifold density type of fuel control.

The application of the Speed-Density metering principle without direct injection apparently was conceived at approximately the same time by engineers in England at the Farnborough Laboratory of the Royal Aircraft Establishment and by Bendix engineers in the United States. The drawing of Figure 2 from British patent 428682 to Swan, Griffith and Helmore shows a control with a fly ball mechanism for generating a metering differential proportional to the square of engine speed. Another drawing in this patent shows a similar application with a centrifugal pump means for generating metering head. Both the fly ball type and the centrifugal pump type of head generating device have certain advantages. In general the fly ball device is more complex mechanically, but it is practical to incorporate in it a metering head adjustment, which is very convenient.

The R.A.E. and the English engine and carburetor companies have been very enthusiastic about Speed-Density metering and have done a large amount of research and development in connection with several designs. H. M. Hobson, Ltd. are building a device incorporating a centrifugal pump and also a boost control. This unit is sold under the name "Hobson-R.A.E. Master Control Injector" and is in current use on Bristol engines of the radial air-cooled type with sleeve valves. With these valves there is believed to be a fairly constant valve timing and valve overlap.

Development of a unit by the Bendix Aviation Corporation known as the "Speed-Density Metering Unit" began in 1943 for the Packard V-1650 engine. This device employs the fly ball centrifugal means of developing metering head and follows the general lines of the "Governor Injector" developed at Rolls Royce in England during the war.

The previous models of this engine, as well as the Rolls Royce Merlin engine, were equipped with a carburetor on the atmospheric side of the first stage supercharger. The two-speed, two-stage supercharger of this engine, as used in the Mustang airplane with its high critical altitude, was a somewhat difficult carburetor problem. The Speed-Density device for this engine was just reaching production status when the war ended in 1945. At the present time a modified and improved model is started in production for use on a new model Allison V-1710 engine.

## COMPONENTS OF BENDIX SPEED-DENSITY METERING UNIT

In contrast to other forms of metering equipment wherein the fuel is metered in response to variations in mass air flow through a venturi, this device meters the fuel in response to variations in engine R.P.M., intake manifold pressure, intake manifold temperature, and exhaust back pressure. The name Speed-Density has been adopted since it indicates the fundamental method of operation and function of the device. The components of the metering system are illustrated in Figure 3. The following are the principal elements:

1. An integral, vane-type, engine-driven fuel pump with a by-pass and relief valve, performing the function of the usual engine-driven fuel pump.

2. A centrifugal pressure regulator consisting of a set of centrifugal weights, a diaphragm subjected to the metering differential, and a valve. These component parts establish a fuel metering differential which is proportional to the square of the engine speed.

3. A pressure-responsive bellows assembly in a closed housing, operating a contoured fuel metering needle. The closed housing is vented to manifold pressure. The larger of the two bellows is evacuated, while the smaller is internally vented to atmospheric or exhaust back pressure.

4. A temperature unit responding to changes in intake manifold temperature which consists of a temperature bulb, bellows, and flexible capillary tube filled with liquid, operating a contoured metering needle.

5. A centrifugal vapor venting system which utilizes the rotation of the centrifugal regulator assembly to effect the separation of air and vapor from the fuel. The air and vapor, with some liquid fuel, are drawn from the governor chamber at its centerline and conducted to a float chamber which vents the air and vapor from the unit and returns the liquid fuel to the inlet of the vane-type fuel pump.

6. A constant pressure fuel discharge nozzle for spraying the fuel into the air stream, or means for discharging the fuel from holes in the supercharger impeller. The latter is referred to as "spinner injection".

7. A throttle actuated accelerating pump and in some instances a water regulator, which may be incorporated in the adapter unit which houses the discharge nozzle.

8. An air throttle valve (not shown in Figure 3) for controlling engine power.

## DESCRIPTION OF OPERATION

The air flow to an internal combustion engine is affected by the following principal factors in approximately the following manner:

1. Directly as the first power of the R.P.M.

2. Directly as the absolute intake and exhaust manifold pressures, when these are equal.

3. A modification of the relation stated in item 2 because of change in content of the cylinder clearance space. This adds to the air flow when the intake pressure exceeds the exhaust and reduces the air flow when the exhaust exceeds the intake pressure.

4. Inversely as the manifold temperature, to some power less than one.

These four engine variables are recognized by the metering unit, and fuel is metered to approximate the desired rate for any combination of these variables.

Most of the parts can be seen in their proper relationship on the flow circuit diagram of Figure 4. The connections between the metering system and the engine installation are shown on the assembly sketch of Figure 5.

The vane type fuel pump is driven through a shear pin from the central driving shaft (not shown) which passes through the center of the pump to drive the centrifugal regulator. Fuel is supplied by the fuel pump to the governor chamber. The thrust of the rotating governor weights creates a force proportional to the square of the engine speed.

This force is balanced against the metering head diaphragm in such a manner that the poppet valve regulates the metering head to be proportional to the square of the engine speed, with some modification from an idle spring and a constant force from an unbalanced valve. Since fluid flow is proportional to the square root of the head, the flow through any fixed jet area will then be approximately proportional to the engine speed.

The manifold pressure and exhaust back pressure bellows assembly moves a contoured needle which establishes the metering jet area for each combination of intake manifold pressure and exhaust back pressure.

The temperature metering assembly includes a second contoured needle and fuel orifice in parallel with the pressure responsive orifice. The area, and fuel flow, of the temperature unit orifice are made proportional to the engine intake manifold temperature. By proper contour of the temperature metering needle the change in fuel flow per unit of temperature change is made to correspond to the change in air flow of the engine at some cruise power. At this manifold pressure the compensation for manifold temperature will be exact.

At other manifold pressures the change of engine air flow per unit of manifold temperature change will be different and, therefore, this arrangement does not provide a constant fuel/air ratio over the whole range of manifold pressures. Instead, there is a tendency in the idle range to run rich with cold manifold temperatures and lean with hot manifold temperatures. In the high power range, there is some enrichment with high manifold temperatures, and leaning with low manifold temperatures.

It is impractical to adjust the effective jet area to obtain proper idling mixture; therefore, the idle mixture is adjusted by an idle spring which changes the idle fuel flow by adjusting the metering head.

Figure 6 shows the metering head characteristics of the Stromberg SD-400 series Speed-Density Metering Units. This system possesses a fundamental advantage over the air flow system in that the metering forces are not limited by the air venturi suction available. The ratio of the driving gear train is selected to give a pump speed of approximately 2400 R.P.M. at the maximum engine speed. At this maximum speed the governor design is such that there are approximately 150 inches of gasoline metering head across the jets. Since engines operate at a higher percentage of maximum speed than of maximum air flow, this also gives an advantage to this system from the standpoint of high heads at cruising power. At 50% of maximum speed there are 37.5 inches of gasoline metering head. Assuming the lowest idling speed to be one-sixth the take-off speed, there are still 4.1 inches of gasoline metering head available. Thus it can be seen that it is possible to meter over the entire operating range without a separate idle system customarily found in suction carburetors.

Figure 7 shows the basic fuel metering characteristics of the Speed-Density Metering Unit and a method of plotting the fuel flow requirements in terms of the controlling variables. These curves provide substantially constant mixture ratio up to the maximum cruising manifold pressure, after which an enrichment takes place as necessary to meet engine requirements in the power range. Since enrichment is obtained by a change in contour of the pressure metering needle, it can be started at any manifold pressure desired. Action of the enrichment must necessarily be a function of manifold pressure and exhaust back pressure rather than of air flow. The exhaust back pressure correction on the lower scale indicates changes in fuel flow resulting from back pressure changes, as shown for one example by the dashed lines.

Expressing the fuel flow requirements for a given engine in terms of the controlling engine variables shown on Figure 7 is more convenient and appropriate than fuel/air ratios when working with Speed-Density metering systems, and it is hoped that this method of expressing setting requirements will find acceptance. The same coordinates plotted on logarithmic scales are particularly convenient for plotting the performance of metering units for comparison with the requirement curves because equal increments of distance represent a constant percent of deviation from a requirement at any point along the curves.

The schematic diagram of Figure 4 shows means for providing only a single mixture curve. On a later model, provision has been made for selection of "cruise" and "normal" mixture curves, as well as provision for derichment used with water injection.

## IDLING

The air-breathing characteristics of a multi-cylinder internal combustion engine are influenced by many factors. Among these the valve timing is particularly important because of its relation to the idling condition. The practice of having both inlet and exhaust valves partially open for a period near the end of the exhaust stroke is common, and is referred to as valve overlap. This period, which varies with different model engines up to a maximum of approximately 80°, is utilized to aid in sweeping the spent charge from the clearance space by the inertia of the exhaust gases and the pressure of the new charge. This is illustrated on sketch "A" of Figure 8 for a power condition.

Although very effective for improving scavenging and maximum power output, a large valve overlap period makes engine idling difficult. Sketch "B" of Figure 8 shows the conditions of gas flow at the end of the exhaust stroke for a sea level idling condition. Scavenging of the clearance space is not accomplished because of lack of exhaust inertia; even worse, the exhaust products have been forced into the inlet manifold under the existing pressure differential. Under this idling condition a considerable proportion of the new charge is made up from flow through the exhaust valve which, depending upon the exhaust system, may be either fresh air or exhaust products. In any case this results in a high percentage of dilution of the new charge and the necessity for a rich induction pipe mixture to obtain a best power mixture in the cylinder for idling.

The idling problem is further complicated on air-cooled engines by changes in valve timing due to cylinder temperature changes. This results in variation of the relative amounts of charge drawn into the cylinder from the exhaust and inlet manifolds. It also requires a change in intake manifold pressure vs. fuel flow requirement. It is believed that if a satisfactory type of constant or zero clearance valve lifter could be developed for these engines, the idling problem would be made generally easier; and particularly with the Speed-Density system.

It is interesting to note that if a nine-cylinder engine has an $80^{\circ}$ valve overlap the exhaust manifold is in direct communication at all times with the inlet manifold through one cylinder. For engines with more cylinders the number of communicating passages obviously increases in proportion with the number of cylinders. If such an engine is motored slowly, there will be little intake manifold depression and difficult starting is quite understandable. This partially explains the characteristic idling and low power manifold pressure curve of Figure 9 for an engine with considerable valve overlap.

With the Speed-Density system the fuel for idling, as well as at power, is metered by the four controlling engine variables, with the exception that manifold pressure influence cannot be used at manifold pressures less than that corresponding to minimum idle. In general, the engines to which this metering system has been applied have not had a very significant rise in manifold pressure near the minimum idle point, as shown on Figure 10. These curves are very greatly influenced by the idling fuel flow rate. The result of these flat manifold pressure curves is that the metering is done primarily as a function of speed with an undercorrection for manifold temperature which results in enrichment with colder than normal manifold temperature. Data concerning the effect of manifold temperature on the idling fuel flow requirements are not available to the author.

It will be noted that this system provides altitude compensation for the idle since the engine speed and manifold temperature are not directly related to atmospheric conditions.

This method of idling control has proven very satisfactory on installations made to date, and gave particularly good idling on the Packard V-1650 engine.

## LOAD COMPENSATION

The term load compensation as commonly used refers to the ability of the metering device to deliver to the engine a constant fuel/air ratio for a given power through some combination of manifold pressures, R.P.M. and other engine conditions. The use of variable pitch propellers, which makes possible the use of high cruise BMEP combined with low R.P.M., constitutes the principal necessity for load compensation. With the advent of variable pitch propellers on light aircraft it is apparent that any fuel metering device for these engines will be required to also have a basically correct means for providing the desired mixture ratios through a combination of engine conditions.

Consider an engine which is always operated on a fixed schedule of speed, manifold pressure, and manifold temperature, as might result with the use of a fixed pitch propeller used at constant air speed and constant air density. On such an engine large changes in volumetric efficiency with speed would present no difficulty to the designer of a Speed-Density fuel metering device since a given speed would always be associated with a given manifold pressure and thus large changes in volumetric efficiency could be compensated for in the contour of the manifold pressure metering valve. To go even further, there would be no need for a separate component to correct for change in manifold temperature since each value of manifold pressure is associated with a given temperature and a proper contour on the manifold pressure needle would provide the desired fuel flow. It is only when it is desired to change speed at some manifold pressure as is ordinarily done for cruising with variable pitch propellers that we become concerned with the effect of speed on the volumetric efficiency of an engine. The smaller the range of combinations of speeds and manifold pressures through which an engine is required to operate the easier the problem of fuel metering becomes. It is important in this connection that the tendency of the Air Materiel Command is to limit the necessary load compensating requirements by the use of power controls which will provide only limited selection of combinations of manifold pressure and speed.

The actual ability of the metering unit to meter a constant fuel quantity per engine revolution over a wide range of speeds at a given manifold pressure is shown by the fuel flow data of Figure 11 taken from North American Aviation, Inc., flight test results.

## POWER ENRICHMENT

There has been controversy as to the relative merits of manifold pressure and air flow mixture enrichment. For engines in which the coolant system can provide adequate cooling of the parts, enrichment must be provided only to suppress detonation. Some engine manufacturers are quite convinced that mixture enrichment as a function of manifold pressure and temperature is best, while others feel that enrichment according to air flow has the most advantages.

The curves of Figure 12 show the knock limited fuel flows for the maximum and minimum manifold temperatures expected in normal flight for the Packard V-1650 engine, and indicate that for this engine manifold pressure and temperature are a good index of the need for enrichment. All these data pertain to operation without water or other internal coolants. The curves reveal that for the same conditions of manifold pressure and R.P.M. more fuel will be required for the lower manifold temperatures below 59" manifold pressure. This is due to the increased air flow at lower manifold temperatures and, therefore, more fuel is required to hold the 0.070 fuel/air ratio. At the minimum manifold temperatures shown, no enrichment above 0.070 fuel/air ratio is required below 67" manifold pressure. Enrichment is required above 53½" manifold pressure at maximum manifold temperatures to prevent detonation. At 67" manifold pressure detonation will occur at high manifold temperatures even with the rich mixture of 0.10 fuel/air ratio.

Figure 13 shows the mixture ratio delivered by an early model Speed-Density metering unit in flight at 5000 ft. altitude for the Packard engine. The enrichment with rising manifold temperatures can be observed. Since the metering unit is not designed to provide change in fuel flow proportional to change in engine air flow per unit temperature change at all power conditions, a curve of fuel/air ratio vs. air flow has little meaning unless the schedule of manifold temperature is defined. Similarly, fuel enrichment at high power is a function of the manifold pressure. It is possible to operate the engine at a given power and air flow with various combinations of manifold pressure and speed. If the manifold pressure is changed at constant power or air flow, a varying fuel/air ratio will result. This is illustrated on Figure 14. This is an additional reason why the plot of fuel/air ratio vs. air flow has little meaning unless the manifold pressure and speed schedules are also defined.

Air flow is proportional to the product of manifold density and speed. Therefore, a carburetor with air flow enrichment will permit an engine to operate at higher manifold pressure and BMEP without encountering the fuel enrichment range if the speed is kept lower than the normal schedule. With a device having pressure enrichment it is necessary that the maximum manifold pressure used for economical cruising be a lesser value than the manifold pressure at which enrichment must begin for the protection of the engine.

In some of the air-cooled engines mixture enrichment must be started prior to the detonation limited value in order to aid engine cooling. It is a common opinion that for these engines mixture enrichment as a function of air flow will be most desirable, because the heat generated is a function of power and, therefore, of air flow. Data to substantiate this opinion is not available to the author at this time. Only after such information is available can a decision be reached concerning the type of power enrichment which is best.

A discussion of the method of fuel flow enrichment for power is pertinent because it greatly influences the design of the fuel metering equipment. When fuel is made to flow as a function of manifold pressure by means of a contoured needle valve, the enrichment can be made a function of manifold pressure by proper contour of the needle valve. Thus no added parts are required to produce the enriching action and metering control is directly accomplished by the engine operating variables. If enrichment is to be a function of air flow, the control variables must first be properly integrated into a single function of the air flow. This can probably be accomplished, but it will result in a larger and more complex device with additional possible sources of metering in accuracy.

The problem of power enrichment serves to illustrate the point that many special devices are required to supply all the departures from the basic fuel flow required by a modern aircraft engine. It is particularly important when considering this new variety of metering control that the engine fuel flow requirements be carefully examined with the objective of making possible the most accurate and reliable metering device which can be built. This will require close engineering cooperation between the engine and carburetor manufacturers so that each will appreciate the problems of the other. It is possible to arrive at the most intelligent compromises only when this exchange of information exists.

## VOLUMETRIC EFFICIENCY

When the suitability of Speed-Density fuel metering for an engine is considered, its volumetric efficiency characteristics are very significant. For example, it has been pointed out in the discussion of load compensation that if the volumetric efficiency of the engine is affected only slightly by change in engine speed, the problems of fuel metering are easier. For this discussion, volumetric efficiency is defined as the ratio of the mass of air induced per cycle to the mass of a volume of charge equal to the piston displacement at the induction pipe (intake manifold) density. This has been discussed and defined by various authors[4] and is expressed by the following equation:

$$E = K \frac{M}{N \quad V \rho_i}$$

where:

$E$ = volumetric efficiency

$K$ = a constant

$M$ = wt. of air taken in per unit time (intake manifold)

$N$ = suction strokes per unit time

$V$ = piston displacement for one cylinder

$\rho_i$ = density of air at engine inlet

This equation, it should be noted, excludes the direct influence of manifold density changes caused by superchargers or by carburetor throttling. It is a very convenient quantity for comparing the pumping characteristics of the cylinders and valves of different engines.

The principal operating factors which influence the volumetric efficiency for a given engine are[5]:

1. Engine R.P.M.
2. Manifold Pressure
3. Exhaust Back Pressure
4. Manifold Temperature

Typical data will be presented for several engines to show the relationship between air flow or volumetric efficiency and these four major engine variables.

## AIR FLOW AND VOLUMETRIC EFFICIENCY VS. SPEED

The phenomena causing change in volumetric efficiency with speed are very complex, and it is impractical to derive equations relating the air flow or volumetric efficiency to R.P.M. It is, therefore, important to examine the consistency of the volumetric efficiency through the normal speed ranges for various manifold pressures with different engines. Figure 15 shows such data for an Allison V-1710 engine, a typical large displacement liquid-cooled engine. It will be noted that the greatest variation occurs at low speed combined with low manifold pressure. The variation shown by the 20- and 25- inch manifold pressure curves at low speed is principally due to blow back resulting from valve overlap, previously discussed. The departures of the 20- and 25- inch lines from the remaining grouped curves are tolerable since these manifold pressures on this engine lie on a fixed or propeller load schedule and their effect can be compensated for in the setting of the unit. The medium power conditions of M.P. and R.P.M. show volumetric efficiencies in excess of 100%. This also is probably the result of the large valve overlap of the engine (78°) which permits the new charge to fill not only the piston displacement but the clearance space as well. The curves show approximately 8% variation in volumetric efficiency accompanying a speed change from 2200 to 3200 R.P.M. Since under normal schedules the complete range of manifold pressures are not used at the two speeds, the error in the air/fuel ratio that would be caused by the changing volumetric efficiency of the engine may be largely removed by proper contour of the manifold pressure needle.

Data on air flow per engine R.P.M. at several constant manifold temperatures and pressures are shown for the Packard V-1650 on Figure 16. The percent change in air flow per R.P.M. for the speed ranges shown is indicated on the curves. From this it may be concluded that a fuel metering device which meters fuel in direct proportion to speed will provide satisfactory speed compensation for these engines through the ranges required for normal operations.

## AIR FLOW AND VOLUMETRIC EFFICIENCY VS. PRESSURE

An engine air system consisting of ducts and valves is essentially equivalent to an orifice, and analysis reveals that the air flow to the engine is a function of the ratio of inlet manifold pressure and exhaust pressure[4]. In most Speed-Density types of fuel metering devices the relationship between fuel flow requirement and manifold pressure is obtained by a contoured fuel metering needle, or in the case of the German systems, by a contoured cam. Obtaining this desired relationship, therefore, presents no serious problem. From the standpoint of fuel metering a more significant relationship to examine is the relative effect upon air flow caused by changes in manifold pressure and exhaust back pressure.

The curves of Figure 17 show for the Packard V-1650 engine the effect of change of exhaust back pressure upon the air flow per engine revolution at various manifold pressures and speeds. The dashed lines show the compensation for altitude that can be provided by an exhaust back pressure correction that functions according to the relation:

$$\frac{\text{Air Flow}}{\text{R.P.M.}} = K_1 \left(\text{manifold pressure} - \frac{\text{exhaust back pressure}}{K_2}\right)$$

where $K_2$ has the value of 8. These data show, as also indicated by the above equation, that the correction for back pressure increases on a percentage basis as the manifold pressure is reduced.

The divergence of the solid and dashed lines of constant manifold pressure indicates that the value of the constant $K_2$ in the above equation relating the intake manifold and exhaust pressures is not single valued. The maximum error in the correction occurs at the lower manifold pressures, partly because this manifold pressure can be obtained over the largest altitude range. The maximum error in the exhaust pressure correction is less than 1.5%, which occurs with the lower manifold pressure of 33.5" Hg. when going from ground level to 35,000 ft. altitude.

The total correction necessary to compensate for changes in exhaust back pressure at high power is quite small. For the Packard engine the variation in air flow is only 4% for a change from ground level to 15,000 ft. at 61" Hg. manifold pressure. Partly because of the small total correction necessary, the mechanism described, which responds to the difference of the inlet manifold and exhaust pressures, is believed satisfactory.

Since a compromise value of the constant is necessary in this design, it should be selected to give a minimum error in fuel metering at all altitudes. As stated, the lower values of manifold pressure can be carried to the highest altitudes, and on a percentage basis the effect of unit back pressure change is a maximum at low manifold pressure. For these reasons it is usually best to select the correction constant that applies to the lowest manifold pressure used in normal flight.

With a few engines and installations it is the practice to include in the altitude compensation of the carburetor some enrichment of the mixture with increasing altitude, to aid engine cooling. This can also be accomplished with the Speed-Density metering unit by proper selection of the constant $K_2$, in the above equation. By selecting a smaller value of $K_2$, which is accomplished by a back pressure bellows with reduced total spring rate, the rate of increase of fuel flow with altitude can be made to exceed the rate of increase of engine air flow due to reduced back pressure; thus mixture enrichment will occur.

Theoretically, the exhaust pressure required for correcting the fuel flow is the cylinder pressure at the time the exhaust valve closes. To date flight testing has been done with the exhaust back pressure bellows vented to the accessory compartment pressure since it is impractical in flight to measure the exhaust pressure from separate ejector stacks. This has given satisfactory performance, perhaps in part because the total exhaust pressure correction is relatively small. No installations have been made in connection with turbo superchargers, which would necessitate a pressure tap into the exhaust collector system.

In addition to the above data taken on altitude test stands, the North American Aviation Corporation has gathered considerable flight data showing the effect of exhaust back pressure on air volumetric on this engine equipped with ejector stacks. These data show close agreement with the test stand information reported.

## AIR FLOW AND VOLUMETRIC EFFICIENCY VS. MANIFOLD TEMPERATURE

The cylinder charge density at the time of closure of the inlet valve is an inverse function of the first power of the charge temperature, $T_c$. It follows, therefore, that the air flow should also be inversely proportional to $T_c$. The manifold temperature, $T_m$, and the cylinder charge temperature are not the same because of charge dilution and heat transfer from engine parts. Since it is only practical to measure $T_m$, it is of primary importance to determine the relationship between air flow and $T_m$. This relationship must be empirically determined for each model of engine, and conclusions regarding it should be based on a considerable amount of carefully obtained data.

The curves of Figure 18 show this relationship for the Allison V-1710 engine. The logarithm of the air flow is plotted against the logarithm of the manifold temperature for several manifold pressures at three different speeds. The average slope of the lines for each speed group is shown. The fact that the data for the curves plot as straight lines, demonstrates that the relationship between air flow and manifold temperature may be expressed by an equation of the exponential form:

$$\text{Air Flow} = \frac{\text{Constant}}{(T_m)^x}$$

where x has the average value of the slope of the curves for a given speed. For this engine the average value of the exponent is 0.70. The values of the exponent x, noted on Figure 18, increase with a decrease in speed. This is a result of the longer time available for heat transfer to the charge with the reduced speed.

There is a question as to the accuracy with which the absolute manifold mixture temperature can be measured, since the medium is a mixture of varying proportions of liquid, vapor, and air. When the temperature sensing bulb is placed in this wet mixture, it is expected that it will measure a temperature which lies between the wet and the dry bulb temperature. The most important consideration is that the average bulb temperature bears a consistent relationship to the average manifold temperature. To obtain the best average charge temperature possible, it is desirable that the sensing bulb extend entirely across the section of the manifold. The temperature data presented on Figure 18 indicate that consistent readings can be obtained. Further evidence of this correlation is given by the data of Figure 19 which shows a comparison of manifold temperatures read at two different points in the manifold. These are flight data taken by the North American Aviation Corporation on two different airplanes and engines over a considerable period of time. Although the two temperature bulbs in the manifold do not give the same absolute value, the consistent relationship between them shows that a satisfactory indication is obtained. All our experience with fuel metering settings to date indicates that the manifold temperature sensing device is not a significant source of variation in metering.

The effect of change in cylinder coolant temperature upon volumetric efficiency has been investigated for several manifold temperatures at the Massachusetts Institute of Technology[6]. The data from the Ford V-8 engine tested revealed that the volumetric efficiency decreased approximately 4.5% with a 100°F. increase in jacket temperature. For present day liquid cooled aircraft engine installations it is believed unnecessary to correct the fuel flow for this temperature, because the jacket temperature is automatically controlled. We have been advised by the

North American Aviation Corporation that typical liquid-cooled installations such as their P51-H will automatically maintain the jacket temperature within $\pm$ 15° F. of the normal schedule temperature.

## CONSISTENCY OF AIR CONSUMPTION OF PRODUCTION ENGINE

Data on the consistency of air consumption of production engines are quite meager, because it is very difficult to maintain the air measuring equipment on engine test stands in a condition that will insure accuracy of the order needed for the present study. Some engine companies do not measure air flow during acceptance testing of production engines. In cases of discrepancy of data it is quite common to question the accuracy of engine air flow measured with test stand equipment.

No reliable data is available to the author on the consistency of air consumption of poppet valve air-cooled engines. This is one reason why it is not possible to reach any conclusion at this time on the suitability of this type of fuel metering system for these engines.

As previously mentioned, the accuracy of the mixture ratio is dependent upon uniform air consumption among production engines and throughout the life of an engine. Figure 20 shows the consistency of air consumption of a Packard V-1650 engine during a 100 hour maximum economy mixture endurance run. The variation in air consumption is a maximum of 3%, which includes the errors of test stand measurements. Inspection of the engine after this test revealed considerable deposit under and on top of valve heads.

Figure 21 is a spot plot of the volumetric efficiency of at least 8 different production V-1650 engines run on several different engineering test stands. These data were run at speeds from 1500 to 3000 R.P.M. and temperatures from 50° to 275° F. manifold temperature, for the manifold pressures shown. Lines showing a plus or minus 4% band are shown which include most of the data points. Those familiar with the problem of accurately measuring air flow [7,8] and the difficulties of obtaining correlation on different engine test stands will realize how difficult it is to obtain data on a variety of engines and stands which lie within such a narrow band. The plot indicates that under widely varying conditions of manifold temperature, manifold pressure, and speed, the different engines of this model are remarkable for their consistency of volumetric efficiency, when corrected to a given set of conditions. The detailed data also show that volumetric efficiency for this engine is quite independent of speed and that precise correction can be made for manifold temperature change.

Figure 22 showing the consistency of air consumption of several Allison V-1710 engines at three different speeds reveals that these four engines have observed air flows that lie within a band of variation of plus or minus 3%.

INSTALLATION

A sketch of the components of a complete installation of the metering system is shown on Figure 5.

For maximum power and critical altitude the entrance opening of the air scoop should be placed where it will receive nearly full ram pressure, and the duct joining the scoop inlet to the throttle body should be designed to provide the maximum pressure at the throttle body flange. For safety in heavy rain, snow, and sleet, an alternative air inlet should be provided from some protected region inside the cowl.

It should be remembered when choice of locality for fuel spray delivery is made that ice will form at any point beyond the spray delivery where the wall temperature can drop to 32° F., whether the wall be that of a carburetor casting, of an adapter, part of a supercharger housing, or part of an intake manifold. Care must, therefore, be taken that the point of spray delivery is adequately protected by conducted engine heat. The single exception to this rule is that of fuel discharge from the supercharger impeller referred to as "spinner injection". With this method, no special precautions seem needed to guard against refrigeration ice formation.

In the present designs, the fuel metering unit incorporates the usual vane fuel pump; consequently, the fuel supply pressure to the unit corresponds to the usual boost pump pressure. This pressure should be sufficient to insure vapor-free fuel at the inlet under all conditions of operation. Tapped holes are provided for measuring this boost pump pressure at the metering unit inlet and also the discharge pressure from the engine driven pump.

## ADVANTAGES OF SPEED-DENSITY SYSTEM

Several of the advantages of this system have already been stated or suggested. The following is a summary of the most significant items:

1. An increased consistency of fuel consumption in flight resulting from elimination of metering variations caused by air scoop effect.

2. Some reduction in induction system restriction if it is used in combination with a well-designed air inlet duct.

3. An easier and more direct check of the fuel metering equipment on the ground or in flight, made possible by an observation of the controlling variables and the corresponding fuel flow; but generally there must be better flight instrumentation than is now sometimes used with conventional carburetors.

4. Higher metering forces which are independent of the suction limitations imposed by venturii flowing low pressure air at altitude.

5. A reduction in weight and size of metering unit and air throttle valve compared with those of carburetor and separate fuel pump.

6. A greater flexibility in installation resulting from a separate throttle body, and permitting the metering unit to be independently located.

7. Automatic altitude compensation of the idling fuel flow.

In addition to the above, it is believed that there is a possibility of greater consistency of fuel consumption in flight because the fuel is metered by the same variables which the pilot or flight engineer establishes in flight; consequently, variation in air flow between engines is eliminated as a variable in fuel flow.

## SIGNIFICANCE TO AIRCRAFT INDUSTRY

The main point of interest to the aircraft industry, it is believed, is that the use of Speed-Density metering will require an entirely different procedure than we now have with carburetors. The following items are pertinent:

1. It is important that the limitations of the system be recognized and compromises made. For example, a change in valve timing may make the engine a more accurate air meter and, therefore, be worth compromising in the interest of more accurate and simplified fuel metering equipment.

2. Flight testing will be required to determine the metering requirements under flight conditions at least until our production and service experience with the new system is complete. This will be especially necessary for those engine companies which do not have facilities for reducing exhaust pressure on a test stand. It is believed that it will be easier to check the performance of the Speed-Density metering system in flight than that of the mass air flow type carburetor, because the controlling variables are directly measurable.

3. It will be necessary for the engine and airplane companies to determine the parameters which govern engine safety and engine life in these new terms of manifold pressures, temperatures, R.P.M., etc. The degree of enrichment at high power, the permissible boost pressures, and the permissible modifications with water injection all must be defined in these new terms.

4. The manufacturer of the fuel metering equipment will be able to guarantee only the fuel flow of the unit under specified engine

conditions and will not be able to guarantee Fuel/Air ratio. This should cause no difficulty since the final and most important objective of the engine manufacturer is to obtain the guaranteed brake specific fuel consumption.

5. The use of large and expensive carburetor air box testing equipment can be eliminated at the carburetor and engine manufacturers' plants.

6. It should be made clear that in going to this new system any effort to maintain the old carburetor procedure and specifications will merely retard and confuse, and fuel/air ratio will become an unknown factor on production engines. Fuel/air ratio will continue to have value in the experimental engine laboratory, but should have no place in a fuel flow specification of a Speed-Density metering device. I think reflection will show that Speed-Density metering can be a success only if approached from this standpoint.

## ACKNOWLEDGMENT

We wish to express appreciation for data supplied by the Packard Motor Car Company, the Allison Division of General Motors Corporation, North American Aviation, Inc., and the Air Materiel Center.

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5. The Charging Process in a High Speed, Single Cylinder Four-Stroke Engine, by Reynolds, Schecter & Taylor, NACA Tech. Note, No. 675.

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9. Measurements of the air consumption of a poppet and sleeve valve air-cooled radial aircraft engines with varying exhaust back pressure and intake temperature, by B. Shilling M. Sc. Report No. 3800 Royal Aircraft Establishment, Farnborough, England.

## LIST OF ILLUSTRATIONS

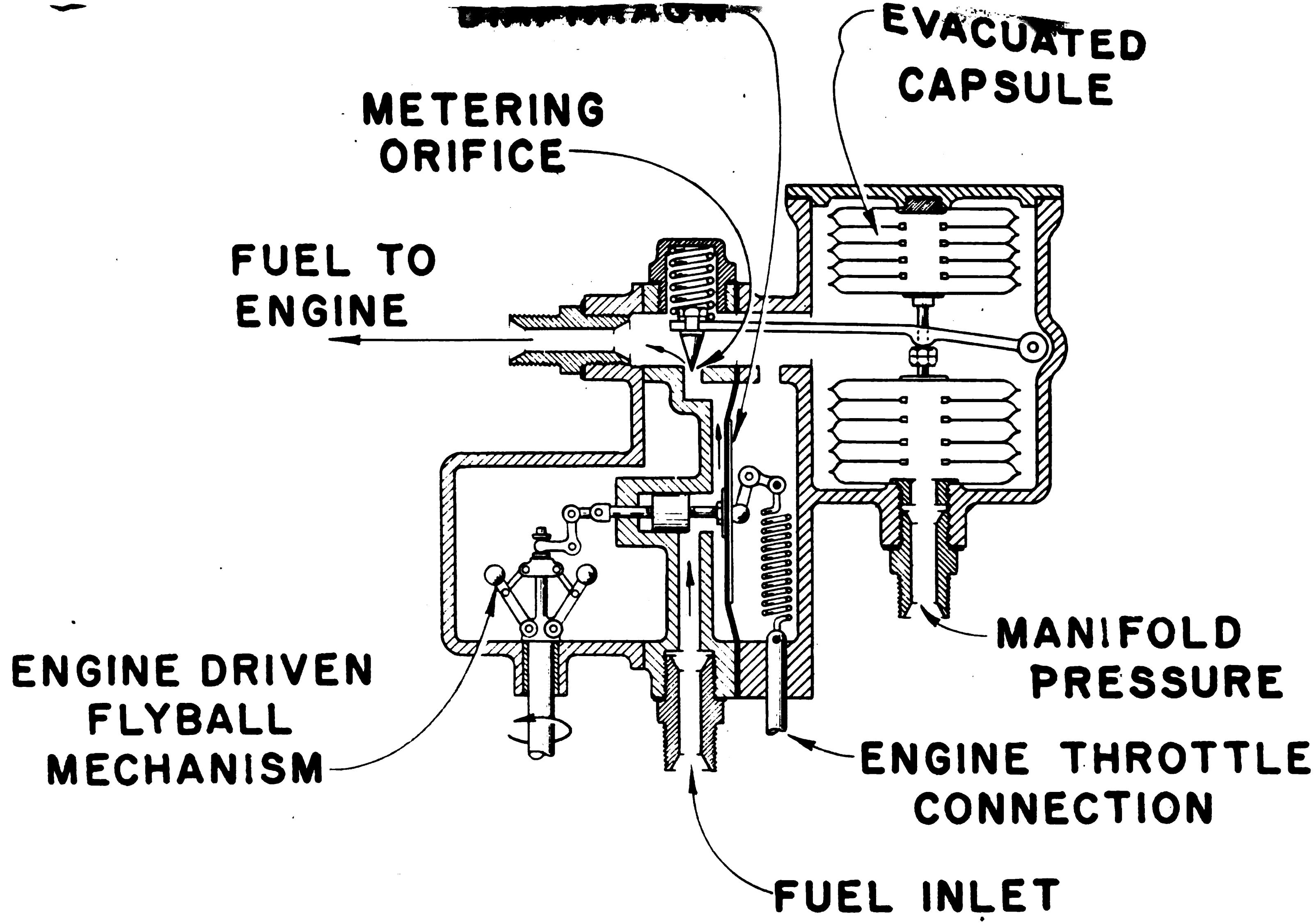



FIG. 2 PATENT SKETCH OF EARLY MANIFOLD PRESSURE AND SPEED RESPONSIVE FUEL CONTROL - FROM BRITISH PATENT 429,682

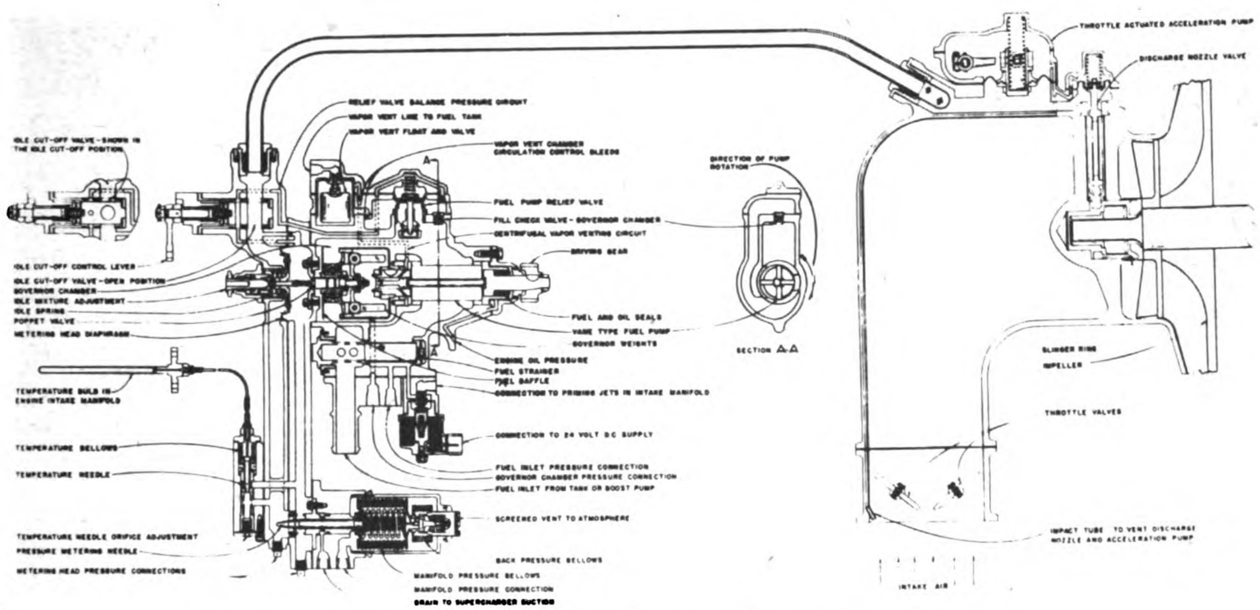



**FIG. 4 SCHEMATIC DIAGRAM OF STROMBERG SPEED-DENSITY METERING SYSTEM**

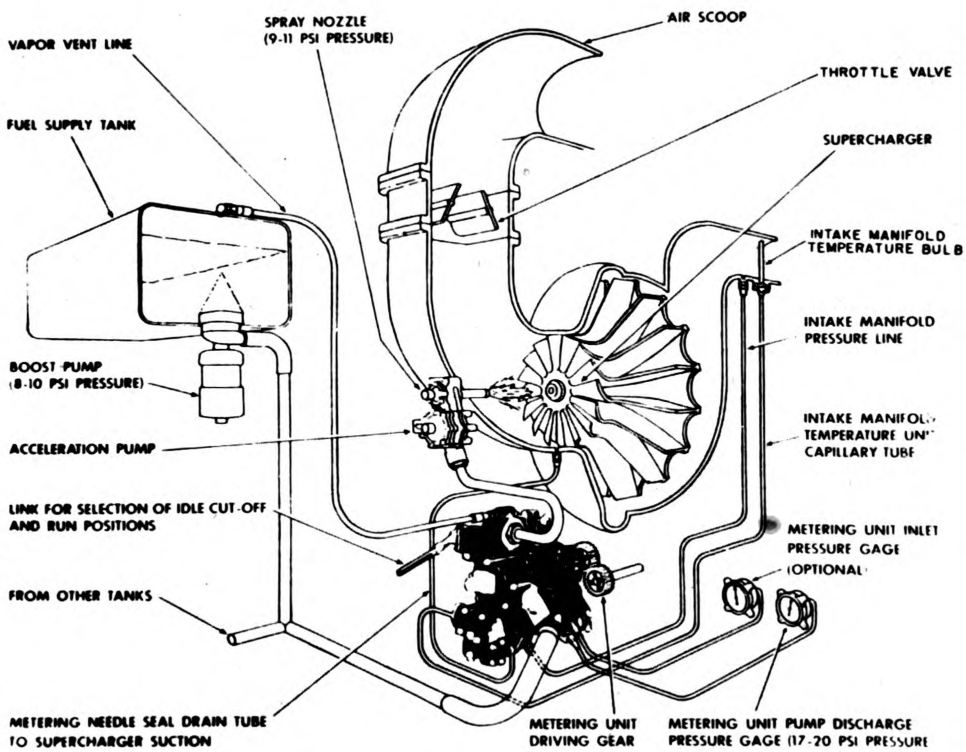



FIG 5 INSTALLATION ASSEMBLY OF SPEED-DENSITY METERING SYSTEM

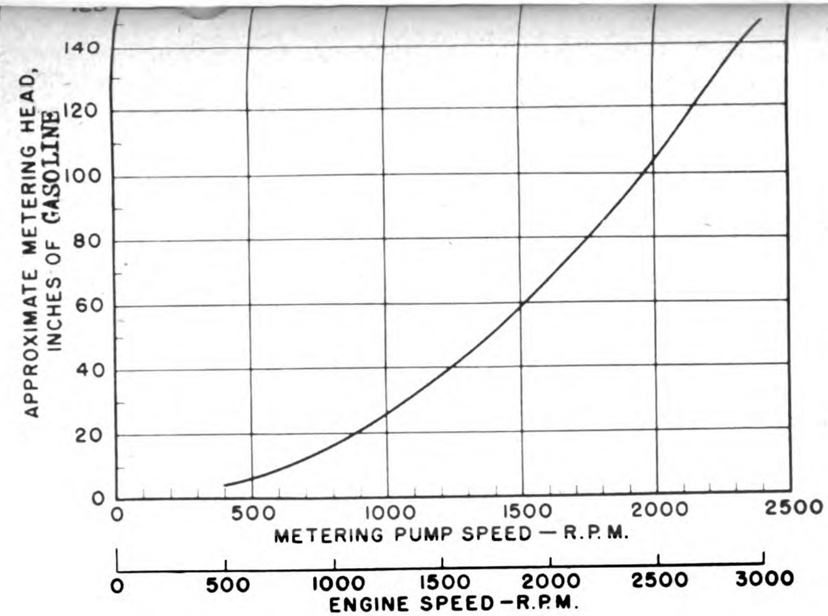



FIG. 6 METERING HEAD OF TYPICAL SPEED-DENSITY UNIT

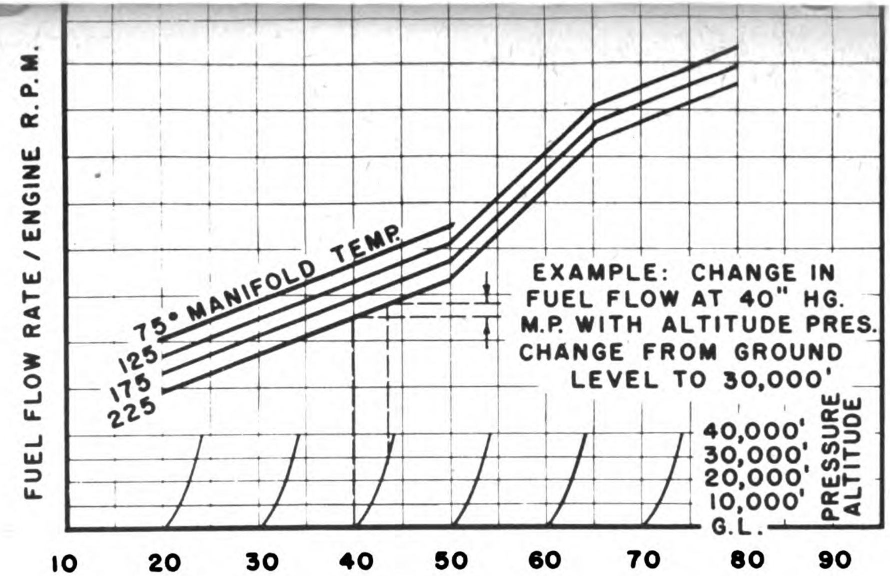
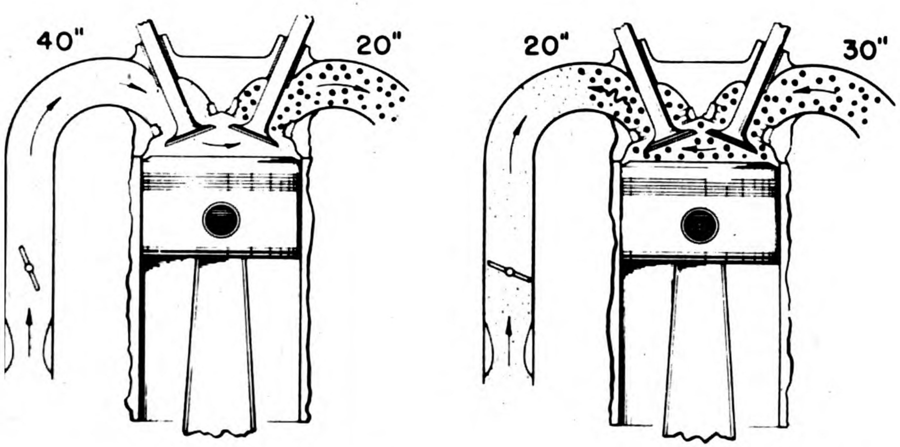



FIG. 7 FUEL FLOW CHARACTERISTICS OF SD-400 SERIES METERING UNITS




POWER CONDITION "A"

IDLING CONDITION "B"

FIG. 8 CHARGE FLOW DURING VALVE OVERLAP PERIOD

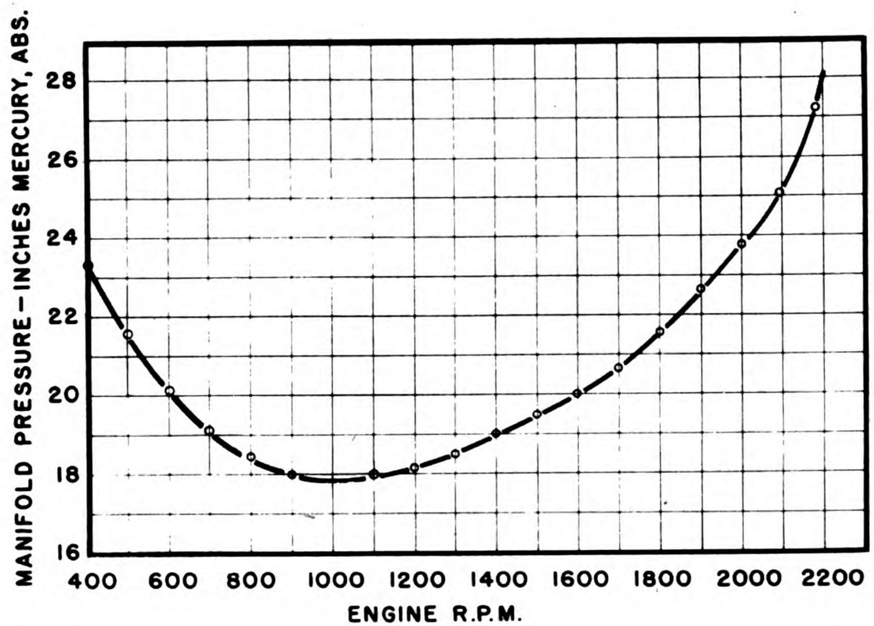



FIG. 9 INTAKE MANIFOLD PRESSURE VS. R.P.M. FOR ENGINE WITH LARGE VALVE OVERLAP PERIOD

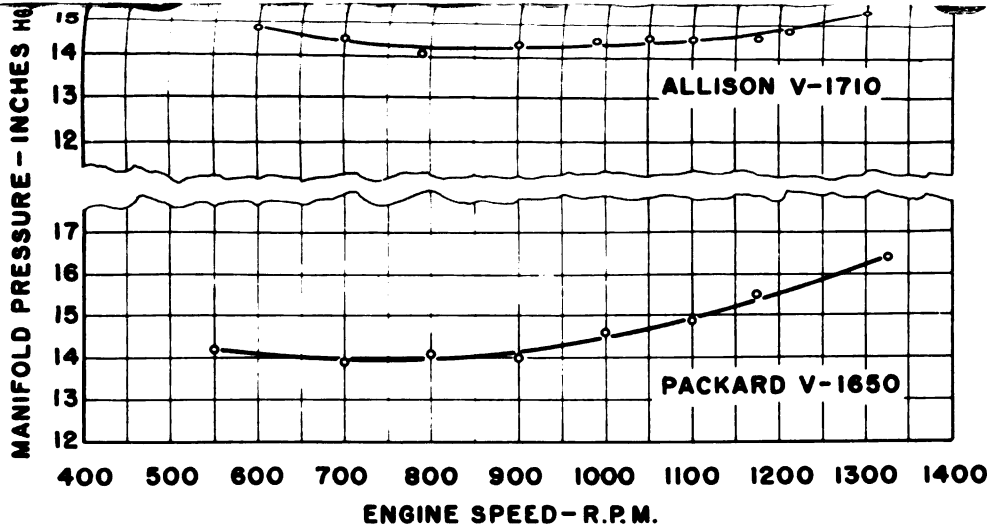



FIG. 10 IDLING MANIFOLD PRESSURE FOR TWO ENGINES AT BEST POWER MIXTURE

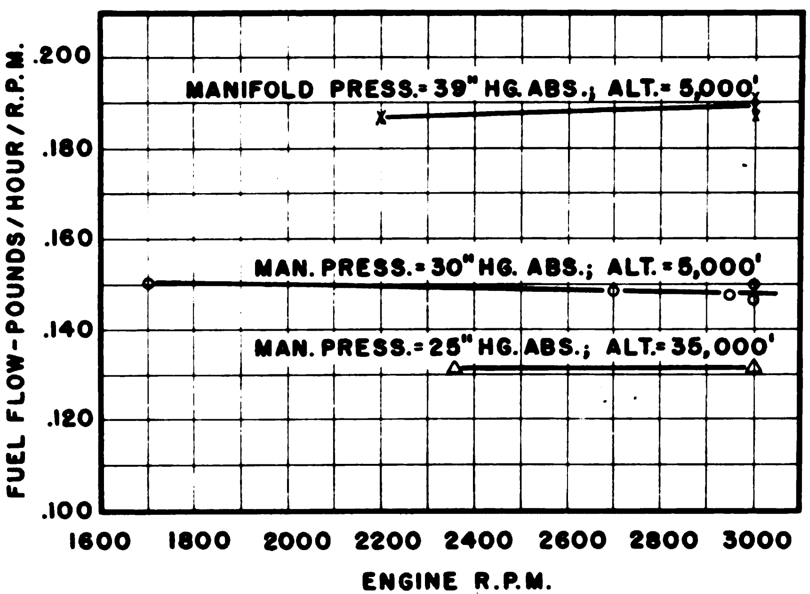



FIG. 11 SPEED COMPENSATION OF METERING UNIT IN FLIGHT

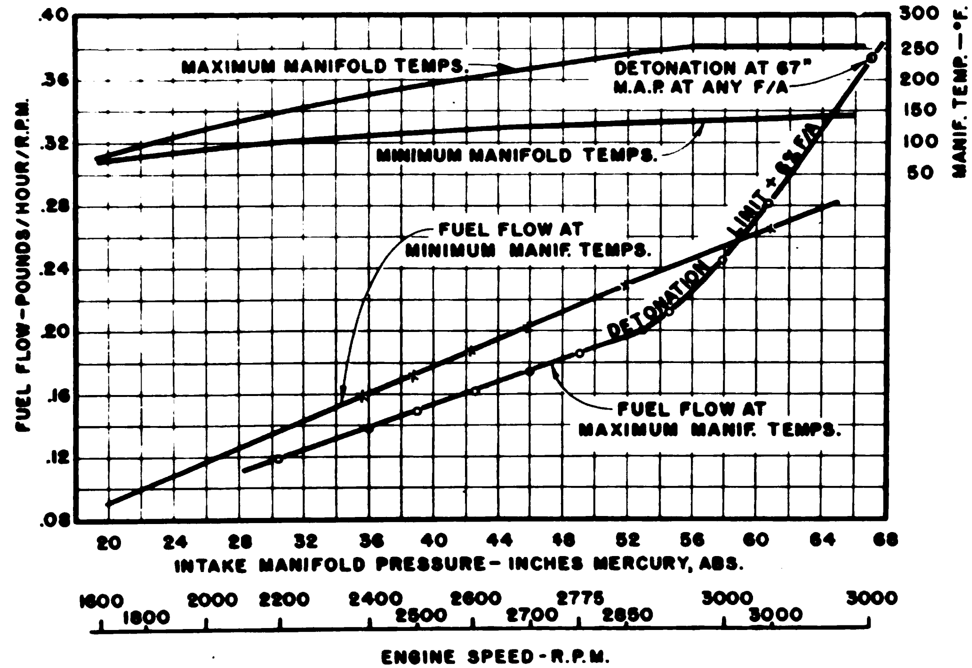



FIG. 12 KNOCK-LIMITED FUEL FLOW REQUIREMENTS FOR PACKARD V-1650 ENGINES

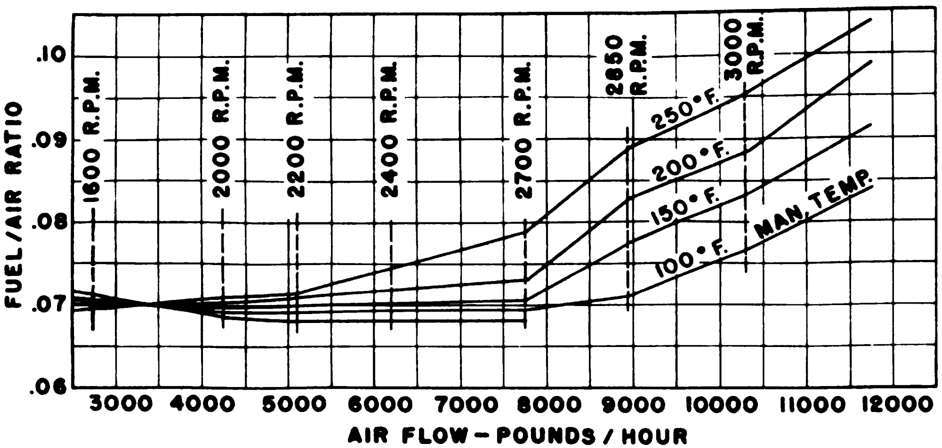



FIG. 13 EFFECT OF MANIFOLD TEMPERATURE ON MIXTURE RATIO—MODEL SD-400 METERING UNIT

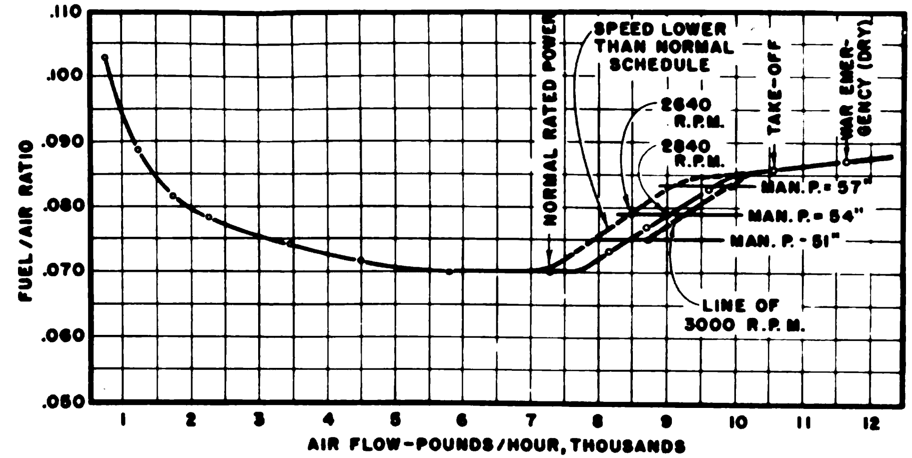



FIG. 14 EFFECT OF INTAKE MANIFOLD PRESSURE ENRICHMENT ON F/A RATIO

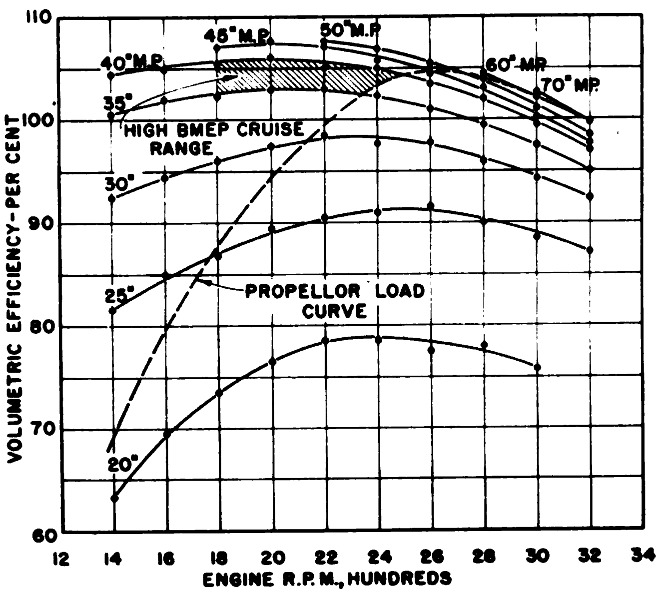



FIG. 15 VOLUMETRIC EFFICIENCY OF ALLISON V-1710 ENGINE

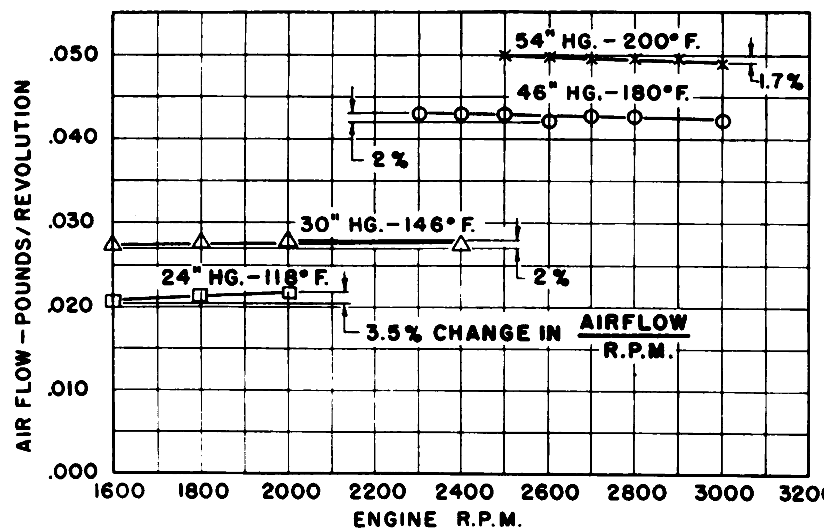



FIG. 16 EFFECT OF SPEED ON AIRFLOW PER ENGINE REVOLUTION—PACKARD V-1650 ENGINE

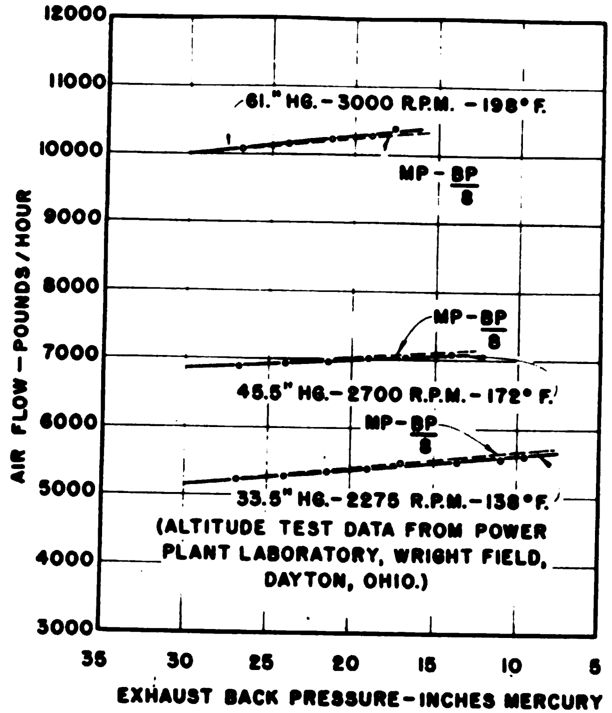



FIG. 17 EFFECT OF CHANGE IN EXHAUST BACK PRESSURE ON AIRFLOW - PACKARD V-1650 ENGINE

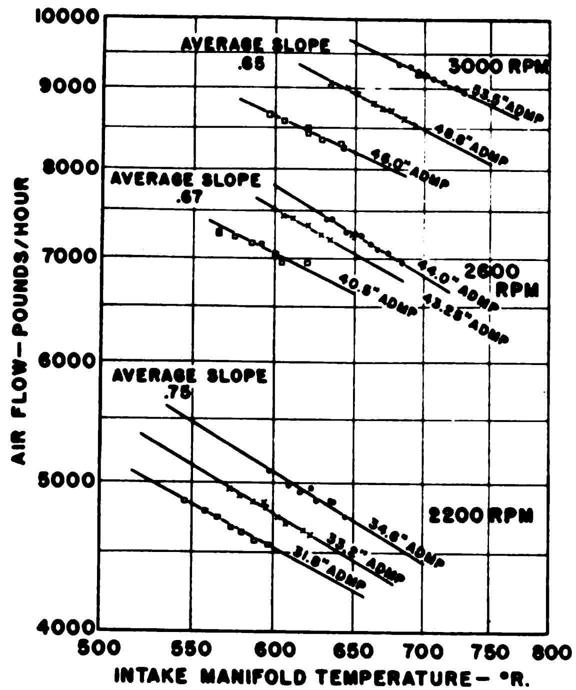



FIG. 18 VARIATION OF ENGINE AIR CONSUMPTION WITH INTAKE MANIFOLD TEMPERATURE ALLISON V-1710 ENGINE

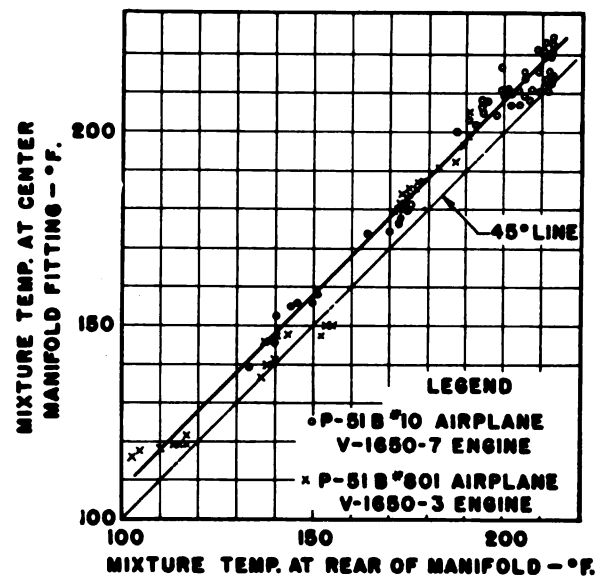



FIG. 19 CORRELATION OF MANIFOLD TEMPERATURE DATA FROM FLIGHT TESTS

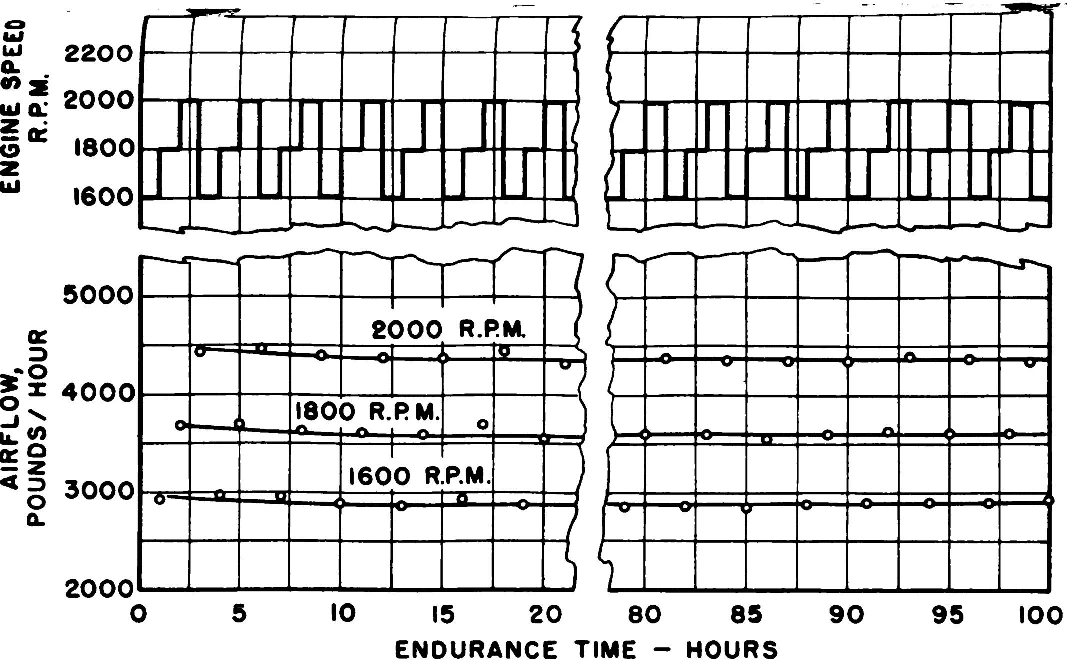



FIG. 20 AIR CONSUMPTION OF PACKARD V-1650 ENGINE DURING ENDURANCE TESTS

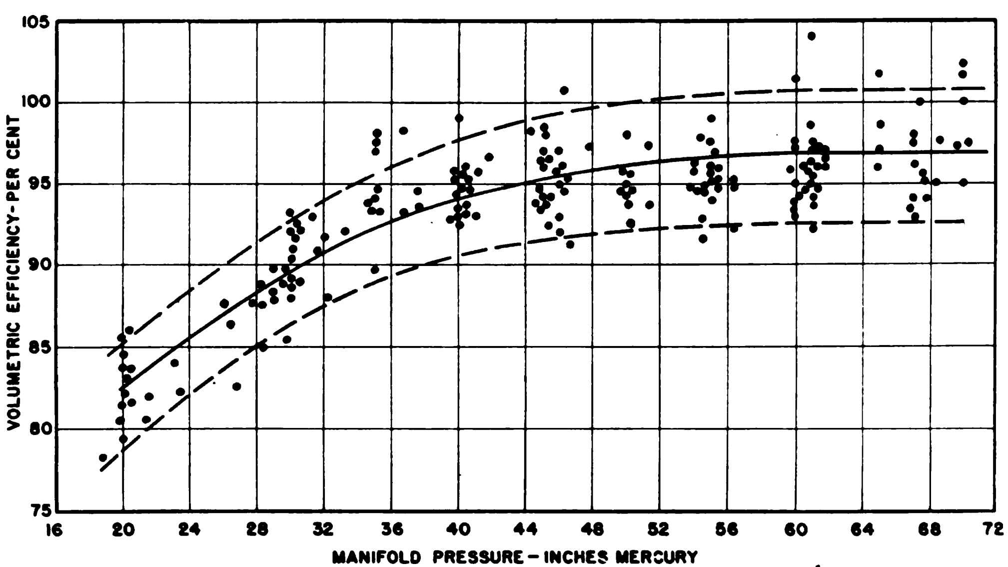



FIG. 21 VOLUMETRIC EFFICIENCY OF EIGHT PACKARD V-1650 ENGINES

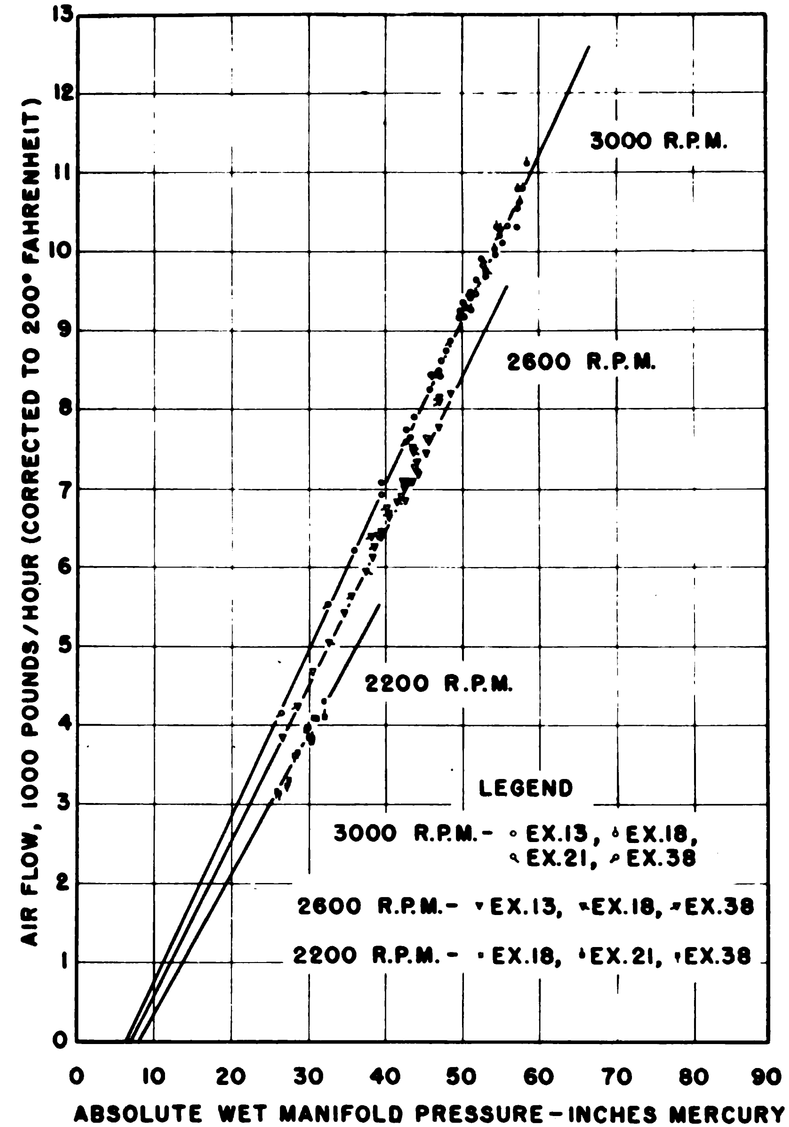



FIG. 22 CONSISTENCY OF AIR CONSUMPTION OF FOUR ALLISON V-1710 ENGINES

'48 ROOM USE ONLY