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Effect of the NACA injection impeller on the mixture distribution of a double-row radial aircraft engine

National Advisory Committee for Aeronautics, Washington, D. C.

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The effect of the NACA centrifugal supercharger impeller on the mixture distribution of a double-row radial aircraft engine was tested. For the normal range of engine power the impeller provided marked improvement over the standard spray-bar injection system. Mixture distribution at cruising was excellent, maximum cylinder temperatures were reduced about 30°F, and general temperature distribution was improved. The uniform mixture distribution restored the normal response of cylinder temperature to mixture enrichment and it reduced the possibility of carburetor icing, while no serious loss if supercharger pressure rise resulted form injection of fuel near the impeller outlet. The injection impeller also furnished a convienent means of adding water to

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By Frank E. Marble, William K. Ritter and Mahlon A. Miller

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Washington
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SUMMARY

The NACA injection impeller was developed to improve the mixture distribution of aircraft engines by discharging the fuel from a centrifugal supercharger impeller, thus promoting a thorough mixing of fuel and charge air. Tests with a double-row radial aircraft engine indicated that for the normal range of engine power the NACA injection impeller provided marked improvement in mixture distribution over the standard spray-bar injection system used in the same engine. The mixture distribution at cruising conditions was excellent; at 1200, 1500, and 1700 brake horsepower, the differences between the fuel-air ratios of the richest and the leanest cylinders were reduced to approximately one-third their former values. The maximum cylinder temperatures were reduced about 30° F and the temperature distribution was improved by approximately the degree expected from the improvement in mixture distribution. Because the mixture distribution of the engine tested improves slightly at engine powers exceeding 1500 brake horsepower and because the effectiveness of the particular impeller diminished slightly at high rates of fuel flow, the improvement in mixture distribution at rated power and rich mixtures was less than that for other conditions.

The difference between the fuel-air ratios of the richest and the leanest cylinders of the engine using the standard spray bar was so great that the fuel-air ratios of several cylinders were well below the chemically correct mixture, whereas other cylinders were operating at rich mixtures. Consequently, enrichment to improve engine cooling actually increased some of the critical temperatures. The uniform mixture distribution provided by the injection impeller restored the normal response of cylinder temperatures to mixture enrichment.

The hazard of engine backfiring was reduced because the volume of combustible charge in the intake system was decreased and because excessively lean cylinders were eliminated through improvement in the mixture distribution. For the engine tested, no serious loss in supercharger pressure rise resulted from the injection of fuel near the impeller outlet instead of from the carburetor spray bar. The injection of fuel near the impeller outlet does, however, reduce the possibility of carburetor icing. The injection impeller furnishes a convenient means of adding water to the charge mixture for internal cooling.

INTRODUCTION

The variation of temperature between cylinders and the improper operation of individual cylinders due to nonuniform mixture distribution contribute greatly to engine-cooling and operational problems. Adequate cooling for the hottest cylinders imposes a serious restriction on airplane performance, whereas overheating due to inadequate cooling leads to engine failure. Poor mixture distribution among the cylinders definitely limits the possibility for economical lean operation because of faulty firing or overheating of the leanest cylinders. The problem of mixture distribution therefore has general importance especially for engine installations of high-performance, long-range aircraft.

Centrifugal and gravitational separation of fuel droplets from the air as well as coarse, nonuniform injection of fuel into the combustion-air stream contributes to the variation in fuel-air ratio among cylinders. Consequently, unless coarse fuel droplets at the impeller entrance are eliminated, fuel-injection upstream of the impeller or of any passage distortion should offer only meager possibilities for improving the mixture distribution over more than a limited range of engine conditions. A basic improvement in mixture distribution should be possible through injecting the fuel at a point where the fuel droplets are least subject to separation from the combustion air and by practically eliminating the large droplets usually present in the charge-air stream.

The NACA injection impeller was developed to avoid the causes of nonuniform mixture distribution by injecting fuel near the impeller outlet, where the elbow and the carburetor disturbances are minimized and where the high velocity and the turbulent conditions may be utilized to minimize the effect of gravitational forces and to provide thorough mixing and fuel evaporation. During the period in which the NACA injector impeller was developed, neither of the two manufacturers of 18-cylinder radial engines was idle in research on spinner-injection impellers. The present report discusses the theory and the design of the NACA injection impeller and presents results of performance tests of a double-row radial air-cooled engine equipped with the injection impeller.

THE NACA INJECTION IMPELLER

The NACA injection impeller is a centrifugal impeller modified to act as a fuel distributor as well as a supercharger. Fuel passages discharge from a centrally located supply chamber into the air passages at a point sufficiently near the impeller tip to avoid fuel impingement on the stationary shroud. The centrifugal force with which the fuel is discharged is much greater than the gravitational forces and consequently a uniform peripheral fuel discharge from the impeller may be attained.

The NACA injection impeller shown in figure 1 was designed for direct application to an engine with a minimum alteration of parts. The metered fuel is fed from the carburetor to a stationary nozzle ring, instead of passing to the conventional spray bar located just downstream of the carburetor, and is delivered from the nozzle ring into a collector cup that rotates with the impeller. A 1/32-inch air gap was provided between the nozzle ring and the collector cup to eliminate surging in the fuel system. The fuel, which is thrown to the surface of the collector by the rotating fuel inducer, flows by centrifugal action through the collector cup and the impeller transfer passages to the fuel-distribution annulus. The rotating collector cup and the fuel-distribution annulus serve as equalization chambers for correcting asymmetrical distribution of the fuel entering the impeller. (This means of transferring fuel from the carburetor to the impeller would be neither necessary nor desirable for installations permitting fuel to be fed directly to a distribution annulus on the web side of the impeller.) From the fuel-distribution annulus, the fuel is thrown through the radial holes into the air stream of the impeller passages. The 11 radial fuel-injection passages of 1/16-inch diameter are drilled through the web of the impeller and enter alternate air passages at a point where the fuel will be struck and dispersed by the advancing impeller blade.

In order to establish the safety of the injection impeller, preliminary spin tests were conducted in which deformation was measured over a range of speeds. The permanent extension of the diameter was 0.010 inch at 200 percent of rated speed and increased rapidly with increasing speed. Inasmuch as the impeller failed at 235 percent of rated speed, it is structurally safe for normal engine operation.

APPARATUS AND TESTS

The tests of the NACA injection impeller were made with an 18-cylinder radial aircraft engine installed in a test cell (fig. 2) and fitted with a flight cowling and induction system. The extent of the instrumentation and the tests was reduced to that essential for indicating the engine performance with the injection impeller.

Test engine and instrumentation. - The engine used for the tests was an 18-cylinder, double-row radial, air-cooled aircraft engine with a normal rating of 2000 brake horsepower at 2400 rpm and a take-off rating of 2200 brake horsepower at 2600 rpm. The engine has a single-stage, gear-driven supercharger with a gear ratio of 6.06:1. An injection-type carburetor was used for the tests. Engine power was absorbed by a 16-foot, 7-inch-diameter, four-bladed, constant-speed propeller and was measured by means of a torquemeter. A circumferential baffle plate was installed in the test cell to eliminate counterflow around the propeller tips. Cooling air was drawn across the engine by a controllable suction system and combustion air was supplied by a centrifugal blower through an air-tempering unit regulated to give a carburetor-deck temperature of 100° F.

In order to determine the fuel-air ratio at which each cylinder was operating, exhaust-gas samples were taken from each exhaust port, passed through an 18-tube oxidizing furnace, and analyzed for carbon dioxide content. The method of determining the fuel-air ratio from oxidized samples is described in reference 1. Sampling tubes, the intake ends of which were flattened to form a 0.01-inch slot opening, were located at the outlet of each exhaust port. (See fig. 3.) No air contamination that might arise from leakage in the manifold system was observed in the exhaust-gas samples.

Cylinder-head temperatures were measured by iron-constantan thermocouples located in the following positions on each cylinder (see fig. 3): rear spark-plug gasket, rear spark-plug boss, exhaust-valve seat. Standard Army-type thermocouples were used at the rear spark-plug-gasket location and specially built thermocouples, imbedded as shown in figure 3, were used in the other positions. The cooling-air temperature was measured by three iron-constantan thermocouples located at the cowling inlet, and the carburetor-deck temperature was checked by two thermocouples located on the screen upstream of the carburetor. All temperatures were recorded on self-balancing potentiometers.

Cooling-air pressures (fig. 4) were measured at five points of baffle inlet to each cylinder and at two points behind the curl of the baffle outlet and at one point above the top head baffle of each rear-row cylinder. The total-pressure tubes at the baffle inlet were located midway between the baffle and the fin tips and far enough behind the inlet radius to avoid the effect of local air-flow separation from the baffle. The absolute manifold pressure, the carburetor-deck pressure, the carburetor metering pressures, and the pressure drop across the carburetor were measured by mercury manometers.

Test procedure. - In order to evaluate the performance of the NACA injection impeller, the mixture distributions of the test engine using the normal spray bar and using the injection impeller were compared at four engine powers and speeds. The following operating conditions were selected:

Percentage rated power	Brake horsepower	Engine speed (rpm)	Carburetor setting
60	1200	2000	Automatic lean
75	1500	2200	Automatic rich
85	1700	2300	Do.
100	2000	2400	Do.

For each test of the engine using the standard spray bar, the cooling-air pressure drop was adjusted to give a temperature of 450° F on the hottest rear spark-plug gasket. The corresponding tests of the engine using impeller injection were conducted at the same values of cooling-air pressure drop and fuel flow. The fuel-air ratio of each cylinder, as well as complete cylinder-temperature and engine data, was obtained using both the spray bar and the impeller injection systems.

In order to observe the effect of over-all fuel-air ratio on the operation of the injection impeller, tests with reduced fuel flows were conducted at 1500, 1700, and 2000 brake horsepower. The same respective values of cooling-air pressure drops were used in these tests as were used in the tests with automatic carburetor settings. In each case the fuel flow was reduced the amount permitted by the limiting rear spark-plug-gasket temperature of 450° F.

RESULTS AND DISCUSSION

Mixture-distribution surveys of the test engine using the spray-bar injection system (fig. 5) exhibited wide variations in fuel-air ratio among cylinders for the four operating conditions. Large differences between the fuel-air ratios of the richest and the leanest cylinders are apparently present at all operating conditions, although a definite improvement in mixture distribution was apparent at high powers and engine speeds. In all cases these differences are of sufficient magnitude to be a source of unsatisfactory engine operation and cooling.

Effect of NACA injection impeller on mixture distribution. - The mixture distributions of the engine using the standard spray bar and the injection impeller are compared at the same operating conditions in figure 6. The fuel-air ratios of the richest and the leanest cylinders and the values of the fuel-air-ratio spread are presented in the following table:

Brake horsepower	1200		1500		1700		2000	
Method of fuel injection	Standard spray bar	Injection impeller	Standard spray bar	Injection impeller	Standard spray bar	Injection impeller	Standard spray bar	Injection impeller
	Fuel-air ratio							
Maximum	0.079	0.076	0.102	0.098	0.103	0.098	0.109	0.110
Minimum	.061	.070	.076	.088	.085	.092	.095	.098
Spread	.018	.006	.026	.010	.018	.006	.014	.012

A marked reduction in mixture spread is shown at 1200, 1500, and 1700 brake horsepower, which indicates that the operation of the NACA injection impeller is entirely satisfactory for these conditions. At 2000 brake horsepower, however, the improvement is less noticeable, apparently because the mixture distribution using the standard spray bar is much better at this power than at the lower powers and because the injection impeller does not operate so satisfactorily at this condition as at the lower fuel flows.

The mixture distributions at reduced fuel flows are shown in figure 7 for 1500, 1700, and 2000 brake horsepower and are compared with the mixture distribution obtained when using a spray-bar at rich mixtures for the corresponding engine conditions. The numerical comparison is given in the following table:

Brake horsepower	1500		1700		2000	
Method of fuel injection	Standard spray bar	Injection impeller	Standard spray bar	Injection impeller	Standard spray bar	Injection impeller
	Fuel-air ratio					
Maximum	0.102	0.077	0.103	0.094	0.109	0.090
Minimum	.076	.071	.085	.083	.095	.084
Spread	.026	.006	.018	.011	.014	.006

The variations in mixture distribution when using the injection impeller and reduced fuel flow are considerably smaller for 1500 and 2000 brake horsepower than were the variations with high fuel flows, but slightly greater for 1700 brake horsepower. These data indicate that the ability of the injection impeller to overcome the effects of gravitational and centrifugal fuel separation is inhibited at high powers and fuel flows (fig. 6) by some factor in the impeller design, the effects of which are eliminated at reduced values of fuel flow.

Effect of impeller injection on cylinder temperature. - The cylinder temperature changes that result from the improved mixture distribution (fig. 8) are similar for the rear spark-plug gaskets and the exhaust-valve seats. The rear spark-plug-gasket temperature is of interest because it is a convenient measurement and is used as a standard; the temperature of the exhaust-valve seat is given because it has been observed that numerous failures occur in this region of the cylinder. (See fig. 3.) The mixture distributions for the standard and the modified engines are given in the same figure in order to facilitate a comparison of the trends. Because the cooling-air temperature varied between tests, the cylinder-temperature values presented in figure 8 have been corrected by the method described in reference 2 to a cooling-air temperature of 70° F. The cooling characteristics necessary for this calculation were obtained from reference 3.

The temperature patterns for the engine using the standard spray-bar injection system follow the trend that might be expected to result from the distribution of fuel-air ratio. Likewise the changes in the cylinder-head temperatures effected by the injection impeller generally correspond to the changes in fuel-air ratio although the two are not always of comparable magnitude. The maximum and the minimum rear spark-plug-gasket temperatures, as well as the temperature spreads, are presented in the following table for both injection systems:

Brake horsepower	1200		1500		1700		2000	
Method of fuel injection	Standard spray bar	Injection impeller	Standard spray bar	Injection impeller	Standard spray bar	Injection impeller	Standard spray bar	Injection impeller
	Temperature, °F							
Maximum	448	420	460	427	462	432	461	427
Minimum	358	361	336	346	345	349	343	337
Spread	90	59	124	81	117	83	118	90

In order to compare the observed improvement in cylinder temperature distribution with that expected from the improvement in the mixture distribution, the theoretical change of head-temperature pattern (reference 2) was computed from the fuel-air-ratio patterns for the engine using the injection impeller and from the temperature distribution of the engine using standard spray-bar injection as follows:

$$\Delta T_h = \Delta T_g \left(\frac{T_{h_1} - T_a}{T_{g_1} - T_a} \right) \quad (1)$$

where

ΔT_h change in head temperature with fuel-air ratio, assuming constant cooling-air flow and charge-air flow, °F

ΔT_g change in combustion-gas temperature with fuel-air ratio, assuming constant carburetor-deck temperature and supercharger speed, °F (reference 3)

T_{h_1} cylinder-head temperature at initial conditions, °F

T_a cooling-air temperature, °F

T_{g_1} initial combustion-gas temperature, °F

The theoretical values for the exhaust-valve-seat temperatures at 1500 brake horsepower using the injection impeller are compared in figure 9 with the observed values. Substantial agreement between the calculated and the observed values of the exhaust-valve-seat temperature is obtained for the rear-row cylinders but unaccountable discrepancies as great as 40° F are shown in some cases for the front-row cylinders. The actual change in head temperature is usually less than the value given by equation (1).

The improved mixture distribution obtained with impeller injection insures that the temperature of each cylinder will have nearly the same response to variations of the engine fuel-air ratio. For lean operation with nonuniform mixture distribution, the fuel-air ratio of individual cylinders may be richer or leaner than the chemically correct mixture. When the mixture is enriched for the purpose of reducing cylinder temperatures, the temperatures of the cylinders whose fuel-air ratios were originally below the chemically correct value will increase until the fuel-air ratio of these cylinders exceeds the chemically correct value. Initial enrichment, therefore, may actually increase the critical cylinder temperatures and the enrichment would have to be carried to great excess, with a commensurate loss in economy, in order to overcome this difficulty. The uniform mixture distribution provided by the injection impeller restores the normal function of enrichment cooling and eliminates the necessity for excessively rich operation.

Use of NACA injection impeller for injecting water. - The NACA injection impeller provides a very simple and effective means of injecting water. Water is metered into the fuel-transfer line and, after the fuel and water pass through the rotating fuel inducer and into the distribution annulus, they are uniformly distributed to the engine. Results of limited tests using water injection indicate trends similar to those shown in figure 10 where typical temperature and mixture distributions with and without water injection are compared for tests at 1700 brake horsepower. The same rate of fuel flow was maintained for the two tests; the engine fuel-air ratio for the tests with water injection was reduced as a result of the increased air consumption required by the addition of water. The reduction in cylinder-head temperatures indicates that, with the possible exception of cylinder 1, the distribution of water was reasonably uniform. The uniformity of mixture distribution was only slightly disturbed by the use of water injection.

Effect of NACA injection impeller on engine operation. - The tests conducted with the engine using the injection impeller showed improvements in general engine operation and revealed functional problems resulting from use of the NACA injection impeller. Although the evidence is of a qualitative nature, it appears that the engine starting characteristics were improved by impeller injection. The use of impeller injection eliminated the fuel usually present between the carburetor and the impeller. As a result of this reduction of combustible mixture in the intake system and the elimination of excessively lean conditions at any cylinder, both the frequency of and hazard from backfiring were apparently reduced. Because the acceleration jet discharged near the carburetor outlet, it was necessary, however, to saturate the air between the carburetor and the impeller outlet before this fuel could be supplied to the engine. Because of this factor and the additional inertia of the lengthened fuel passages, the acceleration response of the engine was below normal. Modification of the carburetor to provide an accelerating reservoir with double the normal volume resulted in acceleration characteristics equaling those of the engine using the standard spray bar. Because of the absence of fuel vapor in the supercharger inlet elbow, the air temperature at the inlet of the injection impeller was higher than that in the standard installation, which should reduce the probability of icing.

During the tests, it was noted that high-power operation required slightly greater throttle openings with the injection impeller than with the standard spray-bar system, which indicates that the injection of fuel near the impeller discharge had a measurable effect on the supercharger pressure ratio. At 2000 brake horsepower, the supercharger pressure ratio was reduced from 1.71 to 1.60 when impeller injection was used. Four possible causes of this loss are:

1. High air temperature at the impeller inlet resulting from absence of fuel vapor

2. Change of air properties resulting from absence of fuel vapor

3. Change in air density at the impeller inlet resulting from increased air temperature and the absence of fuel vapor

4. Change in air-flow pattern at the point of fuel injection

An increase in inlet-air temperature and in sonic velocity is accompanied by a reduction in Mach number (reference 4) and supercharger pressure ratio. This effect may be counteracted by increasing the impeller speed until the original Mach number is attained. Calculations made for an increase in inlet temperature of 50° F at 2000 brake horsepower showed that the supercharger pressure ratio was reduced from 1.71 to 1.63, which is of the same order as the reduction experimentally obtained. The absence of fuel vapor at the impeller inlet reduces the value of the ratio of specific heats, an effect that may counteract, to a certain extent, the increase in sonic velocity accompanying the temperature increase. For a given weight of charge-air flow, the pressure ratio may vary because of change in load coefficient with the inlet-air density. Because of fuel evaporation, the air density at the impeller inlet is increased by the temperature reduction and is decreased by the volume of the fuel vapor. The direction of the density change is difficult to predict but the two opposite trends should insure that the change will be small. This effect will therefore be serious only when the supercharger is operating near maximum capacity; in a properly matched supercharger-engine combination this operating condition will not occur. It is possible that premature flow separation from the impeller wall, with a resulting loss in efficiency, might be induced by the fuel jet. The measured magnitude of the resulting loss in pressure ratio indicates, however, that the loss is not severe.

SUMMARY OF RESULTS

Because the NACA injection impeller attacks the problem of fuel distribution in a fundamental manner, some success in all installations can be expected. The results of the present investigation apply, however, only to the injection impeller installed on a particular radial aircraft engine. Observations indicated that the engine using the injection impeller had better starting characteristics and reduced frequency of backfire than the engine using the standard spray bar. The injection impeller provides a simple and effective means of water injection and, because of the position of the fuel injection, reduces the probability of ice formation in the induction system. The significant results of the investigation may be summarized as follows:

1. Use of the NACA injection impeller markedly improved the fuel-air-ratio distribution for all engine powers and speeds tested. Except for rich operation at rated power, the difference between the fuel-air ratios of the richest and the leanest cylinders was reduced to approximately one-third its value with the standard spray bar.

2. As a direct result of the improved mixture distribution, the maximum cylinder temperatures were reduced about 30° F and the

temperature differences between the hottest and the coldest cylinders were reduced to two-thirds their value with the standard spray bar.

3. No severe decrease in supercharger pressure ratio resulted from fuel injection near the impeller outlet; a reduction from 1.71 to 1.60 was the greatest encountered during the tests.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, November 14, 1945.

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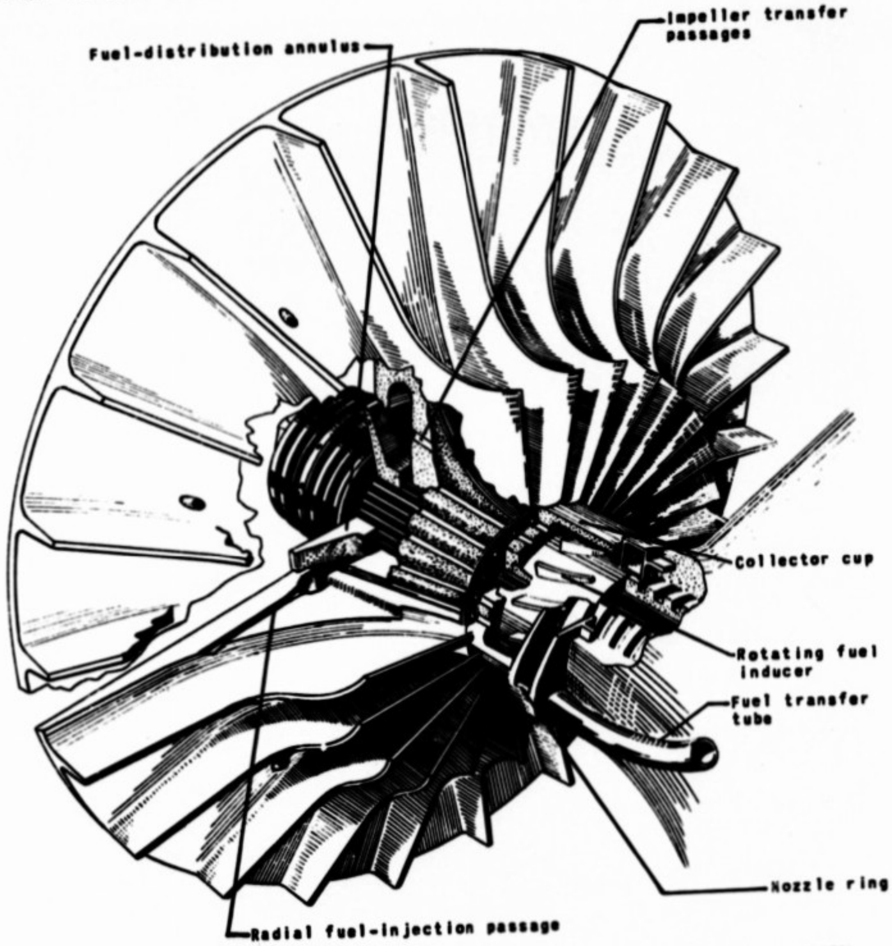

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Figure 1. - NACA injection impeller designed for installation on double-row radial aircraft engine.

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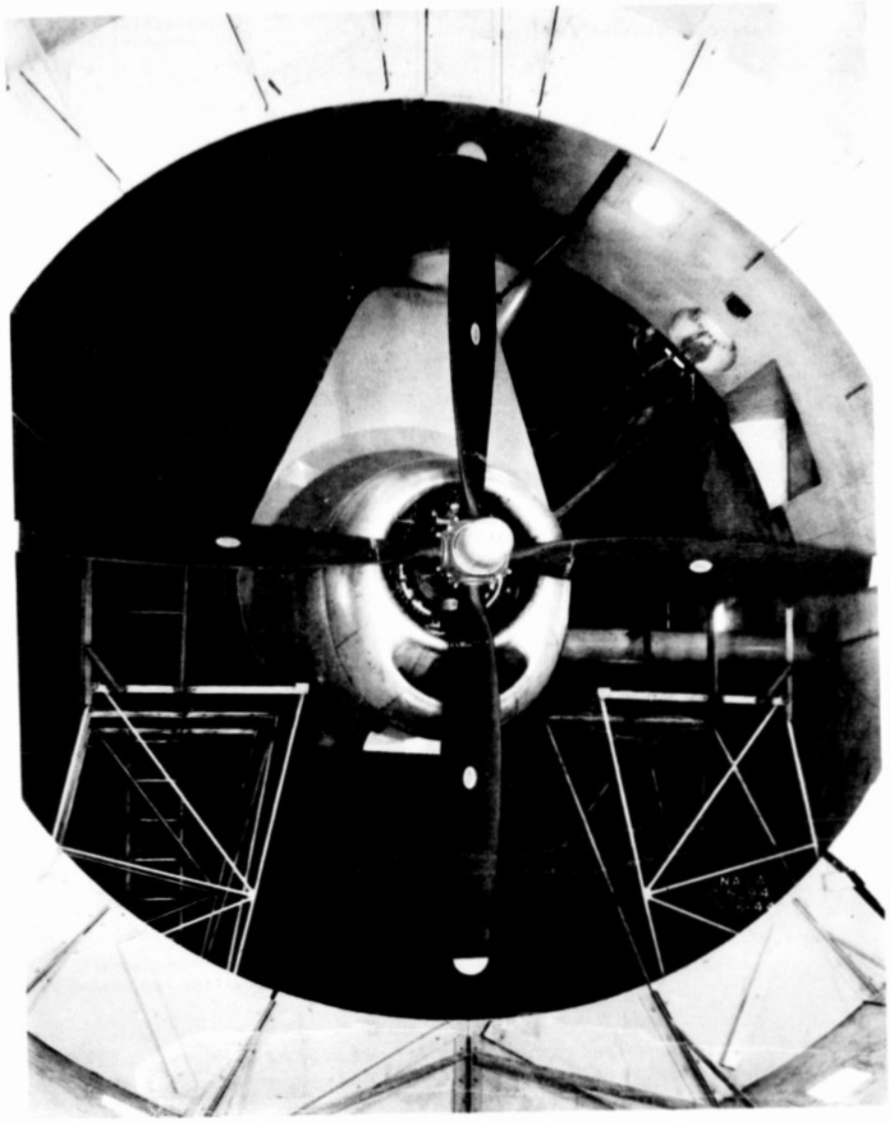

Figure 2. - Test-cell installation of double-row radial aircraft engine and cowling for test of NACA injection impeller.

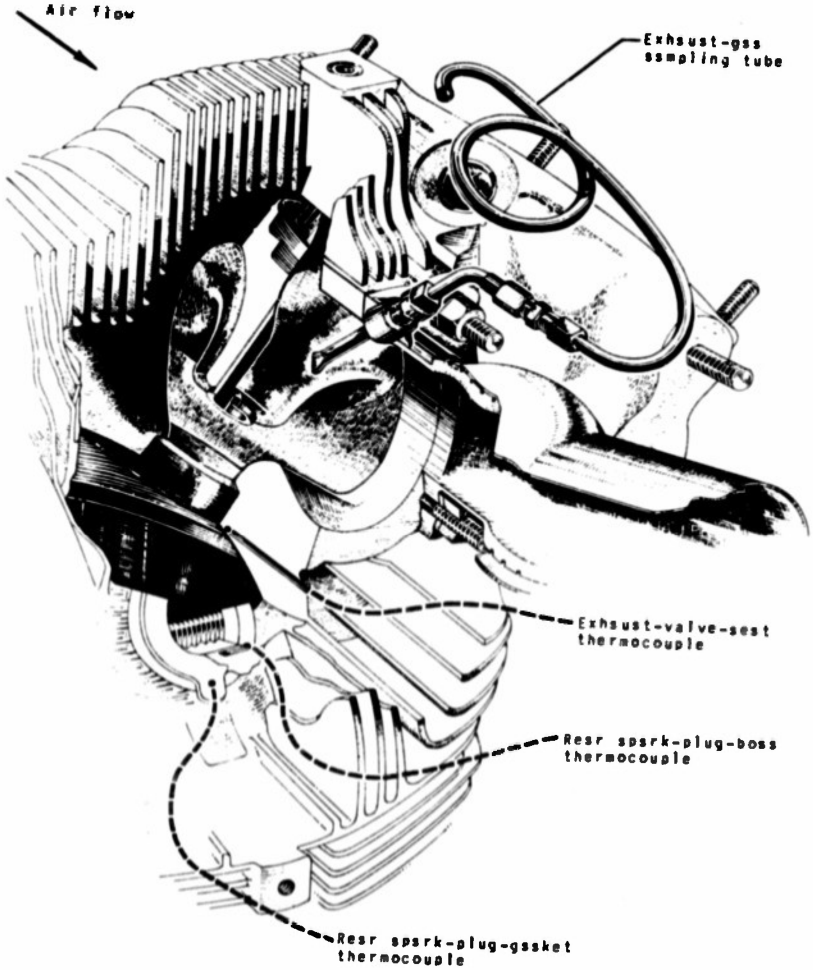

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Figure 3. - Location of thermocouples and exhaust-gas sampling tube.

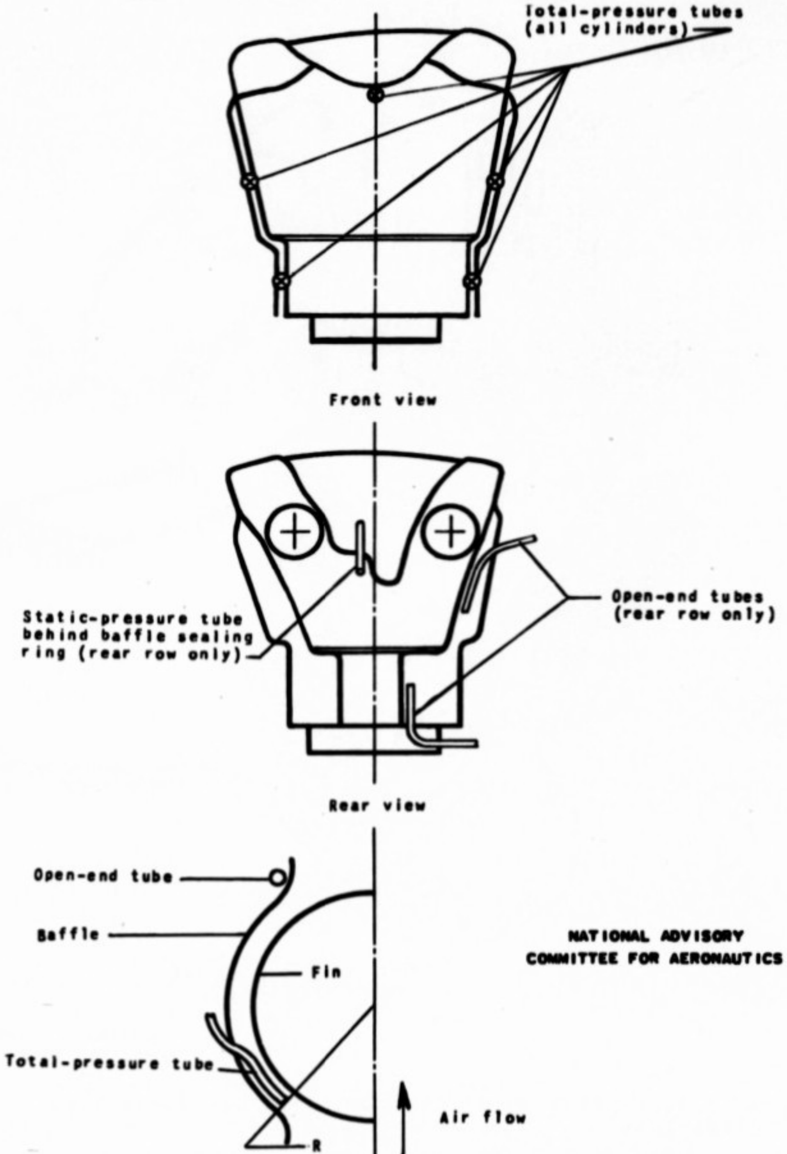

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Figure 4. - Location of cooling-air pressure tubes.

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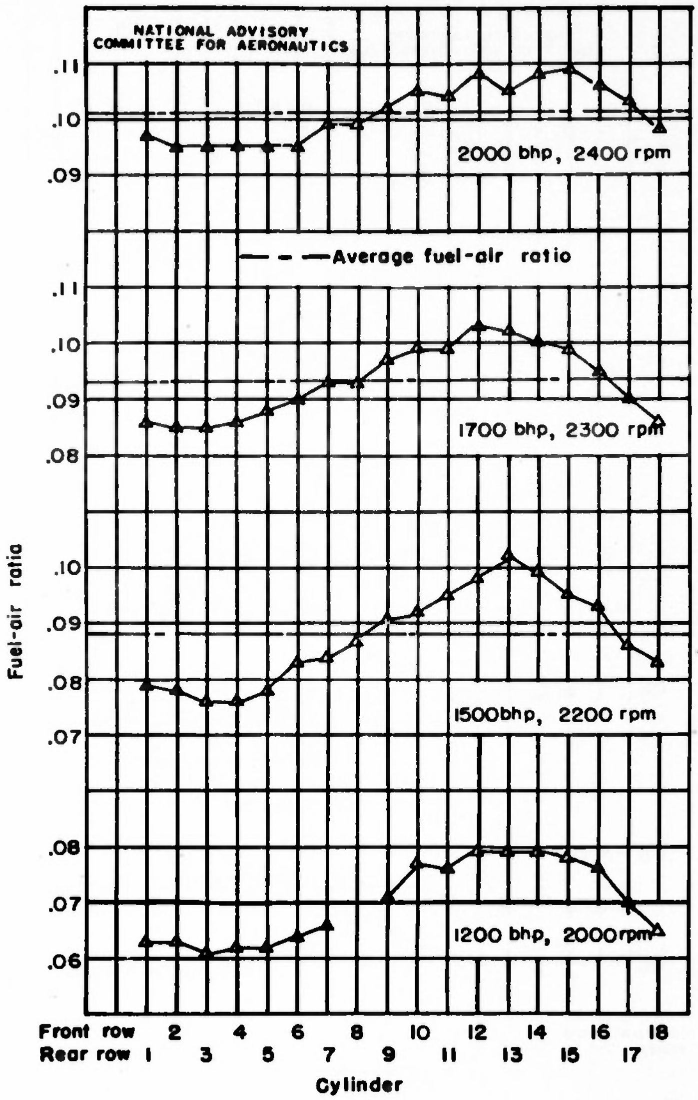


Figure 5.– Mixture distribution of engine using standard spray bar at various engine powers and speeds.

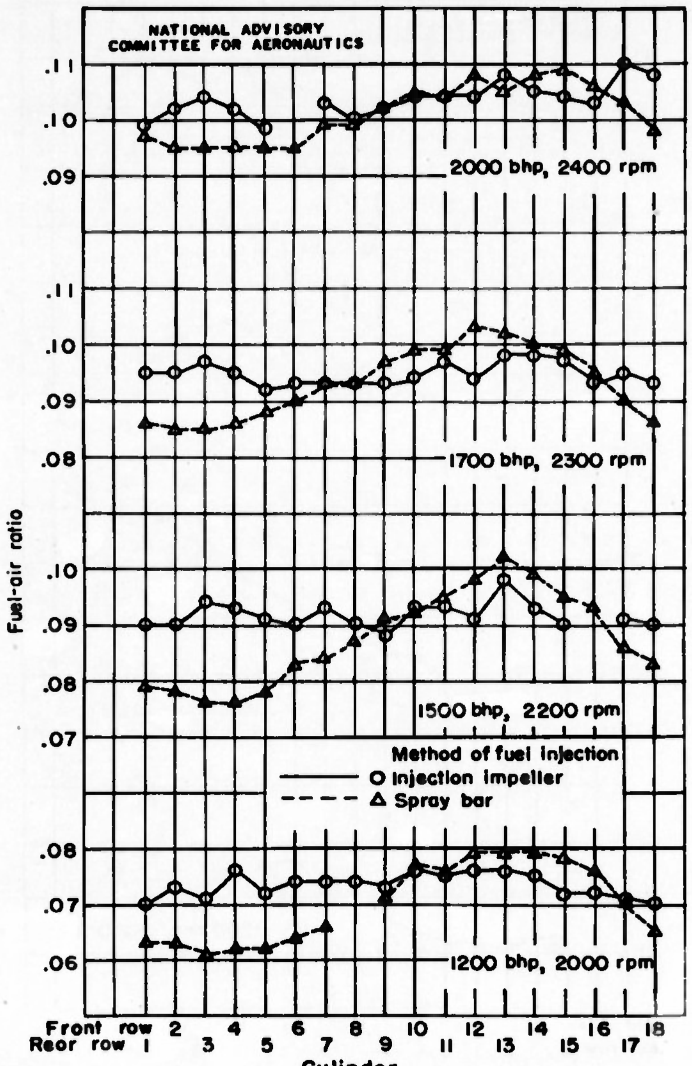


Figure 6. - Effect of NACA injection impeller on mixture distribution of engine at various engine powers and speeds.

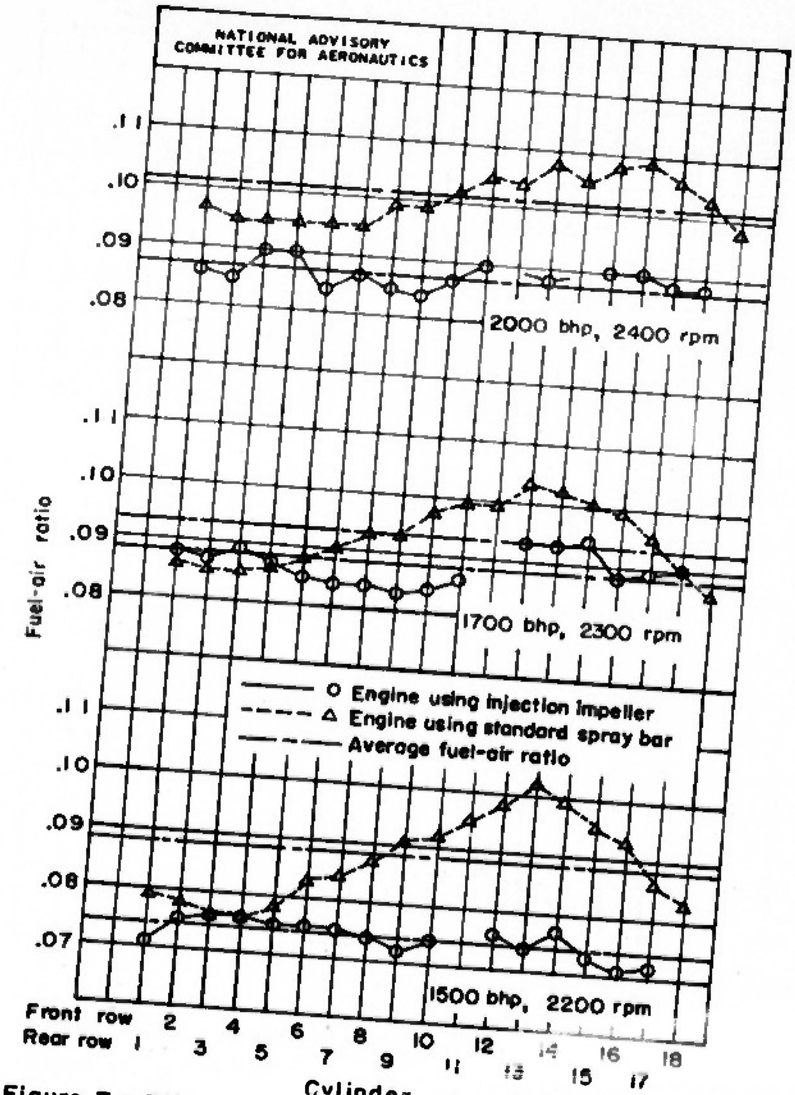
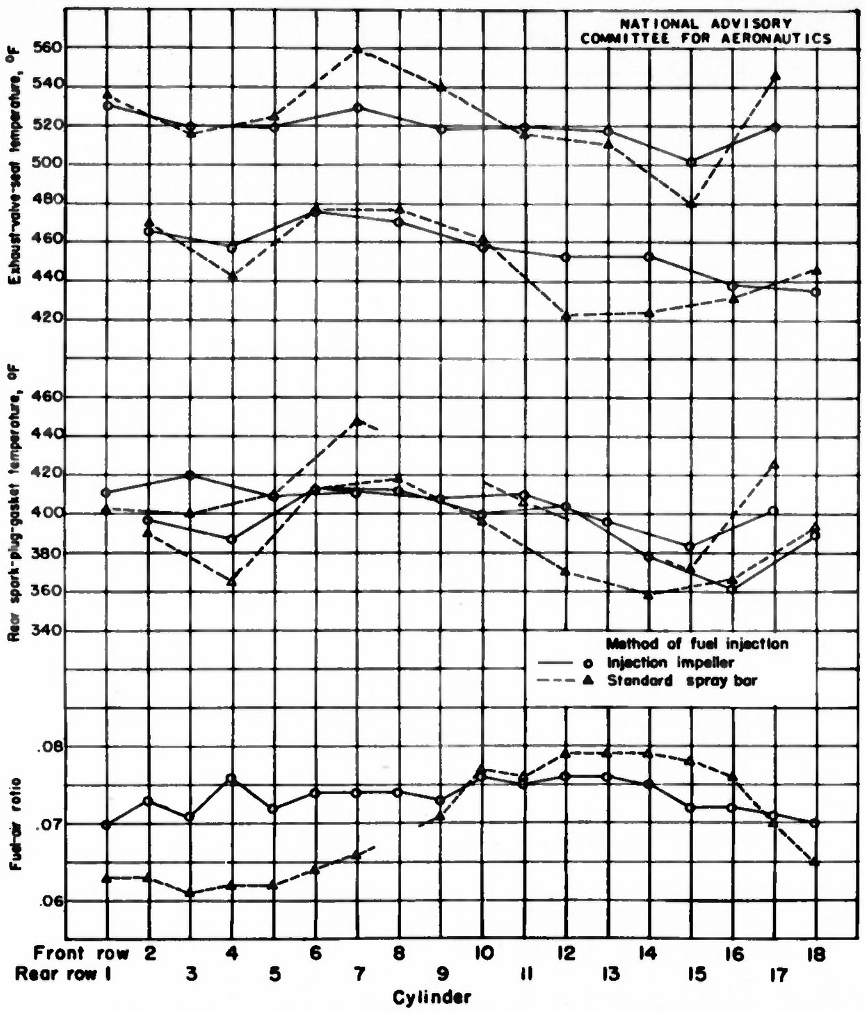
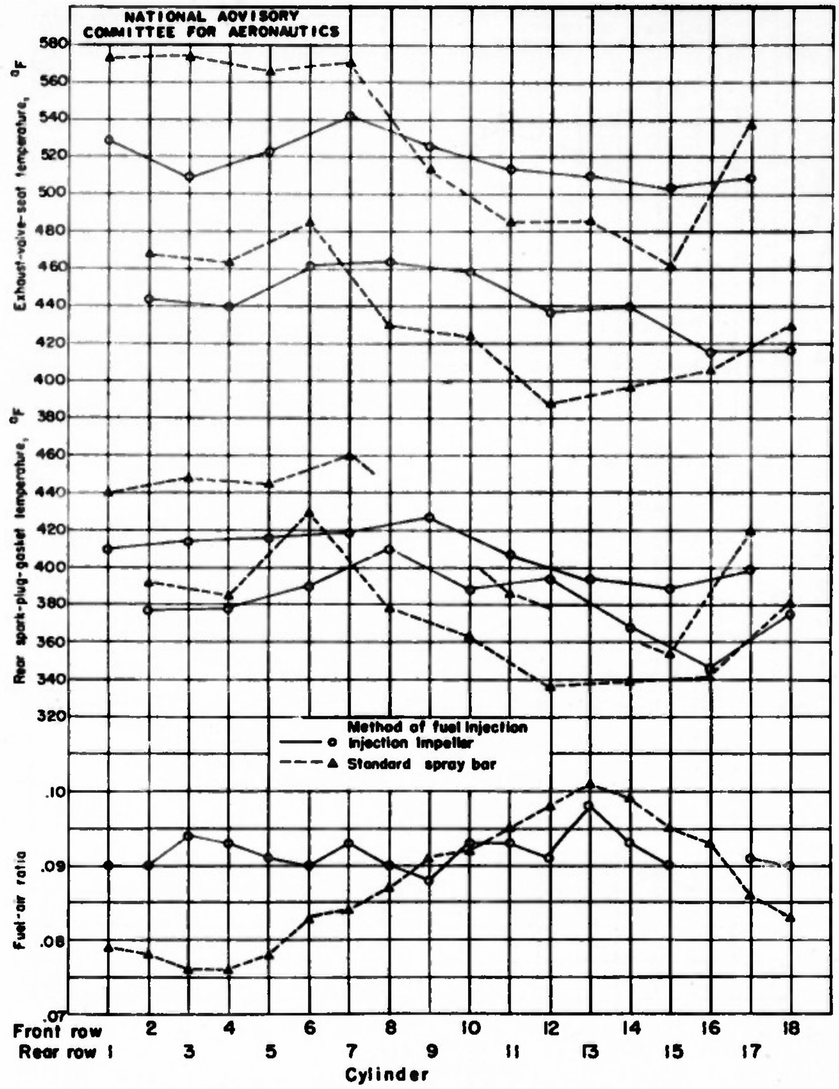


Figure 7.— Effect of NACA injection impeller on mixture distribution of engine at reduced fuel flows.



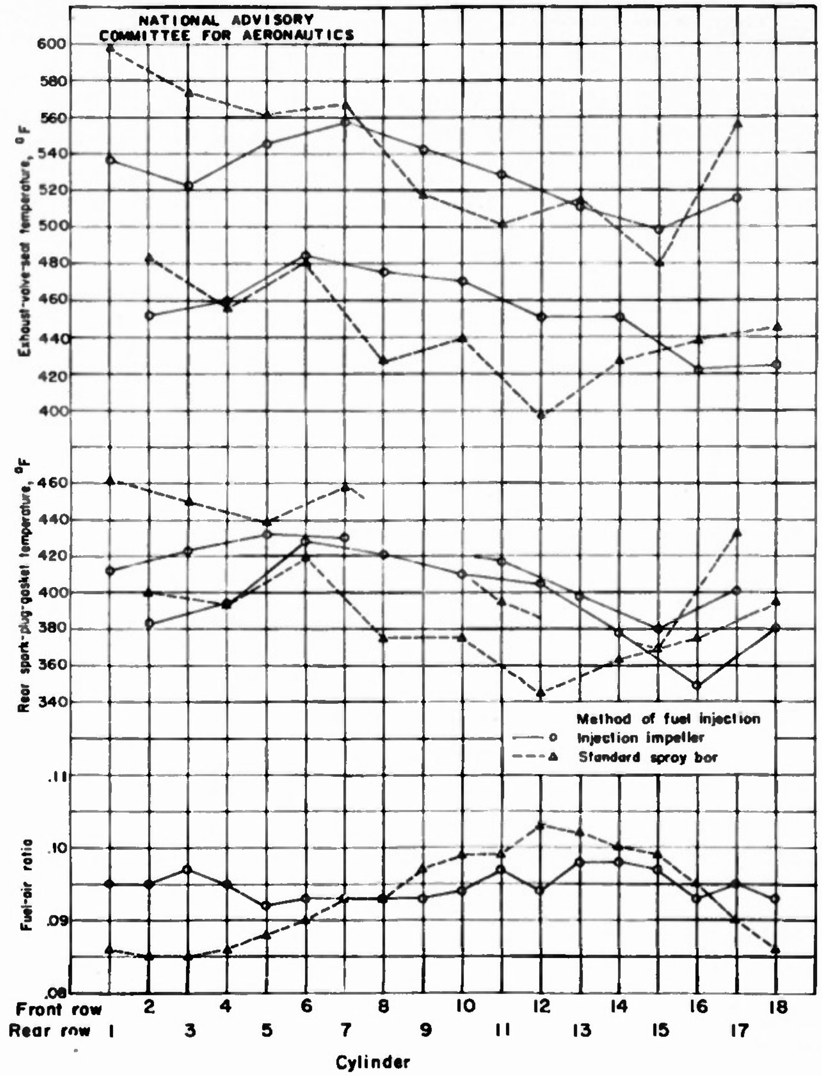
(a) Brake horsepower, 1200; engine speed, 2000 rpm.

Figure 8.— Comparison of temperature distributions for engine using standard spray bar and for engine modified by use of the NACA injection impeller.



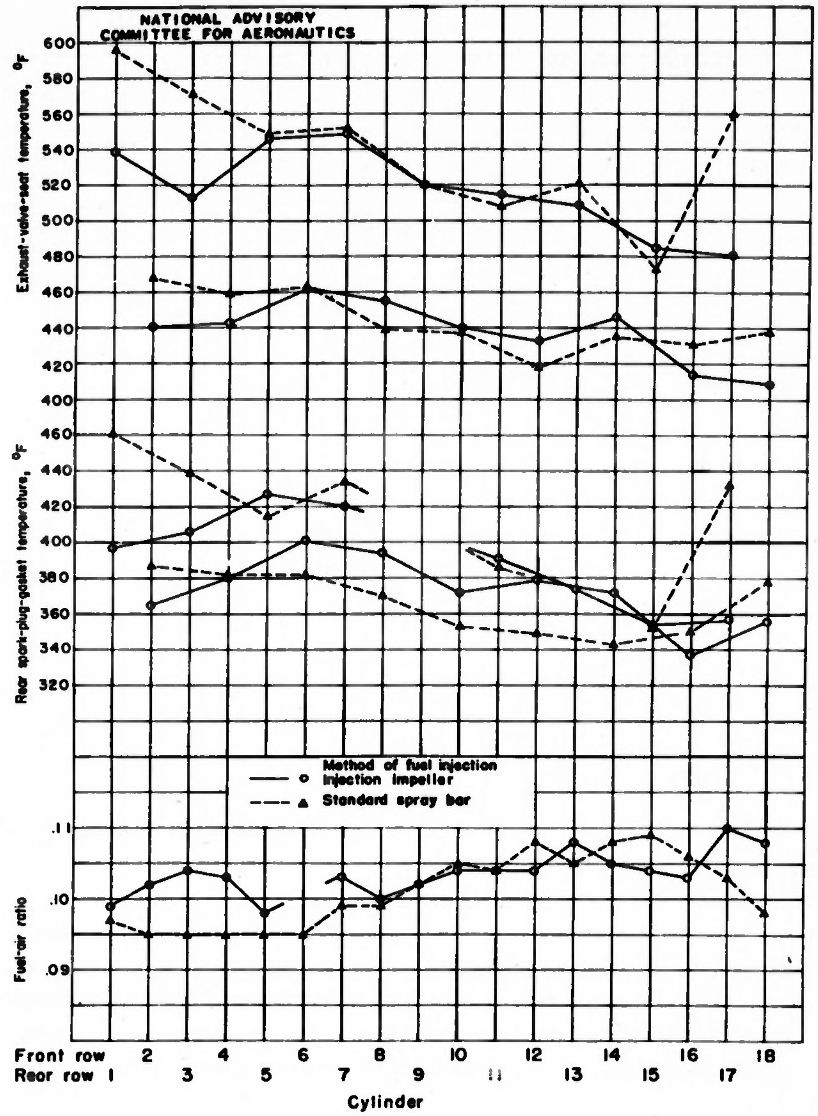
(b) Brake horsepower, 1500; engine speed, 2200 rpm.

Figure 8.— Continued.



(c) Brake horsepower, 1700; engine speed, 2300 rpm.

Figure 8.—Continued.



(d) Brake horsepower, 2000; engine speed, 2400 rpm.

Figure 8.— Concluded.

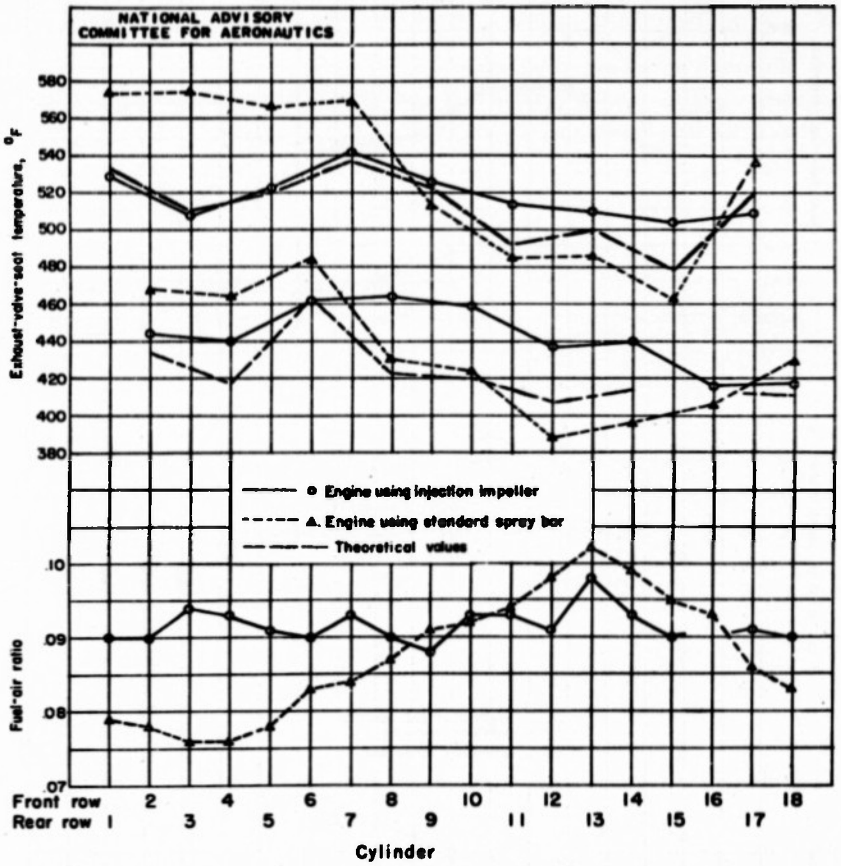


Figure 9.— Comparison of temperature distributions for engine using standard spray bar and engine modified by use of the NACA injection impeller with theoretical temperature distribution computed from standard-engine data and observed improvements in mixture distribution. Brake horsepower, 1500; engine speed, 2200 rpm.

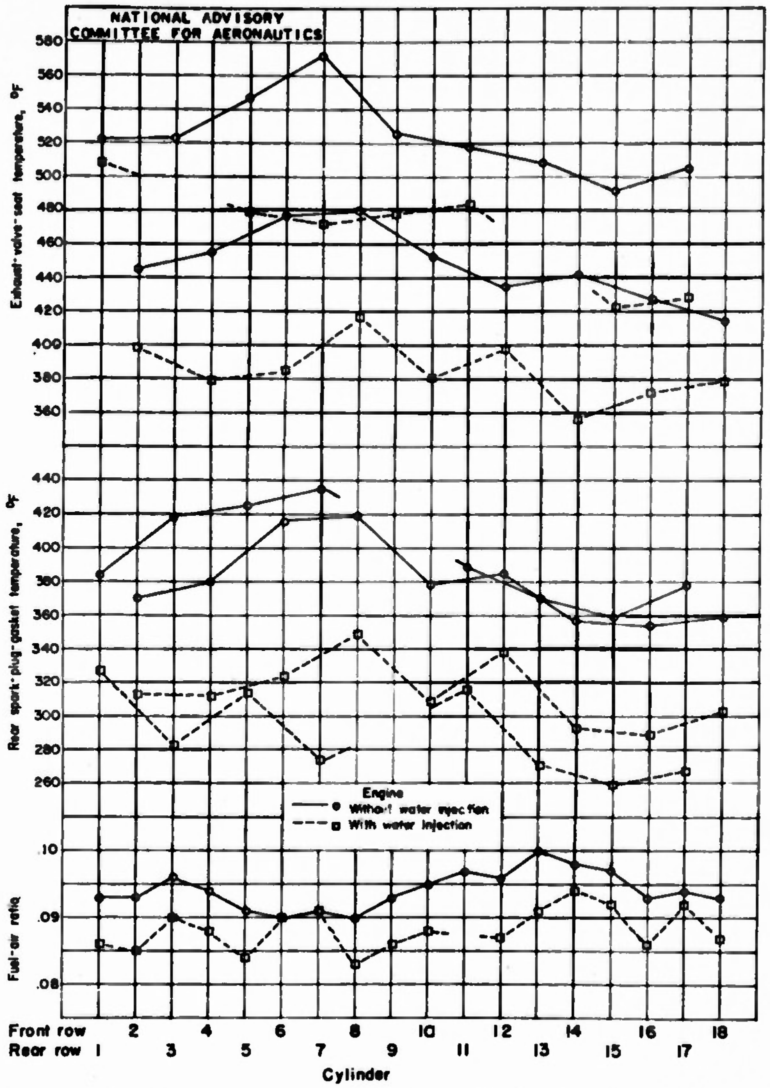


Figure 10.—Comparison of temperature distributions for engine modified by use of the NACA injection impeller with and without water injection. Brake horsepower, 1700; engine speed, 2300 rpm; water-fuel ratio, 0.5.

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ABSTRACT:

For the normal range of engine power the impeller provided marked improvement over the standard spray-bar injection system. Mixture distribution at cruising was excellent, maximum cylinder temperatures were reduced about 30°F, and general temperature distribution was improved. The uniform mixture distribution restored the normal response of cylinder temperature to mixture enrichment and it reduced the possibility of carburetor icing, while no serious loss in supercharger pressure rise resulted from injection of fuel near the impeller outlet. The injection impeller also furnished a convenient means of adding water to the charge mixture for internal cooling.

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SECTION: Induction and Supercharging (2)

SUBJECT HEADINGS: Superchargers, Centrifugal (91007); Impellers, Fuel injection (50936); Impellers - Performance (50933.7)

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⊛ AIRCRAFT CARBURETORS

IMPELLERS