# CHAPTER XVIII

## *Floatless Carburetors and Fuel Injection Systems*

A GREAT many essential parts of an aircraft engine are bought by the engine maker from outside suppliers. Some of these, such as bearings and valves, are integral components of the engine; others, commonly known as accessories, are no less essential for its functioning. This peculiar situation, where a complex and absolutely essential part of the engine is designed and developed by a firm completely separate from the firm designing and developing the engine itself, has naturally created some peculiar and very complex problems in the relations between the specialist and the engine builder, between the specialist and the government, and even between the government and the engine builder.

An excellent example of an absolutely essential accessory developed by an independent firm is the device which governs the rate at which fuel is fed to the engine.[1] There are two principal types of fuel-metering devices. In the first, the fuel is metered, atomized, and mixed with the incoming air stream before this stream is divided by the manifold system and distributed to the individual cylinders; this device is called a carburetor. In the second type, the manifold system divides and distributes only the air, while the fuel is metered and supplied separately to each cylinder;[2] such a device is called a fuel injector.

The primary objective of any fuel-metering system is the maintenance of a flow of fuel which is in a constant ratio to the mass air flow, i.e., the pounds of air per second consumed by

[1]It should perhaps be pointed out for the layman that the throttle does not, in general, regulate the flow of fuel directly, but regulates the flow either of pure air or else of air already mixed with a definite proportion of fuel.

[2]In some systems the fuel is injected into the cylinder head itself, in others into the intake manifold just ahead of the cylinder port.

the engine.[3] The air flow is governed principally by the throttle setting, by the density of the air supplied to the throttle, and by the speed of the engine. The throttle lever might be arranged to regulate directly the flow of fuel as well as the flow of air, and in fact this has been done in some metering systems. In other systems, however, the throttle lever does not affect fuel flow by any direct mechanical linkage and, in any case, at any given throttle setting the speed of the engine varies according to the load and the flow of air varies with the engine speed, so that it is necessary to secure a corresponding variation in fuel flow automatically. Finally, the density of the air supplied to the throttle varies with temperature, with altitude, and with supercharging if the supercharger is located ahead of the throttle,[4] and some provision for compensating for these variations of air density is necessary, although it need not be automatic in all cases.

## The Origins of American Floatless Carburetors

### *General Principles*

Although fuel-injection systems were occasionally used on aircraft engines even before the First World War, by far the most common fuel-metering device was the much simpler and lighter carburetor. From the end of the First World War until almost the end of the Second, carburetors were the only fuel-metering devices used on American production aircraft engines.

All the aircraft carburetors produced in the United States since the First World War depend on two basic principles. First, the air to be burned by the engine passes through a restriction known as a venturi and in so doing creates a suction proportional[5] to the mass flow squared and inversely proportional to the density. Second, the liquid fuel passes through

[3]We here neglect such additional factors as the need for increasing the proportion of fuel to air at very high or very low power outputs, etc.

[4]In American engines single-stage gear-driven superchargers are located after the carburetor, but turbosuperchargers and the first stage of two-stage gear-driven superchargers are ahead of the carburetor.

[5]Provided that the air velocity does not become too great, i.e., provided that a certain Mach number is not exceeded.





a small orifice, known as a jet,[6] with the result that its pressure decreases by an amount proportional to the square of its rate of flow. The essence of the carburetor is some arrangement by which the fuel pressure drop is automatically kept in a constant ratio to the air suction. If the density of the air were constant, this in itself would suffice to maintain the fuel flow in a constant ratio to the air flow. The different arrangements used for this purpose are the characteristics of the various carburetors. The effect of varying air density was compensated for by a manual adjustment on all early carburetors; later on, devices were added to make this adjustment automatically.

### *The Standard Float-Type Carburetor, 1919-1934; Automatic Mixture Control*

At the end of the First World War the only important American aircraft carburetor was the Zenith, used on the Liberty and on the Hispano-Suizas built in the United States. After the war the market for new aircraft engines was so small that the profits to be made from the sale of new aircraft carburetors offered little incentive for further development, or even for the adaptation of existing models to new engines, and the Zenith Carburetor Company eventually left the aircraft carburetor field to a competitor by default.

This competitor was the Stromberg Motor Devices Company, a manufacturer of automobile carburetors, which had not made any aircraft carburetors at all before the end of the war. At about the time of the Armistice, Stromberg made its first attempt to enter the aviation field, almost all of its experimental costs being paid by the Army and Navy, which were interested in the Stromberg carburetor primarily because of its patented air bleed. This air bleed was believed to aid in breaking up into droplets the fuel emerging from the nozzle, and with the very volatile gasoline of that time this improved vaporization appreciably.[7] The Stromberg aircraft carburetor was put in production about 1922-1923.

[6]Again it should be pointed out for the layman that the "jet" is entirely different from the *nozzle* through which the fuel is injected into the air stream.

[7]Although the Zenith carburetor worked well on the fuel used in the war and on the Fighting Grade fuel after the war, it did not do well on the less volatile Domestic Aviation Grade civilian and training fuel introduced after the war.

The Stromberg like the Zenith carburetor used the same arrangement as contemporary automobile carburetors for maintaining the desired constant proportionality between fuel flow and air flow. Fuel was delivered to the jet at a constant pressure which was secured by taking the fuel, not directly from the fuel tank, but from a float chamber to which fuel was admitted from the tank through a valve operated by a float within the chamber in such a way as to maintain a constant level and thus a constant pressure of fuel in the chamber. From the jet the fuel flowed to a nozzle located within the venturi itself, so that the suction there lowered the pressure on the outlet side of the jet and thus directly created a flow of fuel proportional to the flow of air.

Despite a general lack of funds, a very great refinement of the float-type Stromberg carburetor was accomplished during the 1920's. The original Stromberg aircraft carburetor did not even approach fulfillment of the most basic requirement, a constant ratio of fuel to air under varying load, even when the engine was stationary on the ground. Further difficulties arose in radial-engine installations where a carburetor (or one barrel of a multiple-barrel carburetor) fed only three cylinders: the small number of cylinders meant that the air flow through the carburetor was pulsating rather than steady, and metering was poor until a means had been found of compensating for this. The design of the Stromberg carburetor was developed until reasonably straight-line characteristics were obtained quite early in the 1920's. Additional refinements provided an excess of fuel for such requirements as sudden acceleration.

During the same period a variety of changes were made in order to take care of special problems encountered in flight. Early aircraft carburetors functioned poorly in a climb or dive because the float was located before or behind the discharge nozzles and the mixture accordingly became rich or lean when the airplane was inclined up or down. This was corrected quite early by a change in the location of the float or by the use of twin floats, but even after this was done problems arose when the airplane was either flown inverted or put through a maneuver involving "negative g", i.e., one like an outside loop which made the fuel rise to the top of the float chamber as in





inverted flight instead of staying on the bottom.[8] Under these circumstances air rather than fuel was fed to the carburetor jets, and it was some years before an arrangement was provided which supplied any fuel at all to the engine under these conditions. The emergency fuel supply then provided was not a metered one, but it usually allowed the engine to go on running rather than die on the spot.

By the end of the 1920's the float-type Stromberg carburetor had become a generally quite satisfactory fuel-metering device for most conditions of operation of those times. In normal flight it provided the desired relation between fuel and air regardless of the speed or load of the engine. Although this relation was not maintained exactly in inverted flight or conditions of negative g, the engine did continue to operate in most such circumstances, and prolonged inverted flight was not necessary.

The one essential adjustment which the Stromberg carburetor of the end of the 1920's did not make automatically was that for the variation in air density caused by changes in temperature or — more important — in altitude. This, however, was not because no means had been discovered of providing such adjustment automatically. "Automatic mixture control" to compensate for the variation in air density with altitude by means of a pressure and temperature-sensitive aneroid, the essence of the modern controls, was already known in principle and thus unpatentable in 1918. Shortly after Zenith had produced a carburetor with a first attempt at automatic compensation about 1918, Stromberg produced an experimental model of another such device, but there were no sales. A few controls were sold to the Army for service test about 1923, but nothing further was done. Again in 1928 Stromberg under Army contract produced a number of automatic mixture controls which worked reasonably well, although they were clumsy to install, but again the device was dropped.

The fact was that until 1934 there was no real need for automatic altitude compensation. The ceiling of airplanes was very low at the beginning of the 1920's, and even after it had been considerably increased the pilot could tell by the loss of engine

[8] This also happened frequently when taxiing over rough ground.

speed that the mixture was incorrect and could easily correct it by a manual adjustment. For this reason the Army did not think it worth the trouble to install the clumsy existing model on service airplanes, so that no quantity purchases were made, while for the same reason none of the Army's very limited experimental funds were allotted for the development of a refined version which could be built into the carburetor. Stromberg was unwilling to do further development at its own expense because it could not foresee sufficient sales to make it profitable; there was considerable resistance to the price of existing carburetors in the 1920's, to the point that at least one engine company, Curtiss, was considering manufacturing its own to save money. Automatic mixture control was simply not worth what it would cost at this time.

In 1934 the situation changed abruptly: the introduction of constant-speed propellers made it no longer possible for the pilot to observe quickly a loss of power due to incorrect mixture, and automatic control became essential. The old external control of 1928 was mounted on some P-26's in 1935, and further development was at once resumed. Stromberg was paid for its work under an Army contract, but a good deal of the development was done on the basis of running on engines in the plants and at the expense of Wright and Pratt & Whitney. The carburetor with built-in control was used on production engines by 1936.

*Inherent Difficulties with the Float Carburetor; the First Attempt at a New Type*

The story of automatic mixture control is on the whole typical of the improvement which could be made by additional refinements to the basic float-type carburetor: no really urgent need for such refinements went long unsatisfied in the first 15 years after the end of the war, although if the services had had sufficient experimental funds and if the cost of the production article had not mattered these refinements would naturally have come much sooner. From the very beginning, however, there was one very serious trouble inherent in this type of carburetor, and about 1930 two more very serious troubles appeared.





The first trouble was with icing. This arose from the fact that it was essential for the functioning of this type of carburetor that the throttle be located in the air stream *after* the venturi, which contained the fuel nozzle. A part of the liquid fuel emerging from the nozzle struck the throttle and then evaporated, thus cooling the throttle so much that under certain conditions of temperature and humidity the moisture in the air condensed and froze. The ice thus formed blocked the air passage around the throttle and often even froze the throttle tight. Methods were eventually developed for preventing this type of icing by using the exhaust of the engine either to heat the intake air before it entered the carburetor or to heat the carburetor itself or both, but this resulted in a loss of engine power which under some circumstances was very serious,[9] and which worked poorly if at all when the engine was run at low power in a glide.

The troubles which appeared, or reappeared, about 1930 were due to the fact already mentioned, that a float was an inherently unsuitable device for use in an airplane. The fact that these troubles became critical at this time was due to the beginning of extensive practice in dive-bombing by the Navy, followed shortly by the Army. First, although inverted flight and some maneuvers involving large downward acceleration had been made possible without killing the engine by provision of a supplementary supply which fed fuel to the engine at a fixed rate when the fuel was at the top of the float chamber, this makeshift remedy failed completely when the airplane was pushed over abruptly into a dive. When this was done the fuel and air in the float chamber changed places so rapidly that they became mixed together, with the result that the emergency fuel supply fed the engine with an emulsion of fuel and air instead of with solid fuel, the charge received by the cylinders was too lean to burn, and the engine died.[10] Second, and even more important at first than the pushover difficulty, dive-

[9]The refrigerating effect of the evaporation of the fuel could be offset by heating the air about 30°F, which caused only a small loss of power. Even this small loss, however, sometimes could not be tolerated, for example on take-off; and if ice had once started to form while operating without heat, several times 30°F was necessary to eliminate it, with a resulting loss of power which was very serious.

[10]The same trouble arose even without a pushover when the airplane entered a strong enough downdraft.

bombing was done at such a steep angle that the proper fuel level could not be maintained in the float chamber by the system of fore-and-aft floats which had been evolved in the 1920's and which had been adequate for ordinary climbs and descents. The result was that the mixture became over-rich and the exhaust torched, setting fire to the airplane on some occasions. Again a makeshift solution was found, consisting of a check valve which set an arbitrary limit on fuel flow in a steep dive, but again this was far from providing the correctly metered fuel supply which was really desirable.

Before the end of the 1920's, both the services were very anxious to obtain a fuel-metering device which would be free of the troubles associated with the conventional throttle and float, and used as much of their experimental funds as they could spare to encourage the development of such devices. Both services for a number of years, the Army throughout the 1930's, believed that this basic improvement was more likely to be found in a fuel injector than in a different type of carburetor, and the expenditure of the larger amounts of government money followed this belief, but the first usable results were obtained from new types of carburetors.

The first attempt to develop a basically new type of aircraft carburetor in the United States was begun in the late 1920's, as a result of the Navy's initiative.[11] The Navy had become dissatisfied with Stromberg's attempts to improve its standard float-type carburetor, and by this time Zenith was no longer building aircraft carburetors. Thus this first attempt came to be made by the Steel Products Engineering Corporation, a company with no experience at all in carburetor design.[12]

For several years SPE worked on a floatless carburetor at the Navy's expense. Incredible as it may seem, this carburetor consisted essentially of an ordinary float-type carburetor with the float left out and nothing put in its place. The engineers at Wright Field flatly refused to have anything to do with it until the company in 1931 persuaded top officers in Washington

[11]It is not known to what extent the actual design was due to Navy engineers.

[12]The aeronautical work of SPE up to this time had been largely construction of experimental articles designed by the government, including rebuilding of Liberty engines; the company was also engaged in development of a trainer engine for the Navy.





to order Wright Field to purchase some experimental models. Tests run in 1932 proved the basic unsoundness of the design, and it was then dropped by the Army; the Navy seems to have given up hope at about this same time.

*The Chandler-Groves Carburetor*

The first successful floatless carburetor in the United States was only secondarily the result of an attempt to improve carburetor performance; it was primarily an accidental by-product of the entrance of competition into the aircraft-carburetor industry in 1935. M. E. Chandler, vice president of the Bendix-Stromberg Carburetor Company[13] and in charge of all Stromberg carburetor engineering since 1929, had by 1934 become dissatisfied with the policies of Bendix management and particularly with the amount of money allowed for research and development, which he considered excessively small. Stromberg at this time insisted that the engine manufacturers pay directly for most if not all of the cost of any development done at their request, and Chandler knew that one of the two major engine manufacturers, Wright, was becoming so dissatisfied with this state of affairs that that company had begun development of a new type of carburetor and intended ultimately to do all its own development and manufacture. Despite this, Chandler was unable to obtain the funds for rapid development of any of the various new types of carburetors on which he had started to work. By 1934 he was anxious to set up a new company to compete with Stromberg, and had made inquiries which had shown that the services and Wright would be delighted to see competition introduced in this field. He obtained the necessary backing from the Holley Carburetor Company, a manufacturer of automobile and light-airplane carburetors, which had already tried about 1929-1930 to produce a large aircraft carburetor as a private venture, but with only partial

[13]The Stromberg Motor Devices Company of Chicago was bought by the Bendix Aviation Corporation in 1929, and in 1930 was moved to South Bend and renamed the Bendix-Stromberg Carburetor Company. At the beginning of 1934 this subsidiary was merged with others to form a single subsidiary, the Bendix Products Corporation, which later became the Bendix Products Division of the Bendix Aviation Corporation. The aircraft carburetors, however, were still known by the name Stromberg.

success owing to lack of experience in the field. In January 1935 Chandler left Stromberg to become president of the new Chandler-Groves Company.

Chandler's intention in the large carburetor field was to compete with Stromberg partly on the basis of improved performance but especially on the basis of lower price. The Stromberg type of carburetor required very complicated castings which were machined in a long series of operations such that an error at any stage meant complete scrapping of all the previous work. This was causing a scrap rate of as much as 25% on the latest Stromberg models and not infrequently brought a complete stoppage of production, so that a model designed for simpler production promised an important advantage in price; and in any case Chandler-Groves simply did not have foundry facilities adequate for producing a Stromberg-type carburetor.

The new Chandler-Groves carburetor differed from the basic Stromberg design in two essential respects. The first was the use of a completely different, although already known, type of throttle. Instead of a butterfly valve located in the air stream after a fixed venturi, Chandler used a venturi whose cross-section was variable so that it could itself serve as the throttle.[14] This meant that no fuel was sprayed on the throttle, which accordingly was not so likely to freeze up in icing conditions as the Stromberg throttle. It also simplified production enormously; the new type of throttle made it possible to construct the carburetor by bolting together a number of castings each of which was exceedingly simple and easy to produce.

The second characteristic feature of the design was the means by which the pressure at which the fuel was delivered to the jet was kept constant. The valve controlling the entrance of fuel to the chamber feeding the jet was operated, and thus the pressure within the chamber was kept constant, not by the level of the fuel acting on a float, but directly by the pressure

[14]As in the Stromberg carburetor, the fuel discharge nozzle was located within the venturi so that the suction in the venturi could directly determine the pressure at the outlet of the jet and thus create the proportional flow of fuel. Since, however, the suction created by a given air flow now varied with the throttle setting, it was necessary to make the size of the fuel jet variable also, and to link the metering needle with the throttle so that as the venturi was enlarged the jet was enlarged correspondingly.





of the fuel acting on a diaphragm linked to the valve. To some extent this change was made to eliminate the difficulties inherent in a float in an aircraft carburetor; Chandler's primary motive, however, was simply a desire for novelty, for a "selling point" to use in competition with Stromberg.[15] The float was satisfactory in most types of flight, while the market for engines to be used in fighters and especially in dive bombers, where the float performed really badly, was only a small fraction of the total market.[16]

The original development of the new carburetor was carried out with a minimum of resources. Prototypes were ready for test early in 1935, but Chandler-Groves had neither facilities for running the carburetor on an actual engine nor even an "air box"[17] large enough to test a carburetor of this size. The first air-box tests were made at Wright Field, and the first runs on an actual engine were made at the plant of the Wright Aeronautical Corporation. Although Wright and the services were eager from the beginning to have competition created in the carburetor industry, no one was very enthusiastic over the design of the Chandler-Groves carburetor as such until, late in 1935, the Navy in flight-testing the new carburetor demonstrated that it was very much less subject than the Stromberg to icing due to evaporation of fuel.[18] Since the Cyclone lost a very great deal of power when the air was heated by the approximately 150°F required to eliminate ice once formation had started, both Wright and the Navy at once became very much interested and gave wholehearted support to further development of the Chandler-Groves carburetor. Lacking the neces-

[15]For essentially the same reason the Stewart-Warner Corporation had used a diaphragm in place of a float in an automobile carburetor which it tried to sell to Chrysler in 1929.

[16]Even in dive bombing acceleration difficulties of the float-type carburetor could be avoided if the pilot entered the dive by dropping a wing and turning in, instead of doing a straight pushover, and there was considerable controversy at this time among the dive-bomber pilots themselves as to which method was better.

[17]An apparatus for simulating the flow of air through the carburetor caused by an engine.

[18]Not completely free, however, since although no fuel evaporated from the surface of the throttle, it still had to evaporate in the induction system, and ice could be formed there which would ultimately lead to icing of the throttle. The Chandler-Groves carburetor was designed with provision for heating the air to prevent icing, but much less heat had to be used than with the Stromberg and consequently much less power was lost.

sary facilities in his own plant, Chandler himself participated in the very extensive running of the carburetor on actual engines done at the Wright plant at Wright's expense and in that done on the refrigerated air box at the Naval Aircraft Factory at the Navy's expense.

During testing of the new carburetor on the Navy air box, which could simulate performance at altitude since air could be supplied at the proper temperature as well as the proper pressure, a completely unexpected feature was discovered. The carburetor had been designed with an aneroid mixture control, but the original model had been unsatisfactory and the carburetor was run with it disconnected. This running led to the observation that automatic mixture control or altitude compensation appeared to be inherent in the basic carburetor itself, although the reason was as yet unknown. The special mixture control now seemed to be unnecessary and was eliminated, with a resulting saving both in price and in the likelihood of trouble which comes with increasing complexity.

The great deal of assistance contributed to the development of the Chandler-Groves carburetor in the form of experimental running by Wright and by the Navy meant that even though Chandler had taken no development contracts, in order to avoid loss of rights in the design, his company had had to invest only some $100,000 in development before the carburetor was in production in the first half of 1937.

The Chandler-Groves carburetor was adopted as standard on all Navy Cyclones of the new G-100 model put in production about this time. The airlines became interested in the new carburetor almost as soon as they heard of its performance as reported by the Navy and Wright. They were attracted both by the relative freedom from icing, which had been the feature that originally aroused the interest of the Navy and Wright, and by the low price, which had been the guiding principle of the original design.[19] A Chandler-Groves carburetor was put in regular service by TWA in March 1937, and it became standard on new airline Cyclones of the G-100 model as well as on the Navy engines.

[19]The Chandler-Groves carburetor for the Cyclone engine used on most airline DC-3's cost about $200 at this time against about $400 for the Stromberg.





The Army, however, refused to use the Chandler-Groves carburetor. Engineers at Wright Field had discovered that its "magic" altitude compensation was due at least in part to the absence of any provision for the escape of gasoline vapor, with the result that the boiling of the fuel which took place under reduced pressure at altitude reduced the flow of fuel and thus counteracted the natural enrichment which occurs because of decreasing air density at altitude. Later on, further tests by the Navy showed that this was not the only factor involved, but that the variable venturi of the carburetor gave Mach numbers at high altitude which also tended to decrease the flow of fuel. Obviously neither of these principles was ideal as a method of securing altitude compensation, and the fact that the amount of compensation depended partly on the vapor pressure of the fuel meant that the amount of compensation would vary with fuels of varying volatility. The Army was unwilling to use a carburetor based on an unsound principle and made no flight tests, preferring to use the old float-type Stromberg carburetor, which as we have seen was equipped with a true automatic mixture control by 1936.

*The Stromberg Pressure Carburetor*

After M. E. Chandler left Bendix-Stromberg at the beginning of 1935 to found the Chandler-Groves Company, he was replaced as the head of Stromberg carburetor development by F. C. Mock, who had been with Stromberg before 1929 and then had had charge of the development of fuel injectors in the Eclipse Aviation Corporation, another Bendix subsidiary. While at Eclipse Mock had talked about building a floatless carburetor with pressure discharge at the supercharger, and had actually had a small Navy contract for such work, but had made little progress with it. Even after his return to Stromberg, Mock's first work was an attempt to get satisfactory performance from the standard Stromberg float-type carburetor. He was finally forced to give up this approach when a series of tests run by the Navy on a Wright Cyclone, about the latter half of 1935, showed that the performance of the Chandler-Groves floatless carburetor was decisively better than the best that Mock could do with the Stromberg float-type carburetor.

Mock was now at last convinced that it was necessary for Stromberg to develop a floatless carburetor, and he succeeded in convincing Bendix management that unless its development was rapidly carried out the market would soon be lost to the competition: not only did Wright and the Navy definitely prefer the Chandler-Groves to the existing Stromberg carburetor, but the Army, although preferring the Stromberg to the Chandler-Groves, had declared in 1934 (as we shall see) that all single-engine tactical planes would soon be equipped with fuel injection. As a result, the number of engineers working on Stromberg aviation carburetors was quickly increased from four to about ten. Stromberg development expenses for aircraft carburetors were twice as great in 1935 as they had been in 1934, the last year of their monopoly, and in 1936 and 1937 they were still greater by another 25%. Before the end of 1936 Stromberg had at last acquired an engine test stand: the significance of this is not the investment in the stand, which was small, but the fact that Stromberg had given up the policy of relying completely on tests run by the engine companies and the services for the absolutely essential information which could be obtained only by running carburetors on actual engines.

Mock's new design abandoned the whole principle of supplying fuel to the jet at a very low constant pressure and using the venturi suction to create a still lower pressure at the outlet of the jet and thus create the fuel flow. Instead, fuel was forced through the jet by pressure in the fuel supply system. The venturi suction was used to create a force on one diaphragm, while the drop in pressure across the fuel jet (not, as in the Chandler-Groves, the pressure at which the fuel was supplied) created an opposing force on another diaphragm; the two opposing diaphragms together were linked to a valve which regulated the fuel supply in such a way as to keep the forces on the two diaphragms equal and thus maintain the fuel flow proportional to the air flow. After the double-diaphragm system had been adopted by Bendix it was discovered that the principle had been patented years before, having been invented for the control of chemical processes. This patent was bought by Bendix. In the new Stromberg carburetor the throttle was a valve in the air stream after the venturi, just as in the float type,





but since the venturi suction was not used to create the fuel flow directly, the fuel could be discharged after rather than ahead of the throttle, thus greatly diminishing the throttle-icing difficulties of the old float-type carburetors while also avoiding the compressibility difficulties experienced when the variable-venturi throttle of the Chandler-Groves carburetor was closed down at high altitude. In order to diminish air-pressure losses by using considerably less restriction in the venturi, the new carburetor used a double or boost venturi which Stromberg had developed and patented long before for use on automobile carburetors.[20]

A prototype of the new Stromberg pressure carburetor for the Cyclone engine was soon delivered to Wright, whose engineers immediately began to work as intensively on its development as they had previously on the development of the Chandler-Groves. Somewhat later a prototype for a Pratt & Whitney engine was ready. Pratt & Whitney had disliked the Chandler-Groves design and done little to assist in its development, but the firm approved of the new Stromberg design and like Wright did a very great deal of work toward its development.

The new Stromberg pressure carburetor was put in production in 1938 and was an immediate success. Like the Chandler-Groves carburetor, it was completely free from difficulties due to a float,[21] and was much less subject to icing than the float-type carburetor. After Pratt & Whitney some years later developed the system of injecting the fuel at the supercharger instead of immediately after the carburetor, refrigeration icing was at last completely eliminated.[22] The automatic mixture control of the Stromberg was sound in principle, and although it did not yet work perfectly in 1938, by 1940 it had been developed to be completely satisfactory. The Stromberg pressure carburetor was adopted for all its high-power engines by Pratt

[20]The purpose served by the boost venturi on automobile carburetors was quite different, however, from that served in the new aircraft carburetor.

[21]The use of this carburetor on the R-2800 enabled the P-47 to follow the injection-equipped Focke-Wulf 190 through any maneuver, whereas the Focke-Wulf could always break away from a Spitfire by a pushover which the Spitfire could not follow because its Merlin was equipped with a float-type carburetor.

[22]Although icing can still occur because of the cooling due to expansion of air past a partly closed throttle, and a certain amount of carburetor heat is still needed as a result.

& Whitney, and was used by the Army on all the Wright G-200 Cyclones of the B-17's.

*The Holley Carburetor*

The Chandler-Groves carburetor, as we have seen, marked a definite improvement in the opinion of both Wright and the Navy over the old float-type Stromberg carburetor. It was not, however, completely satisfactory in the state in which it was put in production in 1937, since its "magic" altitude compensation was only approximate at best, and varied with the volatility of the fuel, while at extremely high altitudes trouble was experienced which was ultimately explained as being due to sonic velocities in the venturi.

Chandler was anxious to continue intensive development of new and improved models, especially because the appearance of the Stromberg pressure carburetor on the market in 1938 meant that there was now competition from a design which was free from the inherent difficulties of both the float-type and the Chandler-Groves designs. Nevertheless, the Holley brothers, who controlled the Chandler-Groves Company, insisted on maintaining the low ratio of development expense to sales which was sufficient in the automotive field where production was vastly larger. This and other factors led in 1938 to the departure of Chandler and the dissolution of the Chandler-Groves Company.

The Chandler-Groves carburetor continued to be manufactured after 1938, under the name of Holley. About 1940 an improved model of the Holley carburetor replaced the original one, the most important change being the addition of a true automatic mixture control of the standard aneroid type and the introduction of a separator to remove the vapor which had been the chief cause of the "magic" compensation. The Army cooperated in the development of the new model, especially by testing in its refrigerated air box, but the Army was still dissatisfied with the result and refused to use the Holley carburetor on any of its Cyclones for the B-17. The improved model was standard on certain models of the Cyclone used by the Navy and the airlines during the war, and no serious dissatisfaction was reported with it in service, but before the end of the war it





was generally admitted that the Stromberg pressure carburetor was a much superior article.[23]

*The Ceco Carburetors*

After the dissolution of the Chandler-Groves Company in 1938, M. E. Chandler almost immediately formed the Chandler-Evans Corporation with financial backing from Niles-Bement-Pond. Here he proceeded at once to design a new floatless carburetor. Chandler's new design, which he called the hydro-metering carburetor, resembled the new Stromberg carburetor rather than the Chandler-Groves in the use of diaphragms to measure air as well as fuel pressure and in being arranged to discharge the fuel under pressure at any desired point rather than using the venturi suction directly to draw out the fuel. The basic difference from the new Stromberg was that instead of balancing the fuel and air pressure drops directly against each other, a hydraulic connection (whence the name hydro-metering) was made which permitted a very small air suction to control a much larger fuel pressure drop. This promised to be very valuable by making it possible to have much less contraction in the venturi and thus reducing the losses due to it.

Wright Field, Wright Aeronautical, and Pratt & Whitney all gave energetic support and assistance in the development of the Ceco carburetor. Wright Aero was interested particularly in connection with the R-3350 engine, for which the firm tried to persuade all three suppliers (Stromberg, Holley, and Ceco) to produce a suitable carburetor. All three agreed, but Holley never produced a carburetor for test, and the original Stromberg entry, besides being enormous, had various imperfections which Stromberg was unable to eliminate quickly owing to the press of other work. The result was that early in 1942 Wright

[23] It is true that at Wright's suggestion the R-2600, which was originally equipped with the Stromberg pressure carburetor, was switched to the Holley about 1941, and that this engine was used by the Army as well as by the Navy. The reason, however, was not any inherent superiority of the Holley, but the fact that the model of the Stromberg originally supplied for the R-2600, which was the one designed for the Cyclone, had inadequate capacity for the R-2600, resulting in roughness and poor cooling at full power. By this time carburetor production was a critical problem, and since the Holley could be made to work, it seemed better to use it and relieve Stromberg of that much production.

decided to use the Ceco on the R-3350 even though its development was not yet complete.

The Army and Pratt & Whitney wanted a second source for carburetors, especially because Stromberg did not have sufficient production capacity while they were dissatisfied with Holley. They were interested in the Ceco primarily for the R-1830 engine, which was to be used on the B-24 in very great numbers. At about the same time, early in 1942, that Wright decided on the Ceco for the R-3350 the Army decided on it for the R-1830's of the B-24, subject to service test.

Ceco hydrometering carburetors were finally delivered for service test on the R-1830 in the fall of 1942. The usual initial difficulties appeared, particularly in connection with acceleration, and while Chandler and the Army were attempting to eliminate these, Pratt & Whitney continued to have trouble with inconsistent performance on the stand. Early in 1943 Pratt & Whitney suggested that, because the need for production was so urgent, an attempt should be made to alter the Ceco carburetor to use the already proved Stromberg regulating system. An experimental carburetor was turned out in great haste by Pratt & Whitney itself and proved successful on test. Stromberg gave Ceco a license to use the control system, and the Ceco "direct-metering" carburetor was very soon in production. This carburetor was used on the R-1830's in the B-24.

The original Ceco hydrometering carburetor worked rather better in the large size destined for the R-3350 than in the smaller size for the R-1830. Even so the Army would have preferred to change the R-3350 Ceco to the direct-metering system, but production commitments prevented this, and by the time the R-3350 was actually in production the hydrometering Ceco was fully satisfactory. It was used on all the R-3350's of the B-29's except for a few which were converted to fuel injection just before the end of the war, and at the end of the war the Navy was considering its use on the Pratt & Whitney R-4360. The Army, however, adopted fuel injection on all its large engines after the war and production of the small number of carburetors which could be sold for Navy and





airline use did not promise to be profitable. The result was that Ceco gave up the carburetor business.[24]

*The Speed-Density Metering System*

In all the carburetors so far described, both float-type and floatless, a venturi is used which restricts the air flow at the same time that it measures it and thereby causes a loss of power. This loss can be avoided if the air flow is measured by the so-called speed-density system. On each inlet stroke each cylinder takes in a mass of air proportional to the difference between the pressures in the intake and exhaust manifolds and inversely proportional to the absolute temperature in the intake manifold. The total mass flow of air is therefore determined by these factors and the rpm of the engine.[25] A speed-density fuel-metering system is one in which the fuel flow is governed directly by mechanisms sensitive to the difference between the two pressures, the temperature, and the rpm, thus eliminating the venturi and the associated losses completely.

Although no attempt has ever been made in the United States to develop a speed-density system except in conjunction with an injection system which supplies fuel separately to each cylinder,[26] the basic principles are perfectly applicable to a system which, like a carburetor, injects the fuel into the air stream at a single point, before the stream is divided by the manifold system. In the absence of an American example of such a system, we shall take that of Rolls Royce, which, after realizing the magnitude of the losses due to the venturi of the carburetor in a very highly supercharged engine (cf. Chapter VIII, p. 228), decided during the war to develop a speed-density system.

[24]The Stromberg pressure carburetor was used on the Navy's R-3350's and on certain models of that engine by the airlines until all the latter were required by the Civil Aeronautics Administration to switch to fuel injection.

[25]One other factor has a secondary effect: the varying volumetric efficiency of the engine. The speed-density system assumes that this efficiency is constant, but actually it varies with operating conditions, particularly the temperature of the engine. Owing to the effect of temperature on the long push rods of radial poppet-valve engines, the volumetric efficiency of this type is in general less close to constant than that of in-line engines or of sleeve-valve radials, and this may be one reason why no speed-density systems were developed in the United States although both Rolls Royce and Bristol developed them in Britain.

[26]See previous note.

One possible arrangement for such a system is to have the fuel delivered by a piston-type pump driven by the engine, with the stroke of the pump piston made proportional to the difference between the two pressures and inversely proportional to the temperature. Rolls Royce found that the Skinner's Union carburetor division of the Morris group already manufactured a reciprocating swash-plate pump of a suitable type, although it was too small for the purpose, and thereupon invited SU to produce a similar but larger pump, and to develop a control system in collaboration with Rolls Royce. Engineers from SU came to work at the Rolls Royce plant, and were supplied by Rolls Royce with data specifying exactly what the fuel supply should be under varying conditions of operation of the engine. A control system was developed in which the angle of the swash plate and thus the stroke of the pump were regulated by two capsules, one sensitive to the pressure difference and the other to the temperature. The device was first tried out on the Merlin 66, and eventually became the standard carburetor for all Merlin engines.

Concurrently with this development of the SU speed-density system, Rolls Royce itself independently developed another speed-density system which was mechanically much simpler than the SU device. In this system the feed pump supplied fuel at a constant pressure to two jets in parallel. The area of one jet was controlled by a needle operated by a capsule subject to the pressure difference, that of the other by a needle operated by a temperature-sensitive device. The fuel pressure drop across the jets acted on one side of a flexible diaphragm the other side of which was loaded by a centrifugal governor driven by the engine; the diaphragm operated a valve which regulated the fuel flow so that the forces on the diaphragm were balanced.

It was no accident that Rolls Royce was much more directly involved in the development of these two speed-density systems than it had been in the development of the conventional carburetors it used before. Although even a conventional carburetor with a venturi can be perfected only by long development on actual engines, the basic development of such a carburetor can be done without an engine at all by the use of an air box. The





development of the control in a speed-density system, on the contrary, cannot be even begun without the use of an engine, and after it has been developed for one engine, much more work is involved in adapting it to another than is involved with a venturi-type carburetor.

## Fuel Injection

Fuel injection was well known in principle long before the First World War. It was used on the original Wright brothers' engine and on the Antoinette aircraft engine which was popular before 1914; it has always been used on Diesel engines, whose fuel will evaporate only at the high temperature reached by the charge after it is compressed in the cylinder, not at the intake temperature. Carburetors became standard on aircraft engines before the First World War, however, primarily because they are far lighter and simpler than fuel injectors, and the first American attempts at the systematic development of fuel-injection systems for aircraft engines were not made until the late 1920's, at about the same time as the first attempts at a radically new type of carburetor.

### *The Research of the NACA*

The origins of interest in fuel injection are many. The NACA began to investigate it about 1927 in the hope of increasing engine efficiency by using plain air instead of the incoming mixture of fuel and air to scavenge the cylinder, i.e., to clear it of the burned gases from the previous explosion. This, of course, could be done only if the fuel and air were supplied to the cylinder separately. Early in the 1930's the primary purpose of NACA fuel-injection research changed to an investigation of the possibility of using "safety fuels",[27] which resembled Diesel fuel in that they would evaporate only in the heat of the cylinder and thus could not be used with a carburetor. This interest in safety fuels was largely stimulated by the Navy, which wanted to use them in dirigibles, and for this

[27]Most fires resulting from aircraft accidents are due to explosion of the mixture of fuel vapor and air in the fuel tank. "Safety fuels" are fuels whose volatility is too low to form an explosive mixture.

reason the NACA program came to consist mainly of single-cylinder work connected with the Allison engine, which the Navy at this time hoped to use as an airship power plant.

The NACA's research on injection was concerned with basic principles such as the determination of the possible improvement of efficiency, the possibility of the use of safety fuels, the correct form of injection nozzle, the effects of varying fuel viscosity, and proper timing of the injection. A good deal if not most of this work was carried out with components furnished by the private firms developing fuel injectors, and of course no attempt at all was made to develop a complete working injection system, which was outside the province of the NACA. The results of the NACA's research were of some value in the subsequent development of injection systems, but unfortunately the NACA did no work at all on what proved to be the really critical problem in the development of fuel injection: the design and development of a suitable metering or control system.

*The Marvel Injector*

The Army became interested in fuel injection very early as a means of getting rid of the troubles experienced with contemporary carburetors, principally those due to icing and to the behavior of the float in maneuvers, but also other less important difficulties such as the inability of a carburetor to provide for instantaneous acceleration, particularly when the engine was cold. In 1926 the Marvel Carburetor Company, a manufacturer of automobile carburetors, had hired M. G. Chandler[28] to take charge of the development of a fuel injection system which he had invented and patented, and in 1927 the Army ordered from Marvel a system for a one-cylinder engine. After testing the single-cylinder device the power-plant branch at Wright Field reported in 1928 that it was at least as good and economical as a carburetor, and the Army proceeded to order an injection system for the nine-cylinder radial Wasp. In the next few years the Army bought a number of additional experimental systems for the Wasp, Conqueror, and Cyclone engines.

[28]Not to be confused with M. E. Chandler.





The design of the complete multicylinder Marvel injector had one unique feature: instead of having a separate pump cylinder and piston for each engine cylinder, construction was simplified and weight was saved by using a rotary distributor to feed three engine cylinders from a single pump cylinder. There was a certain amount of trouble initially with seizure of the rotary distributor, but this was successfully cured by changes in the metals used in its construction, and from quite early in the development the Marvel pump, including the distributor, gave generally satisfactory performance.

In 1933 the Army placed a service-test order for 37 injectors for the Wasp, and 25 P-26B fighters were equipped with these injectors and tested in 1934. Wright Field reported that the injectors increased the critical altitude from 7,000 to 12,000 feet and gave more power above the critical altitude,[29] gave better fuel economy than existing carburetors, and were completely free from all difficulties due to evaporation icing and violent maneuvers. The general performance of the injectors in service was very good, and these 25 airplanes remained in service equipped with them for about four years, until the airplane model was obsolete. Eight of the 10 Allison engines ordered by the Army in June 1934 were to be equipped with Marvel injectors, and in August 1934 a high Air Corps officer declared that by fiscal 1936 all single-engine combat planes would be equipped with injection, provided that certain essential improvements in injection systems were accomplished.

The most essential improvement which had to be made in the Marvel injector was the development of automatic mixture control. The Marvel injectors of 1934 were adequate to demonstrate the performance of fuel injection as such and the soundness of the Marvel pump as a pump. These injectors were, moreover, about as good as the contemporary Stromberg float-type carburetor as fuel metering devices: since the pump was geared to the engine, the fuel flow was automatically proportional to engine speed, and the fuel flow was made proportional to the throttle setting by a mechanical linkage which varied the pump stroke. This was, however, exactly the date when, as

[29]Owing to the fact that there was no carburetor venturi to restrict the flow of air to the engine.

has been told, the introduction of the constant-speed propeller made it necessary to have an automatic rather than a manual adjustment for the variation of the density of the air with altitude. Development of automatic mixture control for the Stromberg float-type carburetor was energetically pursued beginning in 1934, and unless the Marvel injector could be equipped with an equivalent control it was useless. A speed-density control for the Marvel designed and built at Wright Field before 1934 had proved a failure, as had one designed by Wright Aeronautical, and no progress at all had been made toward development of a satisfactory control.

At this same time, moreover, another very serious weakness in the Marvel injector became apparent. The basic design of the Marvel system was suited to no more than 12 cylinders, whereas a small two-row radial engine with 14 cylinders was already in production and larger 14-cylinder engines were under intensive development: the first R-1830's were in fact flown in this same year, 1934. It was naturally assumed that unless the liquid-cooled Allison came through very quickly the nine-cylinder Wasp would shortly be replaced as the standard power plant for single engine aircraft by the 14-cylinder R-1830, which would deliver much more power for about the same frontal area; and as we have seen it was for single-engine aircraft that the Army particularly desired fuel injection.[30]

Just at this time, however, when despite the difficult problems to be faced the opportunity for quantity sales was excellent, the Borg-Warner Corporation, of which Marvel had become part in 1928, decided that Marvel's investment was already larger than was justified. The Army had supported the development wholeheartedly, and in addition to doing the largest part of the testing (the rest being done by the engine companies), as well as a good deal of experimental modification of the injector in its own shops, had paid Marvel $124,000 for experimental and service-test injectors by the middle of 1934. This treatment was fully as generous as that given to any accessory supplier,

[30]Presumably because such aircraft (fighters and dive bombers primarily) were more likely to want sudden acceleration than multiengine aircraft and were the only ones ordinarily used for the sudden, steep dives which gave trouble with contemporary, float-type carburetors.





and probably more generous than that given to most. Borg-Warner, however, believed that despite the fact that it had not yet produced a usable product, it should have been reimbursed in full and with a profit. In the fall of 1934 the company presented a bill to the Army for $224,000 of direct expense to date, $267,000 of overhead, $18,000 of patent expense, and $51,000 of administrative charges; and to the total of $560,000 it added a 10% profit, making $616,000, or $492,000 after deduction of the $124,000 already received from the Army. All the principal personnel engaged in the injection development were discharged, and further development came virtually to a stop.[31] Within a year the Marvel injector was dead, and plans for development of an injection-equipped Allison were abandoned.

*The Army-Designed Metering System and the Origin of the Bosch Injector, 1935-1939*

The complete halt to which Marvel's development was brought in 1934, just when the Army was enthusiastic for injection in principle but far from satisfied with the existing state of the Marvel injector, naturally caused the Army at once to seek other sources of supply. After the failure of his original speed-density control for the Marvel, J. F. Campbell, the engineer in charge of fuel injectors at Wright Field, had decided that the control should be designed not around the speed-

[31]Borg-Warner claimed that it had been treated unfairly by the Army, and ultimately presented a claim to Congress for $600,000. Its first ground for the charge of unfairness was that from the time of its first contract with the Army Marvel had bound itself to maintain the injector in a secret classification, which flatly forbade foreign sales and had in effect also prevented domestic sales to civilian users. This, however, was a condition imposed on all concerns doing development of this sort under military contract, and was obviously necessary for security. In any case, Marvel simply had nothing of value to sell. By 1935 the company also complained that the Army was, as we shall see, becoming interested in fuel injectors being developed by other companies and was promoting competition between them and the Marvel injector; it was alleged that since the other companies could profit by Marvel's experience, they would drive the price so low that Marvel's investment in engineering could not be recovered. This agreement was unjustified, since all that Marvel had to date was a pump, which the competing pumps scarcely resembled. The Army, however, assured Borg-Warner that it would not in any case choose an injector on the basis of price, while quality competition was a standard and essential part of aeronautical procurement.

density principle but around the direct measurement of mass air flow with a venturi, the same basic principle as was used in carburetors, and that an electric mechanism should be used to regulate the fuel flow in accordance with the measured air flow. The one other fuel injector for aircraft engines on the market in 1934, the Eclipse, which as we shall see had been developed with Navy support, used a control of the speed-density type. After an initial test Campbell decided to give it only very limited support and to create a new source which would develop an injector with an electric mass-flow control along the lines he laid down.

The United American Bosch Corporation, which had a certain amount of usable background since its principal product was Diesel injectors, was willing to undertake the development of an injector according to the Army's ideas, and in June 1935 the Army ordered a first experimental unit from the company. The injector pump designed by Bosch was of the conventional type, with one pump cylinder per engine cylinder, driven by a swash plate.

During the remainder of the 1930's the Army gave Bosch the larger part of what funds it had available for the development of fuel-metering systems, but the prospects of quantity sales were too small and too remote to induce the company to invest an appreciable amount of its own funds. The only testing of the system on actual engines done before 1940 was done on about one nine-cylinder engine each by Wright and by Pratt & Whitney. The Army's funds for injector development were insufficient to pay for additional installations, while neither Wright nor Pratt & Whitney was willing to do much at its own expense: neither company believed at this time that the advantages to be gained from fuel injection were worth its admitted cost in weight and complexity. In addition the companies strongly disapproved of Campbell's desire to have the fuel lines made integral with the engine. Despite the lack of adequate testing, however, Campbell believed by 1939 that both the pump and the control were satisfactory, and that all that remained was to adapt the system to the engines on which it was to be used.





*The Navy and the Eclipse Injector, 1930-1940*

While the Army was supporting the development of the Marvel injector, the Navy had undertaken to support development of an injector by the Eclipse Aviation Corporation, which had become a subsidiary of the Bendix Aviation Corporation at the same time as Stromberg, in 1929. At the time of the acquisition of Eclipse by Bendix, F. C. Mock, who had previously been with Stromberg, was put in charge of fuel-metering devices at Eclipse. At this time the Navy was much interested in injection for spark-ignition engines, for two different reasons: first, a desire to use safety fuels, especially for airships,[32] and second, a growing dissatisfaction with existing carburetors, especially because of trouble with icing. About 1930 the Navy had given Eclipse a contract for development of a fuel-injection system, and lent the company two engines (an R-975 and an R-1340) for use in the development.[33]

Like the later Bosch injector pump, the Eclipse pump was of the conventional type, with one pump cylinder per engine cylinder, driven by a swash plate. The injector was designed from the beginning to have fully automatic metering, of the so-called speed-density type, the basic principle of which has already been described. As in any fuel-injection system, the variation in air flow with engine speed was taken care of by the fact that the proper pump cylinder delivered a charge of fuel to the corresponding engine cylinder each time the latter was fired; the fuel delivered in each charge was automatically made proportional to the amount of air taken in by the cylinder by means of devices sensitive to the difference between the pressures in the intake and exhaust manifolds and to the temperature in the intake manifold, which regulated the position of a sleeve setting the cut-off point for each stroke of the pump.

[32]It will be recalled that from 1930 to 1935 the Navy sponsored the Allison V-1710 as an airship engine, and that during this period the NACA's work on injection was centered, largely at the Navy's instigation, on the use of safety fuels in the Allison.

[33]A little before Eclipse received this contract it had had a Navy contract for development of an injection system for Diesel airship engines. The Navy abandoned the idea of Diesel engines for airships rather soon (cf. above, Chapter X, p. 274), and with it this Diesel injector project.

Development of the injector had proceeded very slowly and it was not until 1934 that Eclipse was ready to deliver an experimental nine-cylinder unit to the Navy. The Navy made flight tests of one of the original nine-cylinder injectors in 1935 and found it promising enough to place an order for two 14-cylinder units for the R-1535, which at this time was the Navy's standard fighter engine. One of these 14-cylinder units was flight-tested in 1936 up to about 20,000 feet, but the Navy now reported that the metering system performed poorly at altitude and that the throttle was very hard to move. Further testing of this model was dropped when the engine equipped with it suffered a connecting-rod failure, and in 1936 the Navy ordered two experimental nine-cylinder units of an improved design[34] for testing on Wasp engines. These units were delivered in 1937.

By 1937, however, the Navy was fairly well convinced that the new Chandler-Groves and Stromberg carburetors would solve the problems of icing and maneuverability; injectors were certainly heavier, more complex, and more expensive than carburetors, and in the Navy's opinion they performed no better and were less reliable. The airship program had come to an end in 1935, and all interest in safety fuels for airplanes ended about this same time because they could not equal the performance of the new high-octane fuels. During the years 1937-1940 the Navy bought and flight-tested a small number of additional engines equipped with Eclipse injectors, but gave no further development contracts to Eclipse.

The Army during the period 1934-1937 purchased and tested examples of each of the injectors built by Eclipse for the Navy. On the basis of these tests the Army concluded that although the pump of this injector was very good and gave no trouble, the metering system was unsatisfactory. Eclipse showed that the Army's first objections to the system were due to the incorrect conduct of the initial test at Wright Field, and insisted that the system was basically sound and needed only a normal amount of further development. The Army, on the contrary, claimed that further tests showed definitely that even the later

[34]In 1935 Mock had been transferred to take the place of M. E. Chandler at the head of Stromberg carburetor development; the injector development at Eclipse was now in charge of D. J. DesChamps.





models of the Eclipse control were sluggish in their response to temperature, "hunted", and failed to meet the Army's metering specification at low power. The Wright Field engineer in charge of fuel injection, who, as we have seen, had himself designed a control of an entirely different type, insisted that the difficulties with the Eclipse control were due to an undesirable basic principle and could not be eliminated by development. Thus, although it did not lose interest in fuel injection as such when the Navy did in 1937, the Army did refuse to pay for further development of the Eclipse injector after the Navy ceased to do so, giving all the available funds to Bosch for development of an injector with a control designed to meet Campbell's ideas.

During the years 1937-1940 the only real activity in connection with the Eclipse injector was the extensive flight testing of one 1937 model done by an airline, TWA, at altitudes up to 30,000 feet. The injector for this work was contributed by Eclipse, the Cyclone engine by Wright, and the Gamma airplane in which it was installed by the maker, Northrop; TWA paid the cost of the flying. These flights were important because they gave evidence that in addition to being absolutely free from refrigeration icing, fuel injection brought about greater uniformity of temperature among cylinders (due to absolutely equal fuel distribution) and thus appreciably lowered cooling drag by permitting the use of less cooling air. By 1940 TWA was convinced that injection was superior even to the new Stromberg pressure carburetor, and in 1941 TWA requested Wright to obtain a type certificate for the Cyclone with the Eclipse injector.

There is (and was) no question that the Eclipse pump was already very satisfactory in 1937, but the actual merits of the 1937 Eclipse control and the justifiability of the Army's refusal to assist in its further development are impossible to assess. There is general agreement that the Army specifications for the performance of injectors were unrealistically severe in this period and simply could not be met in the existing state of the art.[35] It can be argued that the company's view that its

[35]Although there was not in 1937 any formal Army specification for altitude compensation.

system was reasonably satisfactory was borne out by the fact that after three years of flight testing TWA was anxious to have it put in production, despite a forced landing due to the instability of which the Army complained; but on the other hand this may only indicate that the advantages of fuel injection as such outweighed the disadvantages of a poor control. The strongest argument in favor of the Army's position is that after an attempt was made to perfect the speed-density control with renewed Army and Navy support in 1940-1941, and after the engine firms were given complete freedom to use any control they pleased in 1941, Bendix itself gave up the speed-density control and adopted a completely different system, which operated on the basic mass-flow principle advocated by Wright Field in the 1930's although the mechanical arrangement was completely different from the one Wright Field was trying to have developed by Bosch.

*The Acceleration of Fuel-Injection Development During the War*

Beginning with 1940 the pace of fuel-injection development was very considerably increased. Both the services were much impressed by the extensive use which the Germans were making of injection, and appropriations were now large enough to permit the services not only to purchase several injectors at a time but — what was much more expensive and much more important — to give contracts for several hundred thousand dollars within three years to the engine companies to install and test the injectors on actual engines on the ground and in flight. Toward the middle of 1941 a new factor of urgency entered: the Wright R-3350 engine, which was intensely desired by the Army for use in the B-29 and which the Navy also planned to use in two large flying boats,[36] was afflicted with poor distribution of both fuel and air which was partly due to the introduction of fuel into the airstream immediately after the carburetor, according to the standard practice of that time.[37]

[36]The Martin Mars and the Boeing XPBB-1. The latter was ultimately cancelled to free Boeing facilities for the B-29, and the Mars was not put in production until 1945.

[37]"Adapter injection" was fairly satisfactory with low and medium supercharging, but with the very high degree of supercharging used on the R-3350 for the B-29 and also on other engines this brought about a poor distribution of fuel and also





At the same time there was a good deal of trouble with the destructive result of backfires in the very large induction system of this engine filled with highly compressed explosive charge; this problem would, of course, be completely eliminated by the use of fuel injection, since the induction system would contain only air.

The availability of more money made it possible in 1940 for the Army to give a contract to Wright for work on an engine with fuel injection. This contract, which was for work on the Cyclone engine, was replaced in May 1941 by a contract for an R-3350 when it was decided that that engine should have the first priority on fuel injection. At this same time the Navy resumed direct support of injection development. By 1941 the highest authorities in the Air Corps were instructing Wright Field to get the R-3350 equipped with fuel injection as quickly as possible. Late in that year the Army held a conference with the entire engine industry where it announced that it was anxious to have fuel injection used on all engines, not just the R-3350; that each engine builder was free to use any injector and any control system which he thought best;[38] and that all the Army's construction specifications on injectors would be waived. Wright Aeronautical was already not only willing but anxious to develop fuel injection as a possible solution for the troubles of the R-3350; and although Pratt & Whitney maintained that there was no gain to be had from injection on the evidence to date, that firm too agreed to hasten experimentation with fuel injection in order to get the facts. From this time on nothing interfered with the development of fuel injection except the technical obstacles themselves and the shortage of man and machine hours which led to delays in the production of experimental articles.[39]

a poorer distribution of air or lower supercharger efficiency than when there was no fuel mixed with the air fed to the supercharger. It was only about this time that Pratt & Whitney began the development of injection of the fuel at the supercharger which ultimately solved this problem in addition to completely eliminating icing due to evaporation of fuel.

[38]By this time there were two alternate control systems for the Eclipse injector (or Bendix as it was now known): cf. below, p. 542.

[39]Both Bosch and Bendix relied on outside shops for this work, and the tolerances in the pump were so close that a great deal of hand work was required.

*The Bosch Injector, 1940-1945*

The engineer in charge of fuel injection at Wright Field believed, as we have seen, that both the Bosch pump and its control were already virtually ready for service in 1939, and that all that remained to do was to adapt them to specific engines. When funds became available in 1940 to award contracts to the engine manufacturers for the development of injector-equipped engines, the Army's first such contract was with Wright for the development of an R-1820 equipped with the Bosch system.[40] When the Army decided about the middle of 1941 to concentrate fuel-injection development primarily on the R-3350 engine, Wright chose to use the Bosch injector. When Pratt & Whitney resumed work on fuel injection at the Army's request in the fall of 1941, its first choice was a Bosch injector for use on the R-2800.

Development of the Bosch injector was seriously delayed, however, by the extreme slowness of the company in delivering experimental articles to the engine builders and in making suggested modifications in these articles. By the latter half of 1941, furthermore, it was beginning to appear very doubtful whether the electric mass-flow control suggested by Campbell of Wright Field and on which Bosch had been working since 1935 could ever be successfully developed. In October 1941 the Army gave Bosch a contract for a hydraulic mass-flow control as a hedge, although work on the electric control was to be continued. Shortly after this the Bosch program was completely interrupted when it was discovered that over 10% of the ownership of the company was foreign, since according to the Air Corps Act of 1926 such a company was disbarred from Army and Navy contracts. There was a considerable delay before the ownership was transferred to American hands in 1942.

The change in ownership of the Bosch company effected in 1942 brought in a new group of engineers who were more enthusiastic than the old, probably because prospects for sales

[40]Wright's past experience had been almost entirely with the Eclipse, but Wright was anxious to maintain competition among suppliers and therefore wanted to work with Bosch also.





were much improved after the fall of 1941. The design of the pump was altered, and experimental models were produced which were completely free of the seizures which had been experienced with the original model.[41] The electric control was dropped,[42] and the hydraulic mass-flow control introduced before the change of ownership was brought to a state such that the system could pass the Army tests. It was released in 1943 for production for use on the R-3350, although it had not yet been flown.

Bosch failed, however, to solve the tremendous problems involved in the quantity production of an article with the excessively small tolerances involved in the injector pump: the experimental articles which had performed so well had involved a good deal of hand finishing which could not be well done in quantity production. Although a few hundred units were produced before the end of the war, they suffered severely from seizure and were never put on engines for service.

*Success of the Bendix Injector*

In 1941 the Bendix Products Division, to which the Eclipse injector development under DesChamps had been transferred at the beginning of the year, received contracts for about a dozen injectors for the R-3350 for the Army and Navy together, and for two 24-cylinder units for the Lycoming H-2470 from the Navy. The R-3350 injectors were of two types: 18-cylinder single units, which were the simplest solution and the one preferred by the Navy, and twin-nine-cylinder units, which were requested by Wright Aeronautical and approved by the Army because this would permit easily adjustable compensation for the fact that the front row of the R-3350 received more air than the rear.[43]

[41]Despite the fact that this change introduced a positive drive for the plungers in both directions instead of the spring return which had been used on the original pump and which was generally considered to be less likely to seize.

[42]J. F. Campbell, who had conceived this electric control, left Wright Field in 1940 to work for Holley, where he himself attempted to develop a control along these same lines. Holley received an Army contract for this work early in 1941, but this attempt too was a failure and was ultimately abandoned.

[43]In 1943 very serious difficulties appeared in the synchronization of the twin units, but the Army was unwilling to change at this late date and the twin-unit system became standard. Ultimately a simple device was added which removed all difficulty with synchronization.

After the delivery of the R-3350 units in 1942 the Navy ran comparative flight tests in an XPBB-1 of one R-3350 equipped with an injector and another with a carburetor, and reported no improvement in performance with the injector.[44] The Navy was always afraid of maintenance difficulties with an injection system, which was both more complex than a carburetor and less well tried and developed, and the Navy was not critically interested in the R-3350 in any case. The result was that after 1942 the Navy left support of fuel injection to the Army alone.

Late in 1941 or early in 1942 Pratt & Whitney had begun to work with the Bendix injector as well as the Bosch in connection with the R-2800 engine. Shortly thereafter, a Pratt & Whitney engineer suggested that time and effort could be saved if instead of waiting for development to solve all the difficulties still encountered in Bendix's speed-density control, the already fully developed Bendix-Stromberg pressure carburetor was adapted to serve as a control, i.e., used to meter the fuel to the pump instead of to the air stream. This was tried at once; the injector was arranged so that the rate at which the fuel was delivered to the pump itself regulated the cut-off point for each pump stroke so as to distribute the metered fuel equally to the individual cylinders. The Stromberg pressure carburetor, as we have seen, had an automatic mixture control which by this time was completely satisfactory. The new system of control proved to be definitely superior to the original speed-density system, and it was taken up and made standard by the Army.

The Bendix twin-nine-cylinder injector with the new control was released for production in 1943, a little later than the Bosch, and started coming off the lines in 1944. Bendix did a remarkable job of production engineering; although the experimental units had all had hand-lapped plungers and cylinders selectively fitted, the production pumps performed perfectly with machine-ground interchangeable parts. By the end of the war the Army was beginning to substitute the Bendix injector for the carburetor on the R-3350's of all B-29's.

[44] There was actually a slight loss of power owing to the loss of the cooling ahead of the supercharger caused by evaporation of fuel from a carburetor, but this could have been made up by use of a slightly higher supercharger pressure ratio.





The use of fuel injection resulted in complete elimination of destructive backfires and fires due to them and in complete elimination of refrigeration icing; it made possible instantaneous acceleration even with a cold engine, and generally was superior for Arctic service. It considerably simplified the problem of obtaining good fuel distribution, and at least in some cases simplified the problem of obtaining good air distribution. On the other hand, the Bendix fuel injector adds the weight and complexity of the fuel pump to the engine and makes no corresponding saving, since a complete carburetor is used as a control for the pump. Engineers are still far from agreed whether fuel injection or carburetion is superior in the final balance.

## Summary

Although Stromberg made a number of important improvements in its standard float-type carburetor in the years between the end of the First World War and 1935, this type of carburetor was never really suited to aircraft use. In the absence of competition, however, Stromberg simply refused to make any attempt to design a new type of carburetor which would be truly suitable for aircraft. As soon as competition appeared, in 1935, Stromberg quickly doubled its engineering budget, revised its technical thinking, and produced the pressure carburetor which was the only carburetor used on new high-power aircraft engines in the United States after the end of the Second World War. The history of Stromberg carburetors is thus one of the best possible illustrations of the very great need for competition in development.

A great deal of government money was spent on the development of fuel injection after 1927, but until 1941 the specialists who were developing fuel injectors worked almost unaided by the engine builders. The engine builders believed during most of this period that fuel injection would necessarily be inferior to carburetion, and certain detailed technical requirements set up by the Army did nothing to increase their enthusiasm for injection. In 1941 the Army finally received sufficient funds to give really large contracts for the development of injection-equipped engines to the engine builders, and at the same time relaxed all its technical requirements. Great progress was made as soon as Wright and Pratt & Whitney set to work, and within two years the Bendix injector was ready for service. Thus the chief lesson to be learned from the history of fuel injectors in the United States is that it is extremely difficult, if not impossible, for a specialist to develop an accessory without the whole-hearted cooperation of the engine builder.