MR No. E5D19

E 192

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

April 1945 as
Memorandum Report E5D19

CHARACTERISTICS OF THE BMW 801D2 AUTOMATIC ENGINE CONTROL AS DETERMINED FROM BENCH TESTS

By M. E. Scharer and A. N. Addie

Aircraft Engine Research Laboratory
Cleveland, Ohio

NACA

WASHINGTON

E-192

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Army Air Forces, Air Technical Service Command

CHARACTERISTICS OF THE BMW 801D2 AUTOMATIC ENGINE CONTROL AS DETERMINED FROM BENCH TESTS

By M. E. Scharer and A. N. Addie

SUMMARY

The hydraulically operated, automatic engine-control system from a German BMW 801D2 aircraft engine was bench-tested to determine the relations between the control parameters and any special methods by which the control principles are adapted to the control of the engine. Characteristics are presented for a full range of simulated manifold pressures, charge-air temperatures, and engine speeds for altitude pressures corresponding to altitudes ranging from approximately 1000 to 36,000 feet above sea level. The function and the operating characteristics of the manifold-pressure control, the supercharger gear-ratio control, the propeller-pitch control, the mixture control, and the spark-advance control are analyzed on the basis of test results and calculated engine air flow. The relations between the control parameters are graphically presented. The pressure characteristics of the servo-oil system are discussed with respect to the effective ceiling of this automatic engine control, and an analysis is given of the operation of the automatic engine-control system in the event of failure of the servo-oil system.

INTRODUCTION

The introduction of the variable-pitch propeller, the development of modern supercharging techniques, and the application of the relations existing between the various engine variables to obtain optimum performance have so complicated the control of an aircraft power plant that it has become almost impossible to obtain efficiently the desired power-plant performance under all conditions of flight by manual control. This problem is especially serious in military aviation where optimum performance with minimum attention to engine controls is necessary. The necessity of providing an easily operated automatic engine control for obtaining desired power-plant performance by proper correlation of the engine variables has consequently become recognized.

An automatic engine control known to be in military service is the hydraulically operated type mounted on the German BMW 801 series of aircraft power plants. This control by means of a single lever in the pilot's cockpit selects manifold pressure, engine speed, fuel-air ratio, spark advance, and supercharger gear ratio in accordance with the correlation of the engine variables necessary to produce the desired performance.

At the request of the Army Air Forces, Air Technical Service Command, bench tests were conducted at the Cleveland laboratory of the NACA during 1944 to determine the operating characteristics of the automatic-control system of a BMW 801D2 engine. Particular emphasis was placed on the determination of the relations between the control parameters and of any special methods by which the control principles are adapted to the control of the engine.

APPARATUS

The control unit (Mfr. No. 7653) used in the present investigation is from a BMW 801D2 engine (Mfr. No. 304068) and was received with seals intact. This unit together with the accessory pad was removed from the engine and was mounted for bench tests under simulated operating conditions of the engine. A functional diagram of the control system is presented in figure 1; detailed diagrammatic sketches of the control system are shown in figures 84(a) and 85 of reference 1. The control system and the apparatus necessary for the bench tests are schematically shown in figure 2. Figure 3 presents photographs of the test setup. The mechanical construction and the movement of the various linkage systems in the type of control system investigated are described in reference 2 (pp. 293-299).

TEST PROCEDURE

Manifold-pressure control. - Manifold pressure was varied at predetermined settings of the main-servocontrol lever (that is, the lever on side of control which transmits motion of single lever in cockpit to power amplifier in control unit) when the manifold-pressure control was tested. By this procedure the range of manifold pressures and the range of positions of the supercharger intake-air throttles corresponding to a particular position of the main-servocontrol lever could be determined. Closing of the supercharger intake-air throttles indicated the upper limit of the range of operating manifold pressures; opening of the throttles indicated the lower limit.

Supercharger gear-ratio control. - In order to determine the altitude at which the change in gear ratio of the supercharger occurred, altitude pressure was changed at various positions of the main-servocontrol lever. Altitude pressure was varied at a rate corresponding to an altitude rate of change of 3000 to 4000 feet per minute. During the test, the gear-ratio control was allowed to remain at ambient temperatures, which were approximately the same as the temperatures that would exist in the accessory compartment during flight.

Propeller-pitch control. - The load indication of the constant-speed governor of the propeller-pitch control was obtained for each position of the main-servocontrol lever by means of a calibrated position indicator.

Mixture control. - Bench tests were conducted at constant manifold pressures with varied altitude pressure and charge-air temperature to determine the operating characteristics of the mixture control below the critical altitude. Operating characteristics of the mixture control above the critical altitude were determined by varying the manifold pressure and the charge-air temperature at constant altitude pressures.

The position of the fuel-metering indicator was recorded for each test condition. The fuel flow was then calculated for each position of the fuel-metering indicator from figure 4, which was obtained from bench tests of the fuel-injection pump conducted at the Cleveland laboratory of the NACA.

According to information in the FW 190 A-1, A-2, A-3 Manual (Air Ministry Trans., A.I.2(g), June 7, 1943), the change from lean to rich mixture occurs at an engine speed of 2150 rpm. The position of the main-servocontrol lever has no bearing on the action of the mixture control other than to establish a lean-mixture or a rich-mixture setting or to effect a quick cut-off of the fuel-injection pump. For engine speeds less than 2150 rpm the main-servocontrol lever was therefore kept in a lean position; for engine speeds greater than 2150 rpm the main-servocontrol lever was kept in a rich position.

Air flow for various engine operating conditions was calculated on the basis of charge-air density, engine speed, and a constant volumetric efficiency (assumed to be 95 percent). The charge-air temperature was determined from calculation of the temperature rise through the supercharger. The symbols used for the air-flow calculations are listed in appendix A; the method of calculations is given in appendix B.

Spark-advance control. - Spark advance was obtained for various positions of the "advance-retard" control rack. A position indicator was calibrated in terms of control-rack travel, which made it possible to obtain spark advance for all simulated operating conditions of the engine.

PRECISION

The position indicators were so calibrated that errors in the readings of position were limited to the following values:

Supercharger intake-air throttles, degree	± 0.5
Fuel-metering indicator, degree	± 0.5
Spark advance, degree	± 0.13
Load indication of the constant-speed governor, scale division	± 0.53

Manifold and altitude pressures were maintained within ± 0.05 inch of mercury. The error in readings taken while pressure was being varied was estimated to be ± 0.1 inch of mercury.

Charge-air temperatures were maintained within $\pm 4^\circ$ F of the desired values.

The position of the main-servocontrol lever was maintained within $\pm 0.1^\circ$.

RESULTS OF TESTS AND DISCUSSION OF CHARACTERISTICS

Manifold-Pressure Control

The function of the variable-datum, manifold-pressure control is to maintain the manifold pressure that corresponds to a particular engine speed and related power output up to the cricical altitudes of the supercharger. The relation between engine speed and manifold pressure, shown in figure 5, was derived from operating curves of a BMW 801D2 engine that were furnished by the Engineering Division, Materiel Command, Army Air Forces. Above the critical altitude, manifold pressure at any particular engine speed decreases directly with altitude-density ratio, as shown in figure 6. The curves were obtained from the relation between engine speed and manifold pressure given in figure 5 and from the solution of equation (6), derived in appendix B.

The relation shown in figure 5 is maintained by controlling the position of the supercharger intake-air throttles through a combination linkage that allows control of throttle position by the setting of the main-servocontrol lever and by the manifold-pressure control. The position of the main-servocontrol lever determines the range through which the manifold-pressure control can vary the setting of the throttles. The curves in figure 7 indicate the range of possible throttle settings for each position of the main-servocontrol lever as limited by the part of the combination linkage that is actuated by the main-servocontrol lever. The specific throttle setting for each position of the main-servocontrol lever is therefore determined by the manifold-pressure control.

For any position of the throttles within the range shown in figure 7, manifold pressure (for any particular position of the main-servocontrol lever) can vary through the range of values shown in figure 8. This feature was incorporated in the manifold-pressure control by the design of the servopiston control valve in order to prevent fluctuation of the throttles when extremely small changes in manifold pressure occur.

A diagram of the manifold-pressure control with the control valve in the equilibrium position is shown in figure 9. (Information for this figure was obtained when BMW 801D2 engine control No. 7393 was disassembled. The oil passages are shown in fig. 9.) The condition of equilibrium requires that the pressure force plus the control-valve-spring force be equal and opposite to the capsule-stack spring force when the ports of the servo-oil system, shown at the right of the control valve in figure 9, are covered by the control-valve lands. Any disturbance of equilibrium will cause a change in throttle position and a consequent change in manifold pressure until equilibrium is again established. The manifold pressure at which equilibrium is reached can be varied by changing the datum of the capsule stack; therefore, because the capsule-stack-datum position is some function of the main-servocontrol-lever position, a definite manifold pressure is developed for each position of the main-servocontrol lever. (See reference 2, p. 297, for description of the linkage connecting the capsule stack and the main-servocontrol lever.)

The solid curve in figure 10 shows the variation of manifold pressure with main-servocontrol-lever position for the control system investigated. This curve is displaced 2.8° to the left of the corresponding curve plotted from data furnished by the Army Air Forces, Materiel Command. This displacement was made because, in a preliminary investigation, the position of the main-servocontrol lever at which the mixture changed from lean to rich was observed to differ 2.8° from that shown on the curve received from the Army Air Forces. The FW 190 A-1, A-2, A-3 Manual states, "The change over 'Weak to rich' when opening throttle lever [main-servocontrol lever] is marked at a position corresponding to p_2 = 1.14 ata [p_2 is manifold pressure and 1 ata equals 1 kg/cm^2] and 2150 revs., by a fall in boost of 0.05 ata." The assumption was made, therefore, that the position of the main-servocontrol lever at which the control system tested changed from a lean-mixture to rich-mixture setting corresponded to these specifications of manifold pressure and engine speed. The 2.8° displacement resulted in a change in the relation between engine speed and main-servocontrol-lever position but the relation between engine speed and manifold pressure shown in figure 5, which is the basis for the tests, was unaffected.

The fall in manifold pressure of 0.05 ata is necessary to compensate for a slight increase in output that accompanies the mixture change from lean to rich. This sudden change in manifold pressure is effected by the manifold-pressure compensating mechanism described in reference 2 (p. 298).

During the investigation it was noted that the mixture change from rich to lean occurred at a main-servocontrol-lever setting 2.8° lower than the mixture change from lean to rich. The FW 190 A-1, A-2, A-3 Manual states, "'Rich to weak' when closing throttle [main-servocontrol lever], with a throttle-lever setting corresponding to p_2 = 1.09 ata and 2150 revs., is recognizable by an increase in boost of 0.05 ata." This increase in manifold pressure is necessary to compensate for a slight decrease in power output that accompanies a change from a rich-mixture to a lean-mixture setting. Figure 11 shows the 2.8° lag in the position of the main-servocontrol lever when the mixture changes from rich to lean. This lag is an unavoidable result of the design of the servomechanism that causes the sudden change in mixture ratio and the simultaneous compensation in manifold pressure.

Figure 11 also shows that, for corresponding positions of the main-servocontrol lever, operating manifold pressures are slightly higher when the position of the lever is being decreased than when the position of the lever is being increased. This difference in resulting manifold pressures is caused by a lag in the linkage that positions the datum of the capsule stack of the manifold-pressure control.

A discrepancy will be noted between the curves of figure 8 and the solid curve of figure 10. Because the relation between engine speed and manifold pressure shown in figure 5 compares favorably with data given in a translated German report (reference 1, p. 10), it is thought that the discrepancy between the two curves is probably the result of a maladjustment in the linkage that controls the capsule-stack datum of the manifold-pressure control.

Supercharger Gear-Ratio Control

Figure 12 shows the effect of altitude-density ratio on calculated air flow. (The method of calculating air flow is given in appendix B.) On the assumption that air flow at a particular engine speed is an index of indicated power output, figure 12 shows the trend of indicated power output as affected by altitude-density ratio. If the gear ratio of the supercharger is changed when the critical altitude of the supercharger in low gear is reached, an undesirable abrupt decrease in brake power output will result because of the decrease in air flow and because of the simultaneous increase in the power required to drive the supercharger in high gear. (The decrease in air flow is caused by the increased charge-air temperature that accompanies increased impeller-tip speeds.) When the supercharger is allowed to operate above the critical altitude in low gear, brake power output decreases gradually and the maximum brake power output at each particular engine speed and altitude can be obtained. Maximum power can be obtained in this manner until a change in gear ratio of the supercharger causes a sufficiently large increase to offset the additional power necessary to drive the supercharger in high gear. The function of the supercharger gear-ratio control is, therefore, to change the gear ratio at the particular altitude that will allow maximum performance to be obtained at all altitudes and to eliminate undesirable abrupt changes in power at the altitude at which the gear ratio of the supercharger is changed.

The change in gear ratio of the supercharger occurs at one definite position of a control valve that is actuated by a variable-datum capsule stack through a spindle and a rocker-arm shaft. (See fig. 13, which was drawn from information obtained when BMW 801D2 engine-control unit No. 7393 was disassembled.)

The movement and consequent position of the control valve are directly proportional to the sum of the displacement of the variable datum and the displacement of the spindle relative to the variable datum. The displacement of the variable datum is caused by a change in the position of the main-servocontrol lever. Because of the definite relation between the position of the main-servocontrol lever and engine speed, the change in gear ratio may be considered as a function of engine speed. The displacement of the spindle relative to the variable datum is effected by a change in altitude pressure on the capsule stack. (See fig. 13.) Because the change in gear ratio occurs at a fixed position of the control valve, the sum of the displacement of the variable datum and the relative displacement of the spindle necessary to produce the change is a constant. An increase in the displacement of the variable datum, resulting from an increase in the position of the main-servocontrol lever, therefore causes the change in gear ratio to occur at a lower altitude.

Figure 14 shows the relation between engine speed and the altitude at which the change in gear ratio occurs. Figure 14 also indicates that the supercharger can be driven in high or low gear throughout a range of approximately 5200 feet. An examination of the control valve and its sleeve showed that the width of the control-valve lands exceeded the width of the two ports in the sleeve by 0.020 inch for one port and 0.019 inch for the other. This feature is incorporated in the supercharger gear-ratio control by the design of the control valve in order to prevent changes in gear ratio when the airplane is flying at an altitude near that at which the change occurs. Positive changes in gear ratio are assured by the action of the shuttle valve (fig. 13), which allows maximum oil pressure to be instantaneously exerted when the control valve reaches the position at which the change in gear ratio should occur.

Displacement of the capsule stack was unaffected by changes in temperature because the capsules were evacuated to a pressure of approximately 3 inches of mercury absolute.

Propeller-Pitch Control

The purpose of the propeller-pitch control is to regulate engine speed by control of a variable-pitch propeller in such a way that the desired relation between engine speed and manifold pressure (fig. 5) can be maintained up to the critical altitude. The FW 190 A-1, A-2, A-3 Manual states that the maximum permissible variation from this relation owing to tolerance in the setting of the control unit is ±30 rpm.

Engine speed is maintained constant by means of a fly-ball governor and an incorporated servopiston valve. The loading of the governor is determined by the position of the main-servocontrol lever. For each governor loading, propeller pitch will vary through a range of values; the exact propeller pitch depends on airspeed and air density. The correlation of the propeller-pitch setting with the load indication of the constant-speed governor was not obtained because no actual engine and propeller tests were conducted.

An appreciable lag in the load indication of the constant-speed governor occurs when the position of the main-servocontrol lever is decreased. (See fig. 15.) This lag is caused by play in the encased flexible cable connecting the control unit with the constant-speed governor. Because the constant-speed-governor loading is an indication of engine speed, this lag signifies that engine speeds for decreasing positions of the main-servocontrol lever are higher than those obtained for corresponding increasing positions of the main-servocontrol lever. Figure 15 also shows the range through which the constant-speed governor may be loaded by a manually operated lever that overrides the automatic control. (See reference 1, p. 18 for an explanation of the mechanism that overrides the automatic control.)

Mixture Control

The mixture control, diagrammatically shown in figure 16, provides the engine with the fuel-air ratios necessary to obtain the desired engine performance. The design of this control appears to be based on a relation of parameters similar to that given in reference 3. Movement of the capsule stack (resulting from changes in manifold pressure, charge-air temperature, and altitude pressure) causes the follow-up lever to rotate about the point of contact between the follow-up lever and the cam, thereby displacing the control valve. This displacement opens one side or the other of the servopiston to oil pressure, causing it to rotate the plungers in the fuel-injection pump by means of a linkage system and thus causing the quantity of fuel metered by the pump to vary. Movement of the servopiston causes rotation of the cam, which through action of the follow-up lever returns the control valve to the equilibrium position and stops oil flow and consequent movement of the servopiston. The contour of the cam is such that for every position of the capsule stack the servopiston has a corresponding position. The capsule stack therefore regulates fuel flow according to variations in the density of the charge air and according to variations in volumetric efficiency caused by changes in altitude pressure. Regulation of fuel flow on the basis of the relation between volumetric efficiency and engine speed is probably accounted for either in the speed-delivery characteristic of the fuel-injection pump or in the design of the contour of the cam.

Calculated fuel-air ratios for low-gear and high-gear operation are presented in figures 17 and 18, respectively. Fuel-air ratios were determined from experimental fuel-flow data and calculated air flow. These calculated fuel-air ratios approximate cruising fuel-air ratios obtainable in conventional carburetor-type engines operating with the automatic-lean setting. The mixture control has no setting that provides fuel-air ratios in the cruising range that compare with the ratios provided by the automatic-rich setting of conventional carburetor-type engines. Figure 19 shows that fuel flow increases with an increase in manifold pressure both below and above the critical altitude of the supercharger. Below the critical altitude, fuel flow increases with a decrease in altitude-density ratio; whereas, above the critical altitude, a decrease in altitude-density ratio produces a corresponding decrease in fuel flow. (See fig. 20.)

The trends of the fuel-flow curves (figs. 19 and 20) compare favorably with those of the air-flow curves (figs. 21, 22, and 12), showing that fuel is metered in accordance with air flow and that relatively constant fuel-air ratios in the cruising range are thus maintained. The principal purpose of the mixture control in the cruising range (1450 to 2150 rpm), therefore, appears to be the maintenance of maximum fuel economy for the desired range of power output. The mixture control seems to accomplish this objective below the critical altitudes of the supercharger when the supercharger is in either low or high gear. Mixture control also appears satisfactory above the critical altitude when the supercharger is in low gear. For cruising speeds above the critical altitude in high gear, however, the mixture control functions less satisfactorily because the width of the band of controlled fuel-air ratios is greater than that obtained during operation in the three conditions previously mentioned.

At an engine speed of 2150 rpm and a corresponding manifold pressure of 32.9 inches of mercury absolute, the mixture changes abruptly from lean to rich, which is desirable because operation at uneconomical transitional fuel-air ratios is obviated and economical operation over a wide range of cruising speeds is permitted. This change is accomplished by a special servomechanism that is actuated at a particular position of the main-servocontrol lever. (Reference 2, p. 298, describes the linkage that causes the change-over.)

The mixture control in the power range (2150 to 2465 rpm) provides fuel-air ratios that are sufficiently rich to insure the desired power outputs and that approximate the fuel-air ratios utilized in power-range operation of conventional carburetor-type engines. Fuel-air ratios are maintained that permit correspondingly high manifold pressures without detonation and without excessively high cylinder temperatures. Fuel-air ratios in the power range with the supercharger in low gear vary between 0.092 and 0.113. (See fig. 17.) When the supercharger is in high gear, the control of fuel-air ratio is more erratic; values ranging from 0.103 to 0.130 are obtained for altitudes below the critical altitude of approximately 21,000 feet. Above the critical altitude, the fuel-air ratios are limited to a range between 0.096 and 0.116. (See fig. 18.) The effect of manifold pressure and altitude-density ratio on fuel flow during power operation is shown in figures 19 and 20, respectively.

Although the mixture control was designed to compensate for changes in charge-air temperature in order to maintain an approximately constant fuel-air ratio at a given engine speed and manifold pressure, variation from 100° to 275° F produced no discernible effect on fuel flow. Consequently, the increase in charge-air temperature accompanying the change in supercharger gear ratio from low to high caused the fuel-air ratios for high-gear operation to be richer than those for low-gear operation. (See figs. 17 and 18.)

Spark-Advance Control

The function of the continuous spark-advance control is to time ignition in order that maximum permissible power with minimum specific fuel consumption is obtained at a given manifold pressure and fuel-air ratio without resulting in detonation and excessively high cylinder temperatures. The degree of spark advance is determined by the position of the mixture-control spindle, which indicates that spark advance is mainly dependent upon fuel-air ratio and manifold pressure.

The effect of manifold pressure on spark advance is shown in figure 23. Idling and starting range is characterized by a retarded spark for easy starting and smooth running at low speeds. The cruising range requires an advanced spark to attain maximum fuel economy when the engine is operating at lean mixtures. As manifold pressure increases, however, the spark must be retarded to prevent detonation. The change from cruising to power mixtures is accompanied by a sudden retarding of the spark to allow for the increased manifold pressure and charge-air temperatures in the power range. Below the critical altitude in the power range, the spark advance remains constant at an intermediate position. Above the critical altitude, however, the decrease in manifold pressure permits an increase in spark advance without the danger of detonation.

Servo-Oil System

When the servo-oil system was subjected to altitude pressures corresponding to altitudes above 24,000 feet, the discharge pressure of the servo-oil pressure pump dropped below the minimum pressure observed (approx. 100 lb/sq in. absolute) to be necessary for efficient control operation. Figure 24 shows the effect of altitude on the discharge pressure of the servo-oil pressure pump. Above 24,000 feet, the rate at which the servo-oil pressure decreased was approximately 12.5 pounds per square inch per 1000-foot increase in altitude. At 32,000 feet, the oil pressure was virtually zero.

The discharge pressure of a gear pump is reduced approximately in proportion to the volumetric percentage of entrained air and vapor in the oil at the inlet port of the pump. When the oil system was subjected to an altitude pressure of 8.1 inches of mercury absolute (corresponding to an altitude of 32,000 ft), the volumetric percentage of entrained air and vapor increased to such an extent that the discharge pressure was virtually zero. This effect would cause sluggish operation or complete failure of the automatic-control system at altitudes from 24,000 to 32,000 feet, depending upon the oil pressure obtainable. The pressure characteristics of the servo-oil system are, therefore, a factor limiting the effective ceiling of this automatic engine control.

Emergency Control

If failure of the servo-oil system occurs, the automatic engine control can provide limited manual control over throttle position for emergency operation of the engine at cruising powers. Emergency control over propeller pitch is also provided by an electrical propeller-pitch control, which is manually operated. The electrical propeller-pitch control, however, does not provide automatic regulation of the propeller pitch for constant-speed operation of the engine.

When failure occurs, the throttles will seek a position along the lower curve of figure 7. The exact throttle angle will fall between 0° and 23° from the closed position, depending upon the setting of the main-servocontrol lever at the time of failure. The throttles can also be manually set at any point on the lower curve of figure 7 by mechanical force through the same linkage that hydraulically actuates the throttles.

When failure occurs, a spring-loaded piston in the servomechanism of the mixture control positions the fuel-injection pump to meter sufficient fuel for emergency operation of the engine. Fuel quantities delivered for engine speeds from 1450 to 2465 rpm vary from 295 to 710 pounds per hour.

Because the degree of spark advance is dependent upon the position of the mixture-control spindle, spark advance will be determined by the range in which the engine is operating when failure occurs. Thus, if failure occurs in the cruising range, spark advance will be changed to approximately 31° B.T.C.; if failure occurs in the power range, spark advance will be changed to approximately 26° B.T.C. In case of failure of the servo-oil system, the supercharger will remain in the gear ratio in which it was operating when failure occurred.

SUMMARIZATION OF CHARACTERISTICS

The following characteristics were determined from bench tests of the automatic engine-control system from a German BMW 801D2 engine and calculated engine air flow. The control system was tested under simulated manifold pressures (12 to 39 in. Hg absolute), charge-air temperatures (100° to 275° F), and engine speeds (1150 to 2465 rpm) for altitude pressures corresponding to altitudes ranging from approximately 1000 to 36,000 feet above sea level.

Manifold-Pressure Control

1. Below the critical altitudes of the supercharger, manifold pressure is a function of engine speed. Above the critical altitudes, manifold pressure is a function of engine speed and altitude-density ratio.

2. At any particular position of the main-servocontrol lever and the corresponding engine speed, the design of the servocontrol valve allows manifold pressure to vary through a small range, which eliminates fluctuation of the throttles and thereby improves stability of the manifold-pressure-control system.

3. The variable-datum capsule stack is a simple, positive, and easily adjustable means for obtaining the desired relation between engine speed and manifold pressure.

4. The manifold pressure compensating device, as designed, provides an effective means of eliminating the undesirable abrupt changes in power output that would otherwise accompany the sudden changes in mixture strength.

5. In the event of failure of the servo-oil system, the combination linkage permits limited manual control of throttle position allowing sufficient air flow for emergency operation of the engine at reduced output.

Supercharger Gear-Ratio Control

1. The change in gear ratio of the supercharger is a function of engine speed and altitude pressure.

2. Because the supercharger is allowed to remain in low gear when the aircraft is gaining altitude above the critical, maximum performance for any particular engine speed can be obtained and abrupt changes in power output when the gear ratio changes can be eliminated.

3. The variable-datum capsule stack provides a simple, positive, and easily adjustable means of obtaining the desired relation between engine speed and the altitude at which it is necessary to change the gear ratio of the supercharger.

4. Undesirable fluctuation between the gear ratios of the supercharger is eliminated by the design of the control valve, which provides a range of altitudes in which the supercharger can operate in either low or high gear. Because this range of altitudes is excessive, the altitude at which the supercharger changes from high to low gear is much lower than the optimum altitude for the gear change. Consequently, undesirable abrupt changes in power are experienced and less than maximum performance at any particular engine speed is obtained at all altitudes when the aircraft is losing altitude.

5. If failure of the servo-oil system occurs, loss of control over the selection of the supercharger gear ratio will result. The supercharger will remain in the gear in which it was operating when failure occurred.

Propeller-Pitch Control

1. Because the loading of the constant-speed governor determines engine speed, the lag in the loading caused by the lag in movement of the encased flexible cable signifies that the desired relation between engine speed and manifold pressure cannot be maintained.

2. In case of failure of the servo-oil system, engine speed can be regulated by an electric propeller-pitch control.

Mixture Control

1. The mixture control is designed to meter fuel to the engine in accordance with some function of manifold pressure, altitude pressure, and charge-air temperature. Laboratory bench tests, however, showed that changes in charge-air temperature had no effect on fuel flow.

2. The mixture control fulfills its purpose for all engine operating contitions except when the altitude is increasing or decreasing in the cruising range with the supercharger operating in high gear above the critical altitude.

3. The mixture control has no automatic-rich setting for cruising speeds as provided for conventional carburetor-type engines. The abrupt change from cruising to power mixtures eliminates operation at uneconomical transitional fuel-air ratios and provides a wide range of economical cruising speeds.

4. The control will meter sufficient fuel for emergency engine operation in case of failure of the servo-oil system.

Spark-Advance Control

1. Spark advance in the cruising range is a function of manifold pressure.

2. Below the critical altitude in the power range, spark advance is maintained constant. Above the critical altitude, spark advance is mainly dependent on manifold pressure.

3. If failure of the servo-oil system occurs, spark advance will be changed to approximately 31° B.T.C. when the engine is operating in the cruising range or to approximately 26° B.T.C. when the engine is operating in the power range.

Servo-Oil System

The effective ceiling of the automatic engine control is limited by the pressure characteristics of the servo-oil system. Tests indicated that the effective ceiling is between 24,000 and 32,000 feet.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, April 19, 1945.

APPENDIX A

SYMBOLS

A	area of intake duct, sq ft (0.171)
c_p	specific heat of normal air at constant pressure, ft-lb/lb °F (189.05)
D	diameter of cylinder bore, ft (0.5118)
g	ratio of absolute to gravitational unit of mass, lb/slug (32.174)
L	length of piston stroke, ft (0.5118)
N	engine speed, rpm
P	total pressure, in. Hg absolute
p_z	ram pressure at altitude, in. Hg absolute
p_o	ram pressure at standard air density, in. Hg absolute
Q_1/n	load coefficient, cu ft/impeller revolution
q_{ad}	pressure coefficient
R	gas constant for normal air, ft-lb/lb °F (53.30)
T	temperature, °F absolute (°F + 459.6)
V	impeller tip speed, fps
V_i	velocity of air in intake duct, fps
V_d	total engine displacement volume, cu ft/min
W	flow rate, lb/hr
C	number of cylinders (14)
γ	ratio of specific heat at constant pressure to specific heat at constant volume for normal air (1.3947)

ΔP pressure drop in intake duct, in. Hg

η_{ad} adiabatic temperature-rise ratio or adiabatic efficiency

η_v volumetric efficiency based on intake-manifold density

ρ_z standard air density at altitude, slug /cu ft

ρ_o standard density of dry air at 59° F and 29.92 in. Hg absolute, slug /cu ft (0.002378)

Subscripts:

1 condition at inlet of supercharger

2 condition at outlet of supercharger

z altitude

z_{cr} critical altitude

APPENDIX B

METHOD FOR CALCULATION OF ENGINE AIR FLOW

For every condition of manifold pressure and altitude to which the mixture control was subjected, engine air flow was calculated by assuming a constant volumetric efficiency of 95 percent based on existing manifold pressure and charge-air temperature.

Below the critical altitudes of the supercharger in low and high gear, manifold pressures corresponding to given engine speeds were obtained from figure 5. Charge-air temperature for each condition of manifold pressure and altitude pressure was obtained from the altitude temperature and a calculation of the temperature rise through the supercharger. Curves showing the relation between pressure coefficient q_{ad}, adiabatic temperature-rise ratio η_{ad}, and load coefficient Q_1/n were obtained from a Pratt & Whitney report entitled "Calibration of the B.M.W. 801D Supercharger," dated August 18, 1943. Values of altitude pressure and the corresponding altitude temperature were obtained from reference 4.

The pressure coefficient and adiabatic temperature-rise ratio for any particular load coefficient were assumed to be constant for altitudes up to 36,000 feet. The expressions for these parameters, which are derived in reference 5 (pp. 9-10), are as follows:

$$q_{ad} = \frac{c_p\, T_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{V^2/g} \qquad (1)$$

and

$$\eta_{ad} = \frac{T_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{T_2 - T_1} \qquad (2)$$

The air temperature at the outlet of the suprecharger can be expressed as a function of pressure coefficient, adiabatic temperature-rise ratio, and impeller-tip speed as follows:

$$T_2 = T_1 + \frac{q_{ad}}{\eta_{ad}} \times \frac{V^2}{c_p g} \tag{3}$$

The temperatures T_2 and T_1 are assumed to be equal to charge-air temperature and altitude temperature, respectively. (Impeller diameter is 13.3 in.; supercharger high and low gear ratios are 8.31:1 and 5.31:1, respectively.)

In the aforementioned Pratt & Whitney report, the operating value of the load coefficient Q_1/n is estimated to be 0.185 at a rated power of 1460 bhp, an altitude of 16,300 feet, and an engine speed of 2400 rpm. The value of q_{ad}/η_{ad} remains relatively independent of impeller-tip speeds through 1100 fps and relatively constant for the operating range of load coefficients. (See fig. 25.) A constant value of the ratio q_{ad}/η_{ad} can therefore be assumed without an appreciable error in the calculation of charge-air temperature. The value of q_{ad}/η_{ad} used in the calculations reported herein is 0.862.

An equation for engine air flow in terms of manifold pressure P_2, engine speed N, and manifold temperature T_2 is derived as follows:

$$\eta_v = \frac{\text{Wt. of air drawn into cylinder}}{\text{Wt. of air in displacement volume at charge-air density}}$$

The weight rate of air flow per hour can be determined from the formula:

$$W = \eta_v \times \frac{P_2 \, v_d}{R \, T_2} \times 60 \times 70.73$$

The volume of air displaced per minute is:

$$v_d = \frac{N}{2} \times \frac{\pi D^2}{4} \times L \times C$$

Therefore,

$$W = \frac{55.708\ P_2\ N}{T_2} \tag{4}$$

For each engine speed, the approximate atmospheric pressure at the critical altitude of the supercharger when operating in low or high gear can be calculated from the following equation, which relates ram pressure, controlled manifold pressure (see fig. 5), and the pressure drop through the intake duct:

$$P_{z_{cr}} = \Delta P - p_z + P_1 \tag{5}$$

Ram pressure at any altitude can be expressed as

$$p_z = p_o \frac{\rho_z}{\rho_o}$$

If an airspeed of 310 mph is assumed,

$$p_z = 3.48 \frac{\rho_z}{\rho_o}$$

Expressing ρ_z in terms of pressure and temperature

$$p_z = \frac{60.3\ P_z}{T_1}$$

The pressure drop in the intake duct was estimated to be one-fourth the velocity head. Thus, in inches of mercury:

$$\Delta P = \frac{1}{4} \times \frac{V_i^2}{2g} \times \frac{\rho_z g}{70.73}$$

The velocity V_i can be expressed as follows:

$$V_i = \frac{WR\ T_1}{3600 \times 70.73\ (P_z + p_z)\ A}$$

Substituting the values for V_i and p_z in the expression for ΔP,

$$\Delta P = \frac{(1.10 \times 10^{-10})\, W^2\, T_1}{p_z\left(1 + \dfrac{60.3}{T_1}\right)^2}$$

If equation (1) is solved for P_1, the following relation is obtained:

$$P_1 = \frac{P_2}{\left[\dfrac{V^2\, q_{ad}}{c_p g\, T_1} + 1\right]^{\frac{\gamma}{\gamma-1}}}$$

The substitution of the expressions for p_z, ΔP, and P_1 into equation (5) gives the following equation for determining the atmospheric pressure at the critical altitudes of the supercharger:

$$p_{z_{cr}} = \frac{(1.10 \times 10^{-10})\, W^2\, T_1}{p_{z_{cr}}\left(1 + \dfrac{60.3}{T_1}\right)^2} - \frac{60.3\, p_{z_{cr}}}{T_1} + \frac{P_2}{\left[\dfrac{V^2\, q_{ad}}{c_p g\, T_1} + 1\right]^{\frac{\gamma}{\gamma-1}}} \qquad (6)$$

Equation (6) is solved by the "trial and error" method, using assumed values for $p_{z_{cr}}$, W, and T_1. The critical altitude with the supercharger in high gear was calculated by using a Q_1/n value of 0.185 to determine q_{ad}; with the supercharger in low gear, an estimated value 0.213 was used. Calculations of critical altitude based on the foregoing estimated value of Q_1/n compare favorably with critical-altitude data given in reference 2 (p. 10).

Above the critical altitudes, the relation between engine speed and manifold pressure shown in figure 5 is invalid. It was necessary, therefore, to determine the relation between manifold pressure and altitude at each engine speed above the critical altitude. In order to obtain this relation, equation (6) was solved for P_2 with P_z substituted for $P_{z_{cr}}$.

$$P_2 = \left[P_z\left(1 + \frac{60.3}{T_1}\right) - \frac{(1.10 \times 10^{-10})\ W^2\ T_1}{P_z\left(1 + \frac{60.3}{T_1}\right)^2}\right]\left[\frac{V^2\ q_{ad}}{c_p g\ T_1} + 1\right]^{\frac{\gamma}{\gamma-1}} \tag{7}$$

Figure 6 shows the effect of altitude-density ratio on manifold pressure above the critical altitudes.

Air flow above the critical altitudes can be obtained by substituting in equation (4) a given engine speed, the corresponding manifold pressure at the altitude (from fig. 7), and the appropriate charge-air temperature (from equation (3)).

REFERENCES

1. Anon.: BMW 801 MA-ML-C-D Aircraft Engines. Trans. No. 376, Materiel Command, Army Air Forces, July 12, 1944. (From BMW Aircraft Engine Corp., Ltd., Munich Training Div.)

2. Anon.: Three German Engine Fuel Systems. Aircraft Engineering, vol. 15, no. 176, Oct. 1943, pp. 293-302.

3. Shames, Sidney J.: Air-Consumption Parameters for Automatic Mixture Control of Aircraft Engines. NACA ARR No. E4I23, 1944.

4. Brombacher, W. G.: Altitude-Pressure Tables Based on the United States Standard Atmosphere. NACA Rep. No. 538, 1935.

5. Ellerbrock, Herman H., Jr., and Goldstein, Arthur W.: Principles and Methods of Rating and Testing Centrifugal Superchargers. NACA ARR, Feb. 1942.

A Combination linkage
B Manifold-pressure control
C Supercharger gear drive
D Supercharger gear-ratio control
E Constant-speed governor
F Power amplifier
G Vent to atmosphere
H Vane-type servopiston
I Mixture-change and manifold-pressure compensating mechanism
J Single lever in cockpit
K Mixture control
L Fuel-injection pump (engine driven)
M Magneto (engine driven)

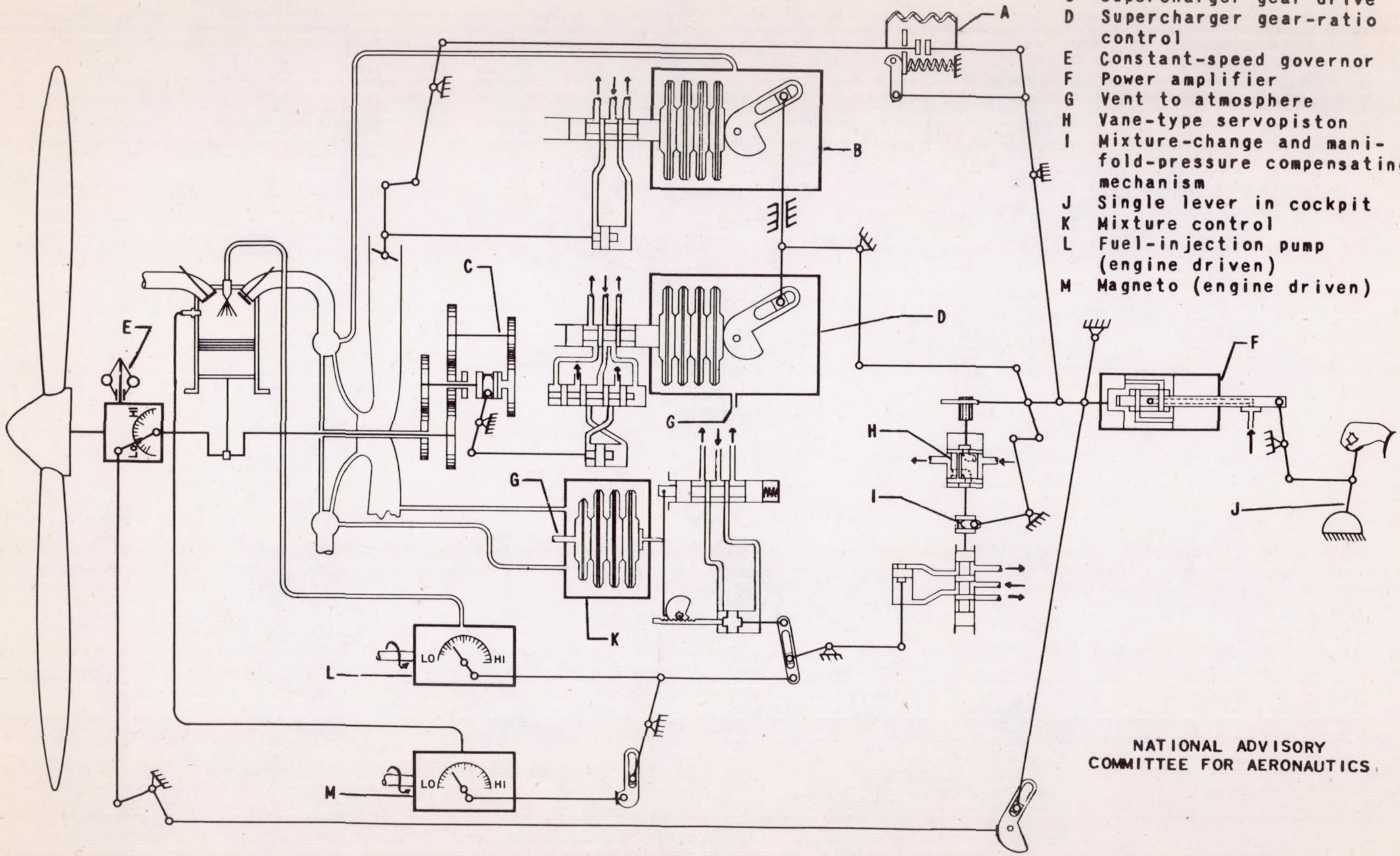
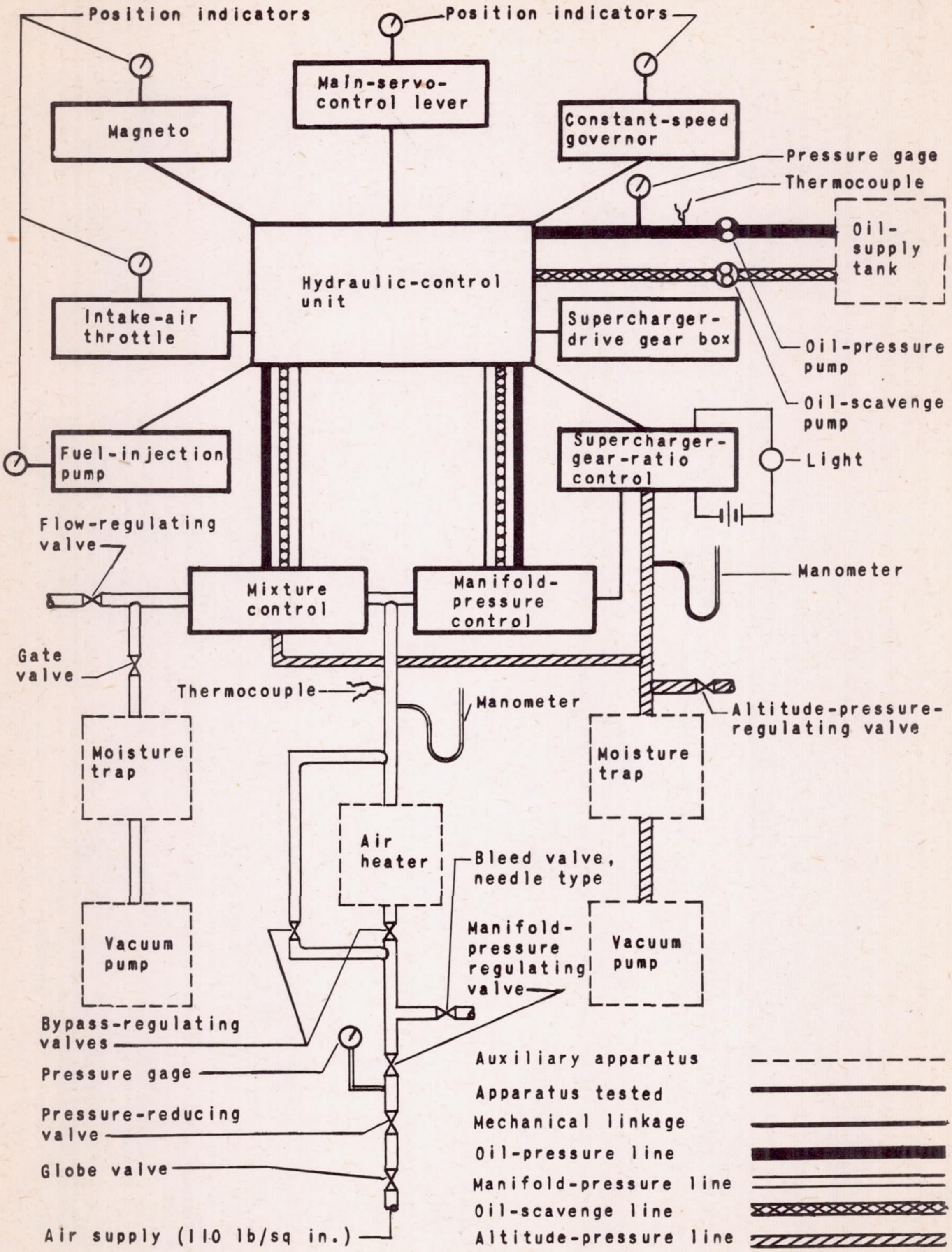


Figure 1. - Functional diagram of the BMW 801D2 automatic engine-control system. Arrows indicate direction of oil flow.

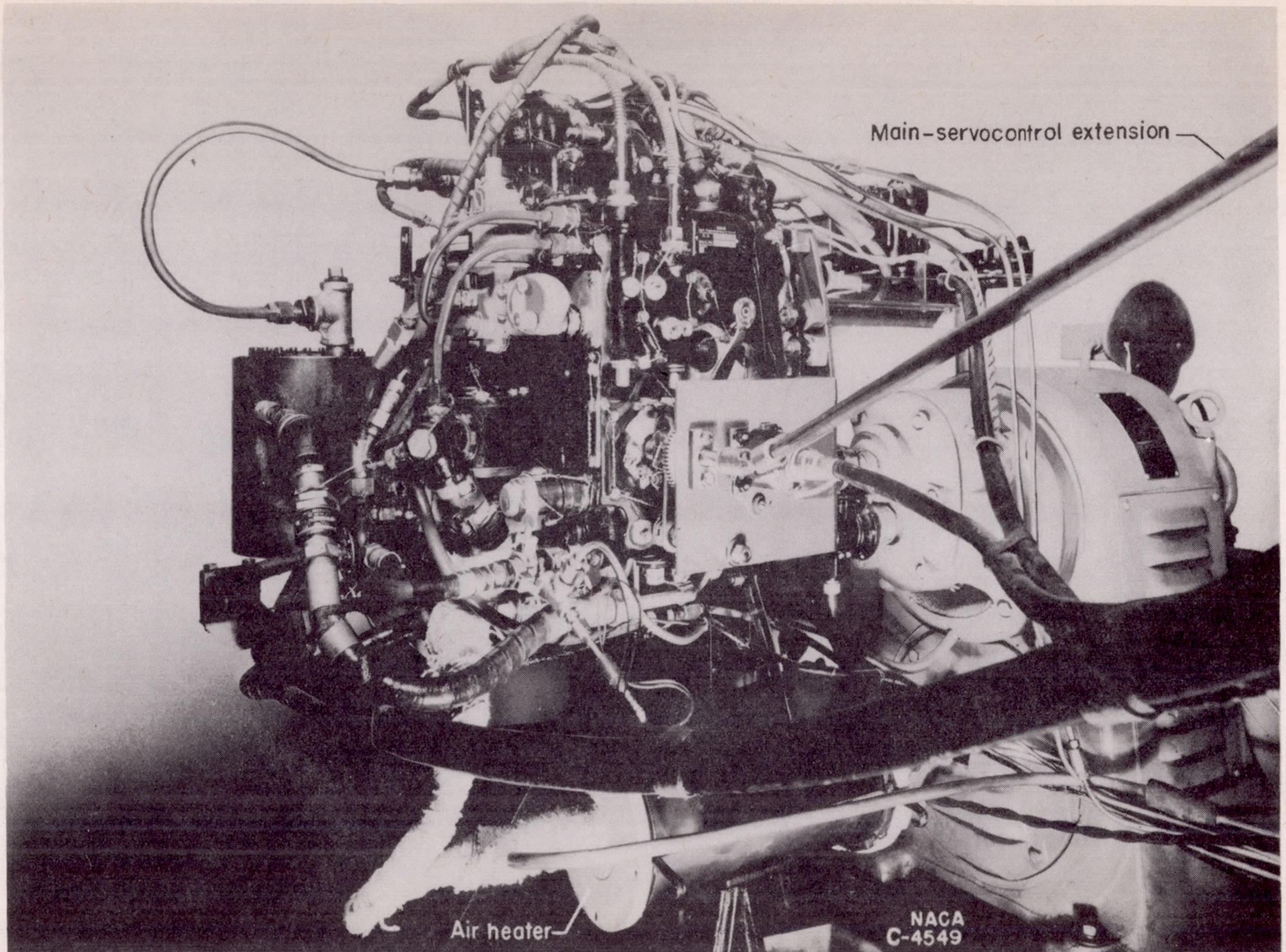
E-192



4-246

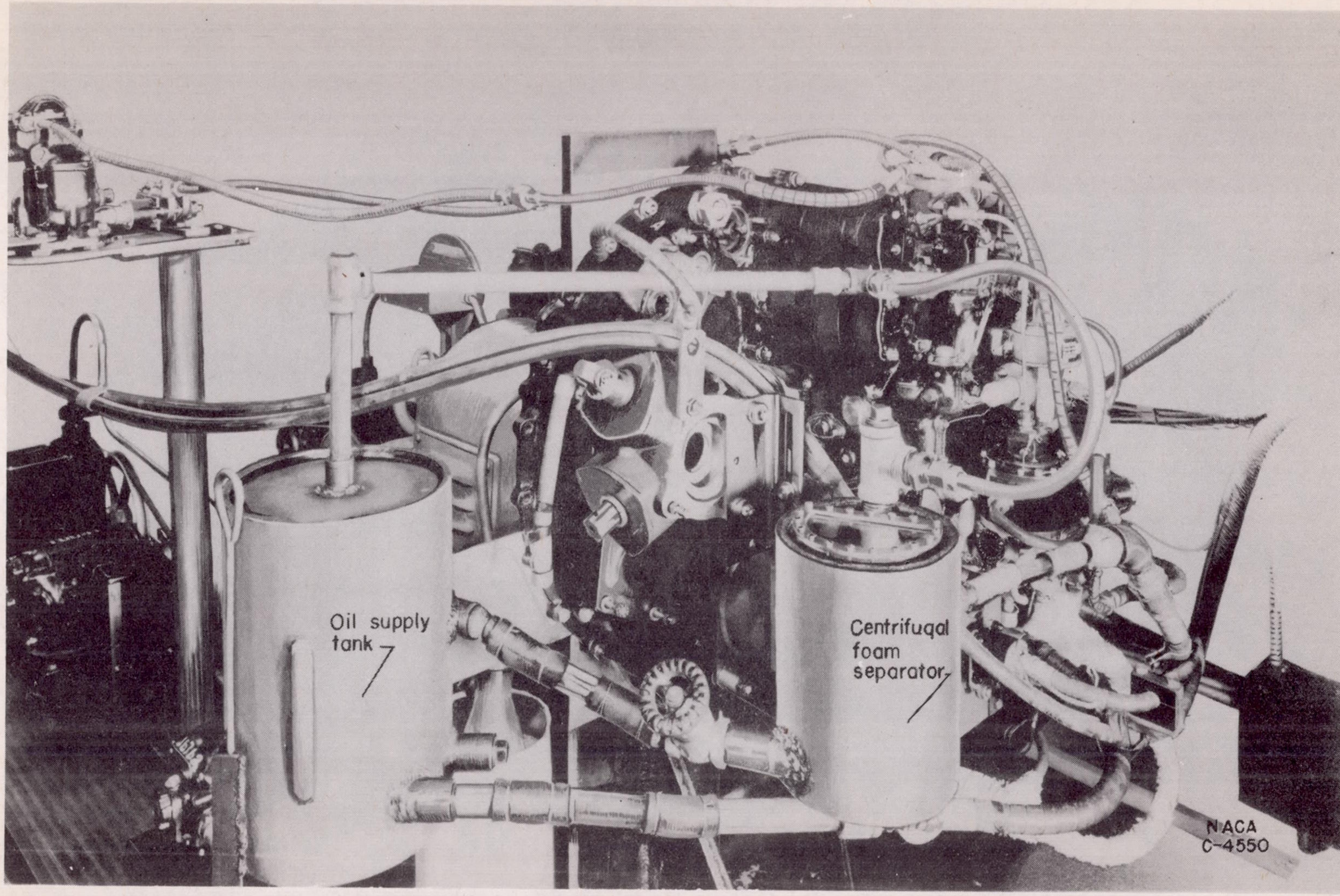
NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

Figure 2. - Schematic diagram of the BMW 801D2 engine-control system and the apparatus used for bench-test operation.



(a) Right rear view.

Figure 3. - Test installation of control system.



(b) Left rear view.

Figure 3. - Concluded. Test installation of control system.

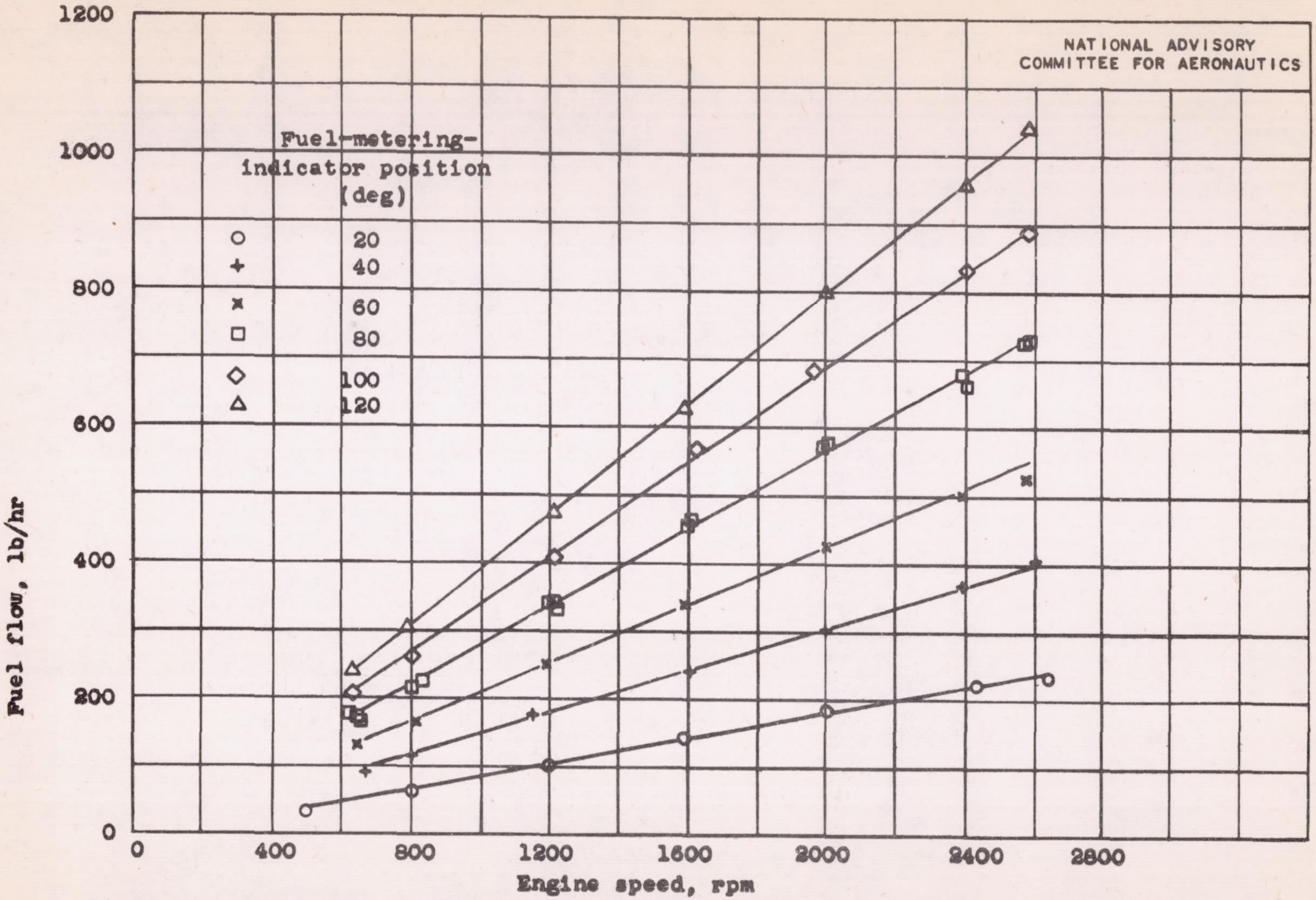


Figure 4. - Variation of fuel flow of fuel-injection system from a BMW 801D2 engine with engine speed at various positions of the fuel-metering indicator. Correction factor for use with German green fuel, 1.098.

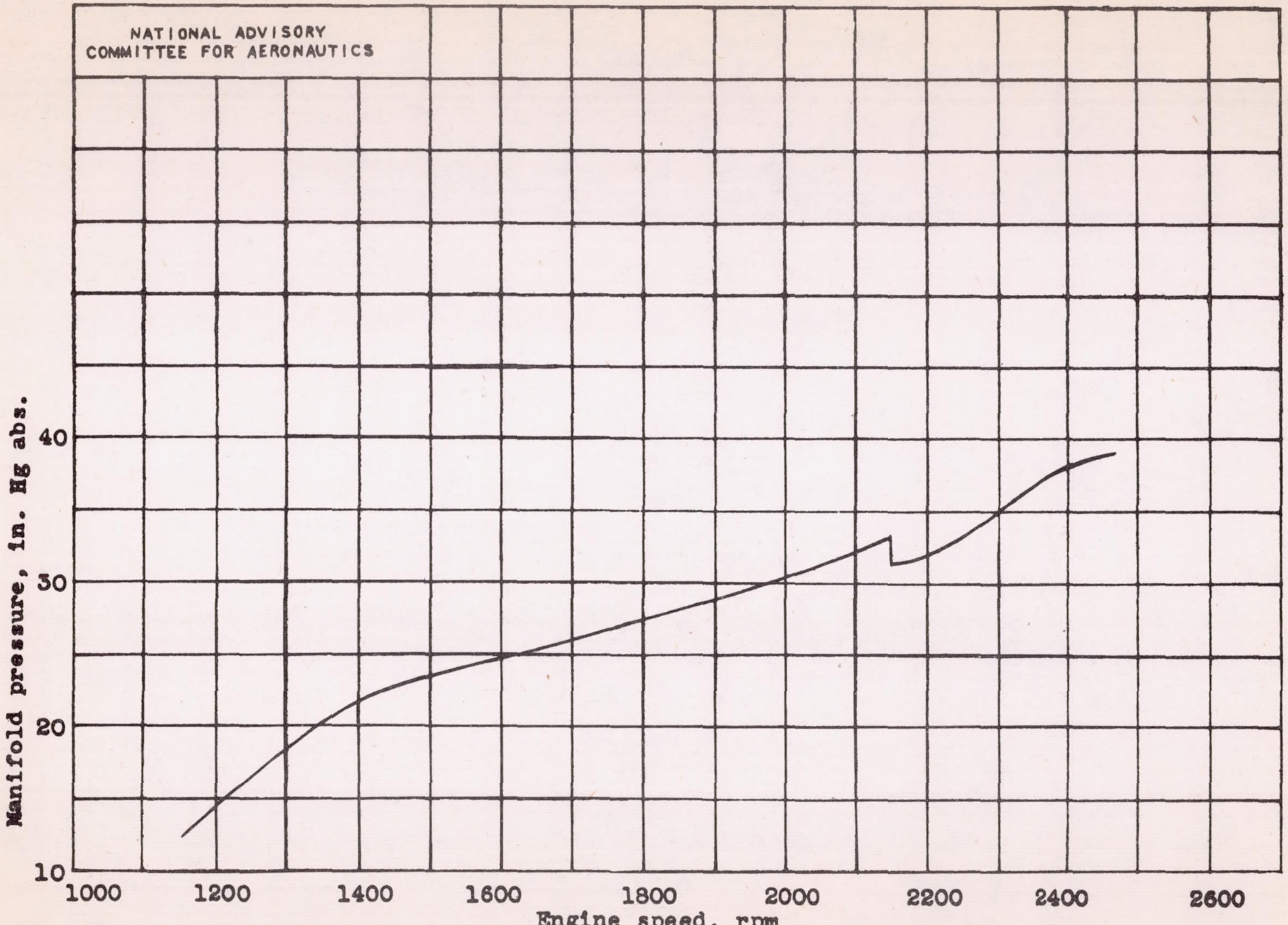
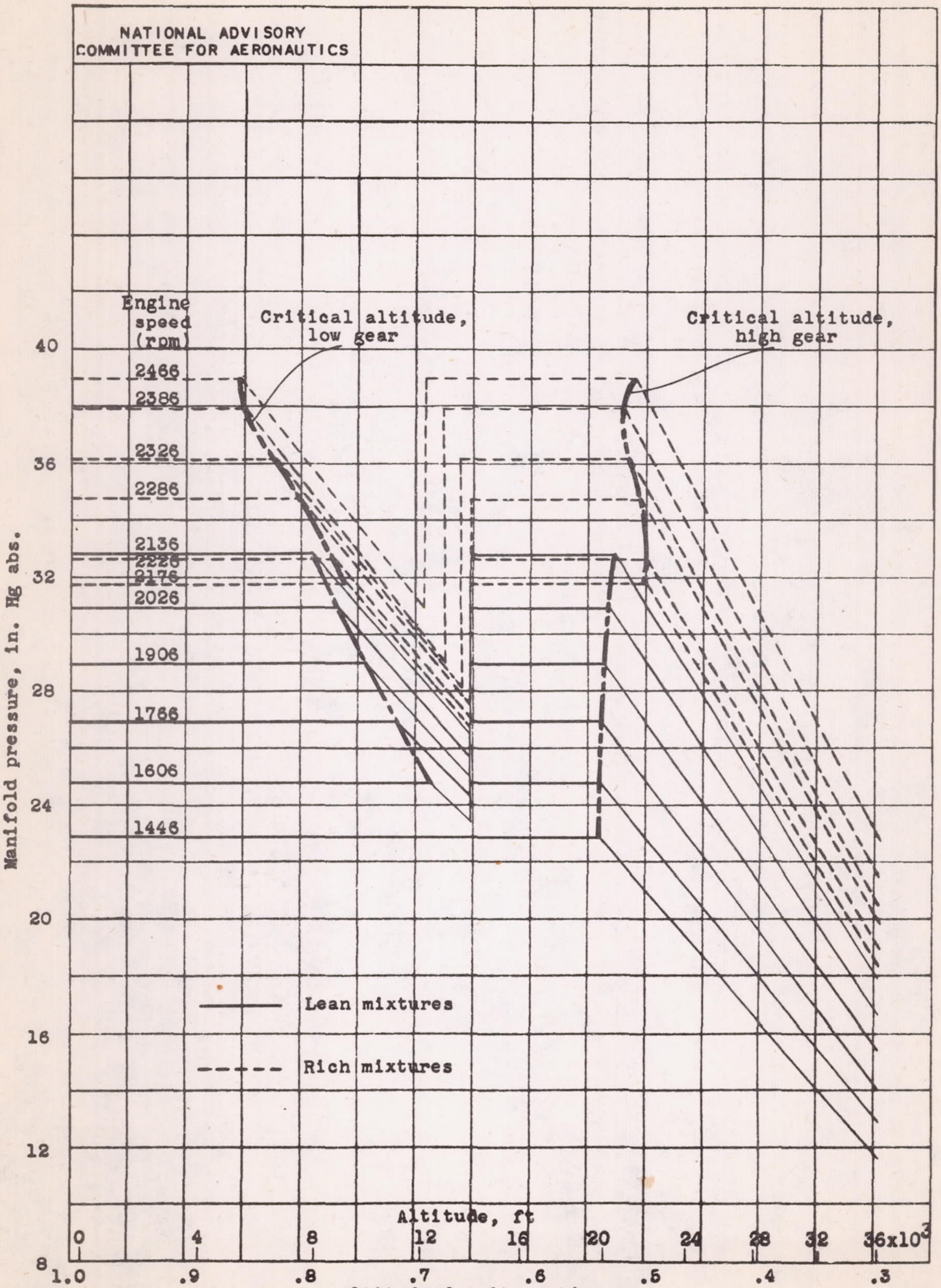
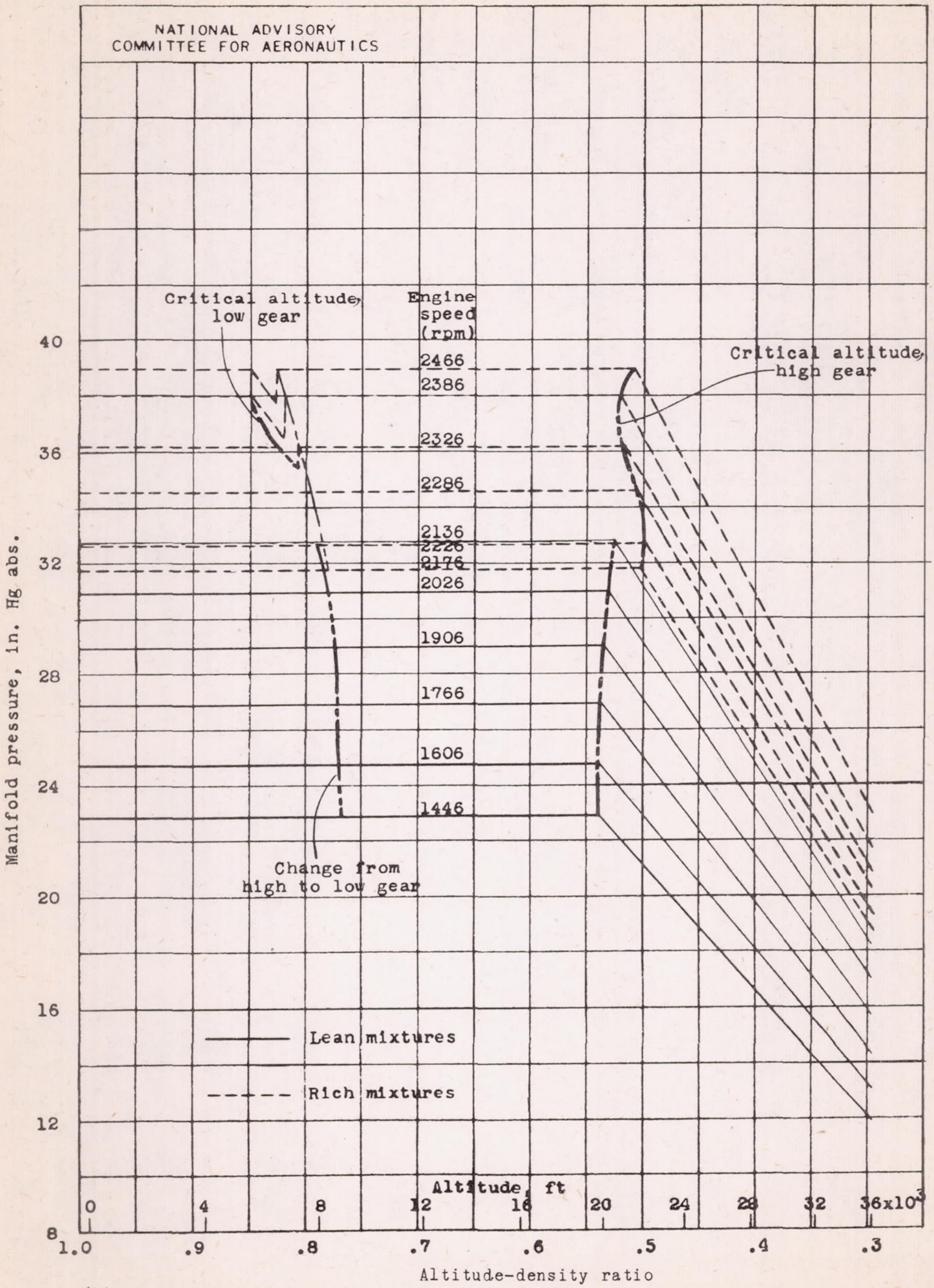


Figure 5. - The relation between engine speed and manifold pressure. (Derived from information obtained from Army Air Forces, Materiel Command.)



(a) Increasing altitude.

Figure 6. - The effect of altitude-density ratio on manifold pressure.



(b) Decreasing altitude.

Figure 6. - Concluded. The effect of altitude-density ratio on manifold pressure.

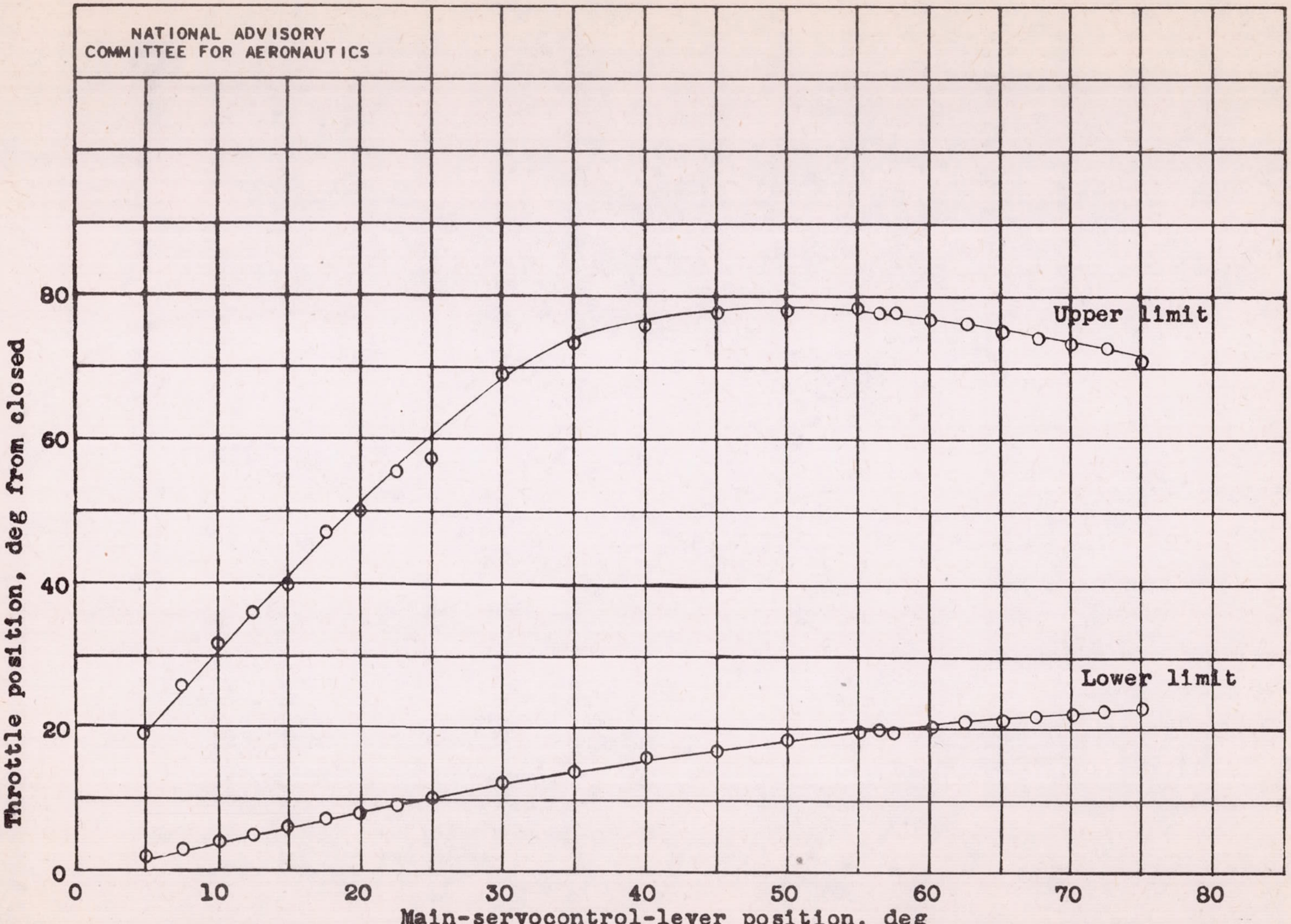


Figure 7. - The effect of main-servocontrol-lever position on the range of possible positions of the supercharger intake-air throttles.

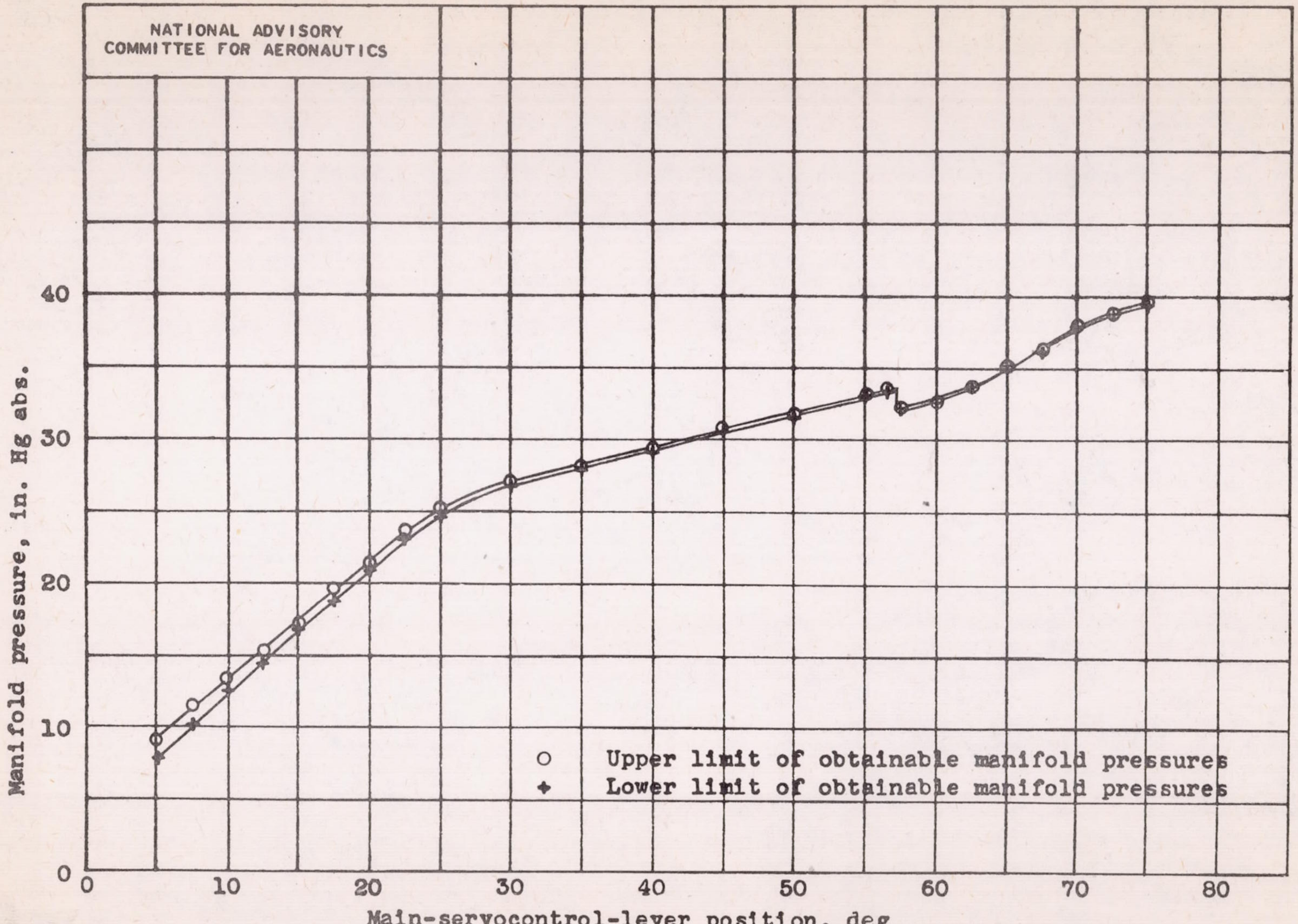


Figure 8. - The effect of the main-servocontrol-lever position on the range of obtainable manifold pressures.

E-192

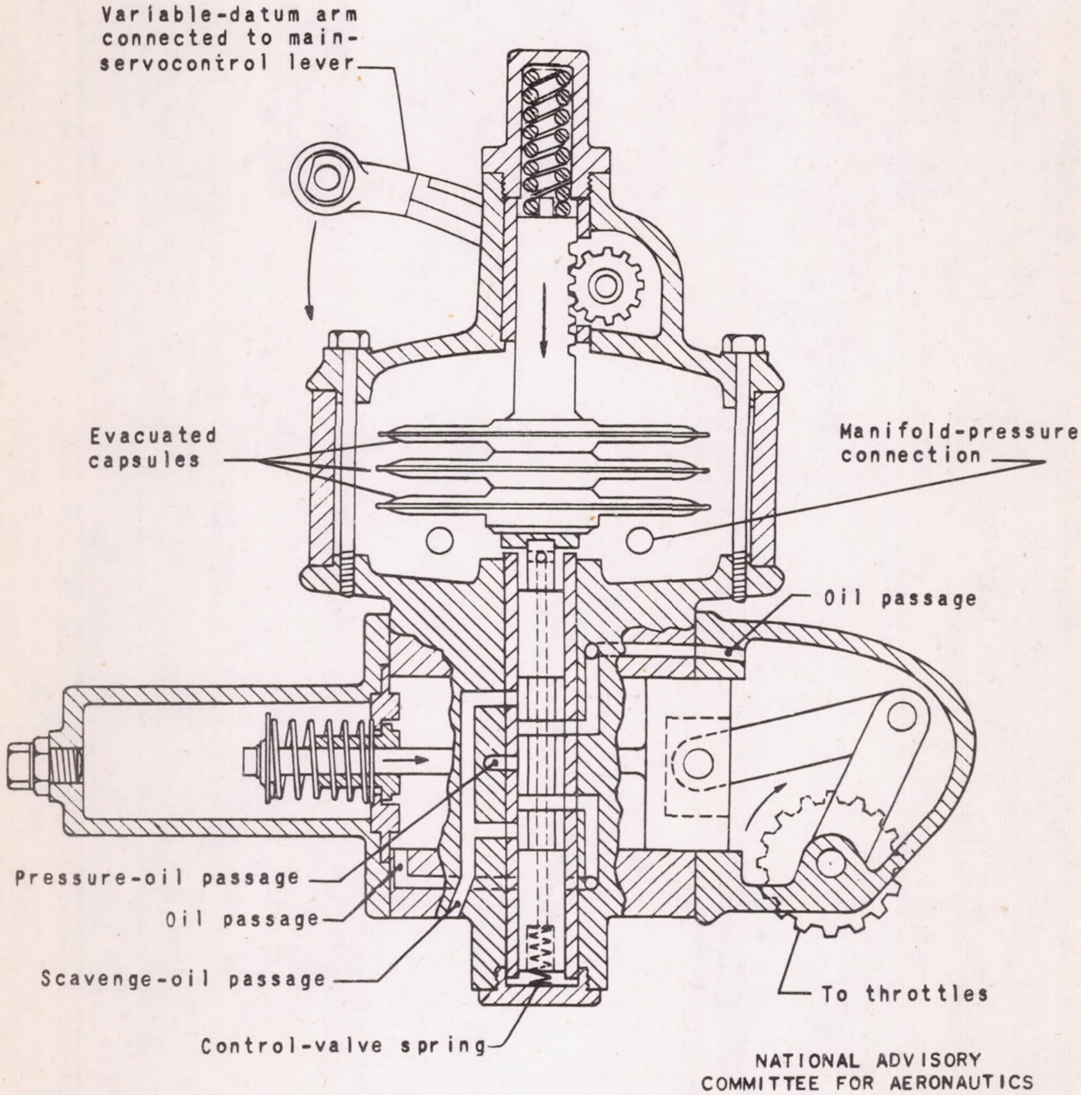


Figure 9. - Diagram of manifold-pressure control. Arrows show linkage movement with increasing manifold pressure.

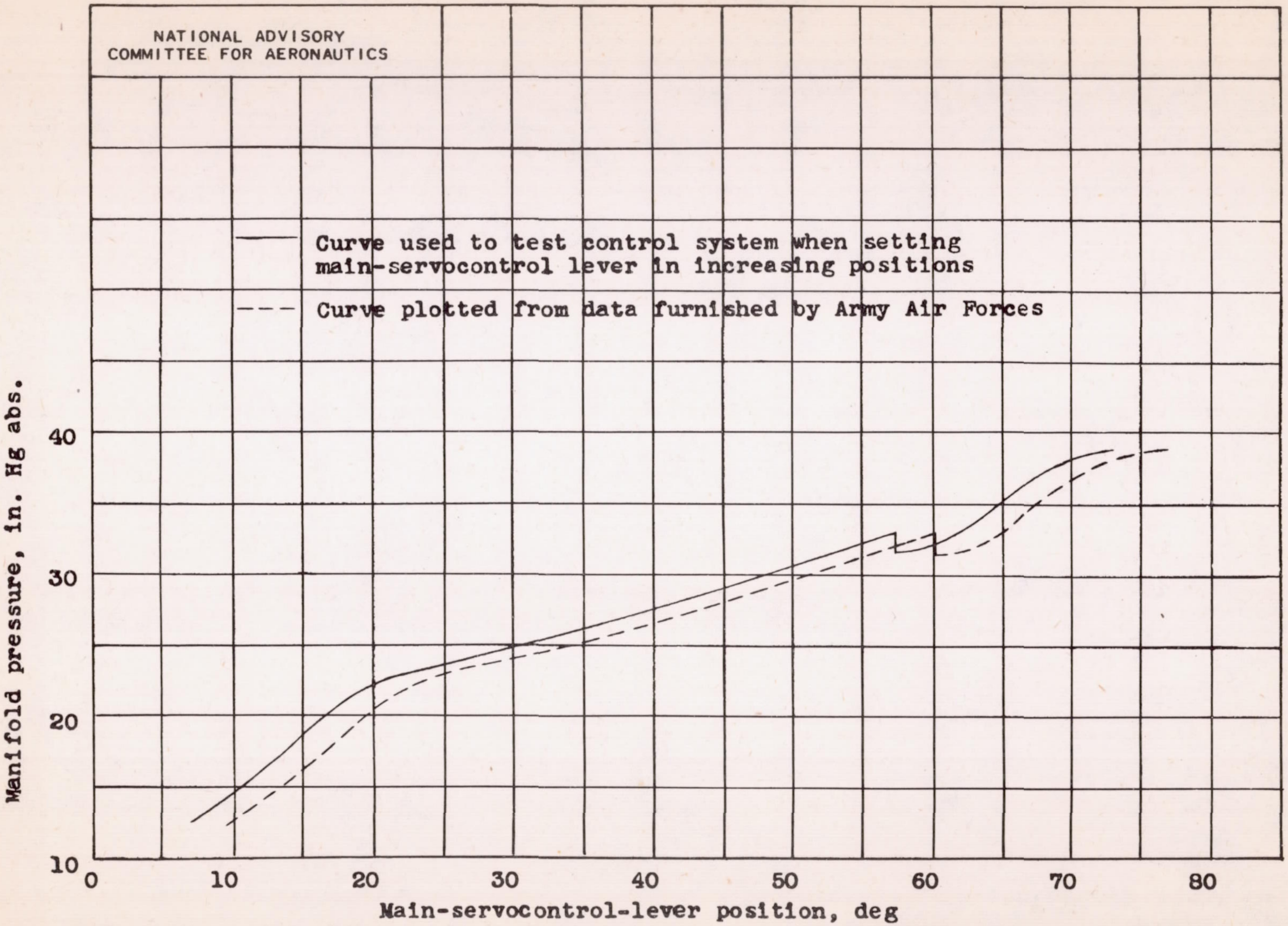


Figure 10. - The effect of the position of the main-servocontrol lever on manifold pressure.

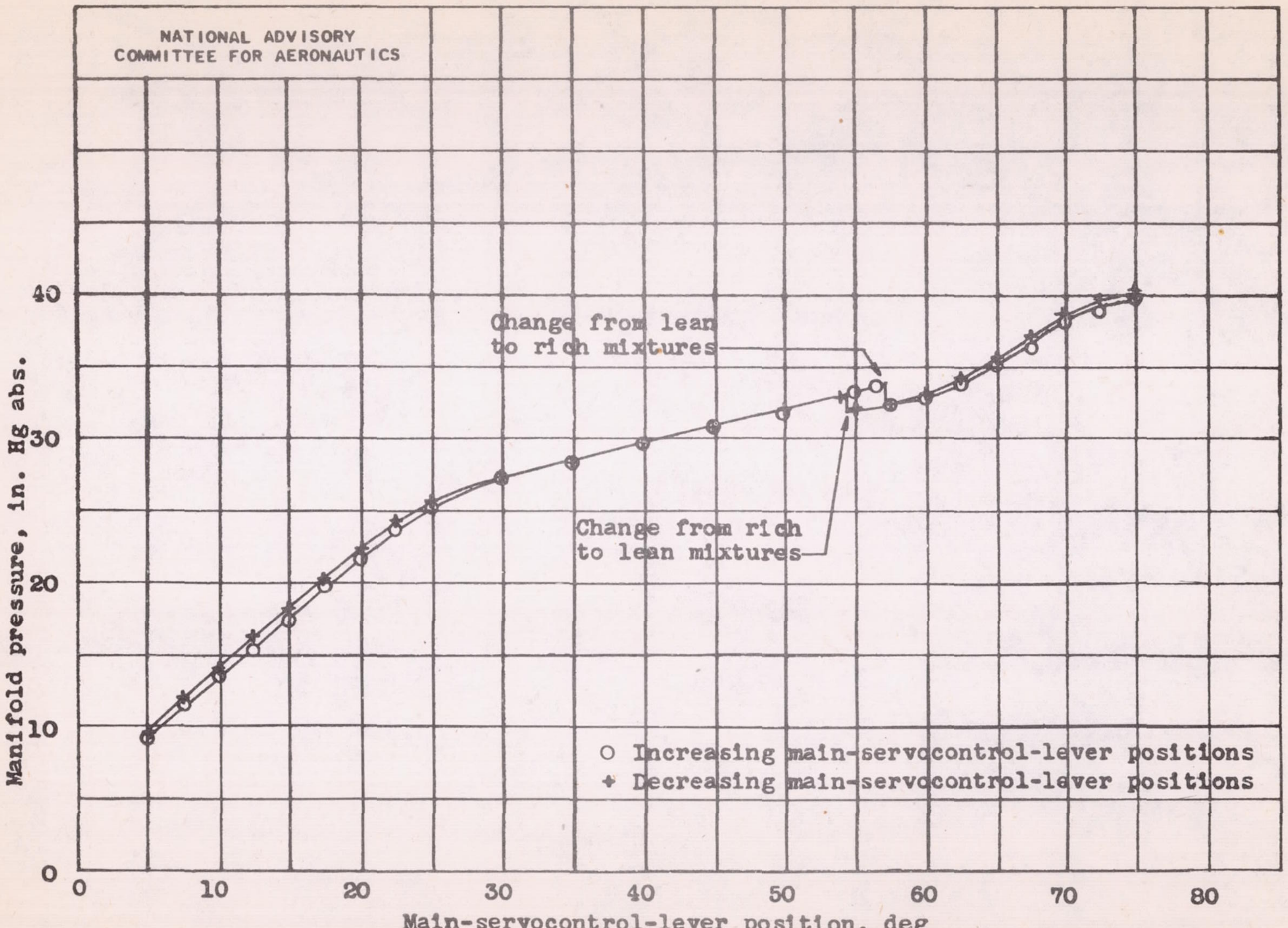
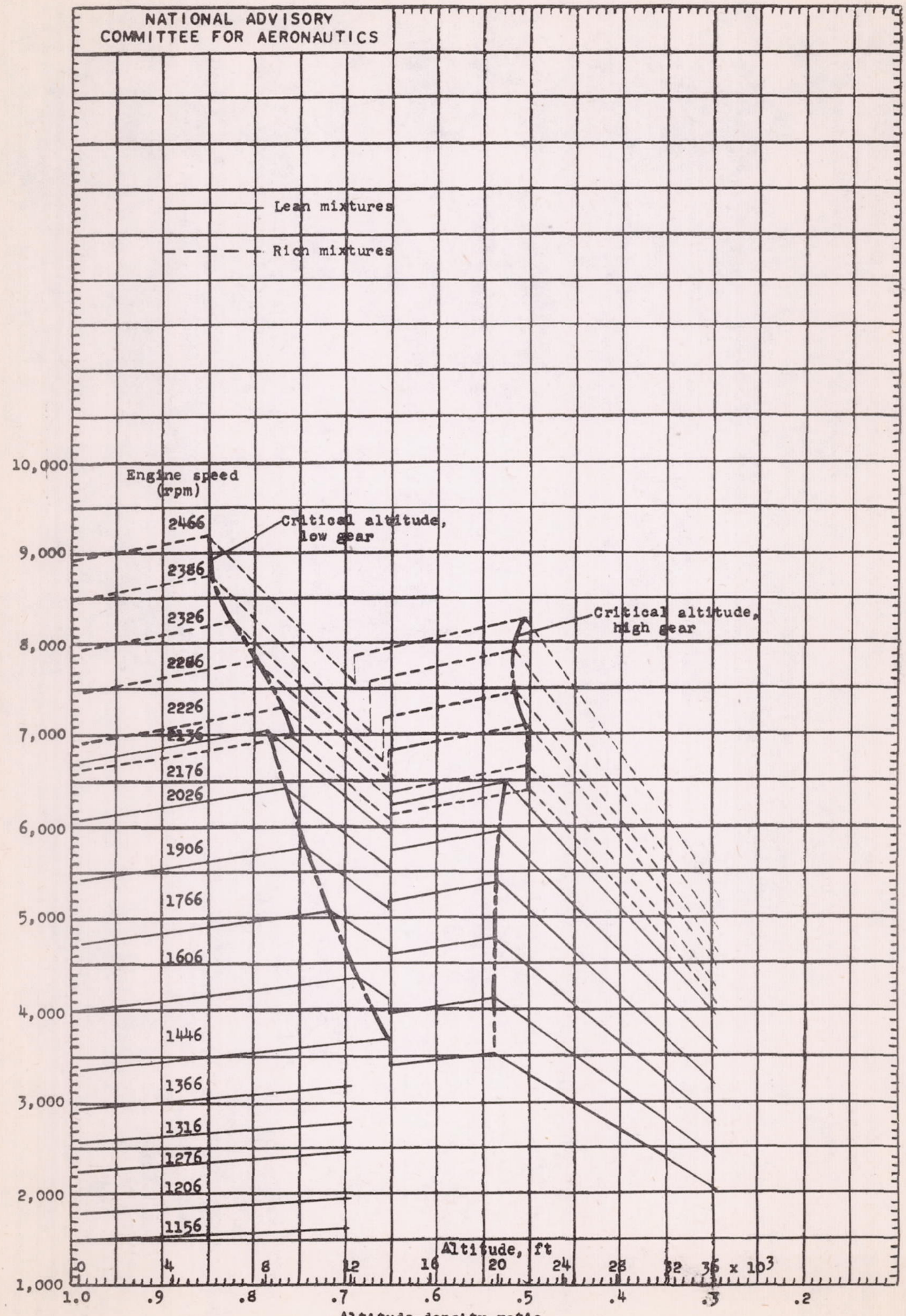


Figure 11. - The effect of the position of the main-servocontrol lever on the maximum obtainable manifold pressure showing the 2.8° lag in mixture change.

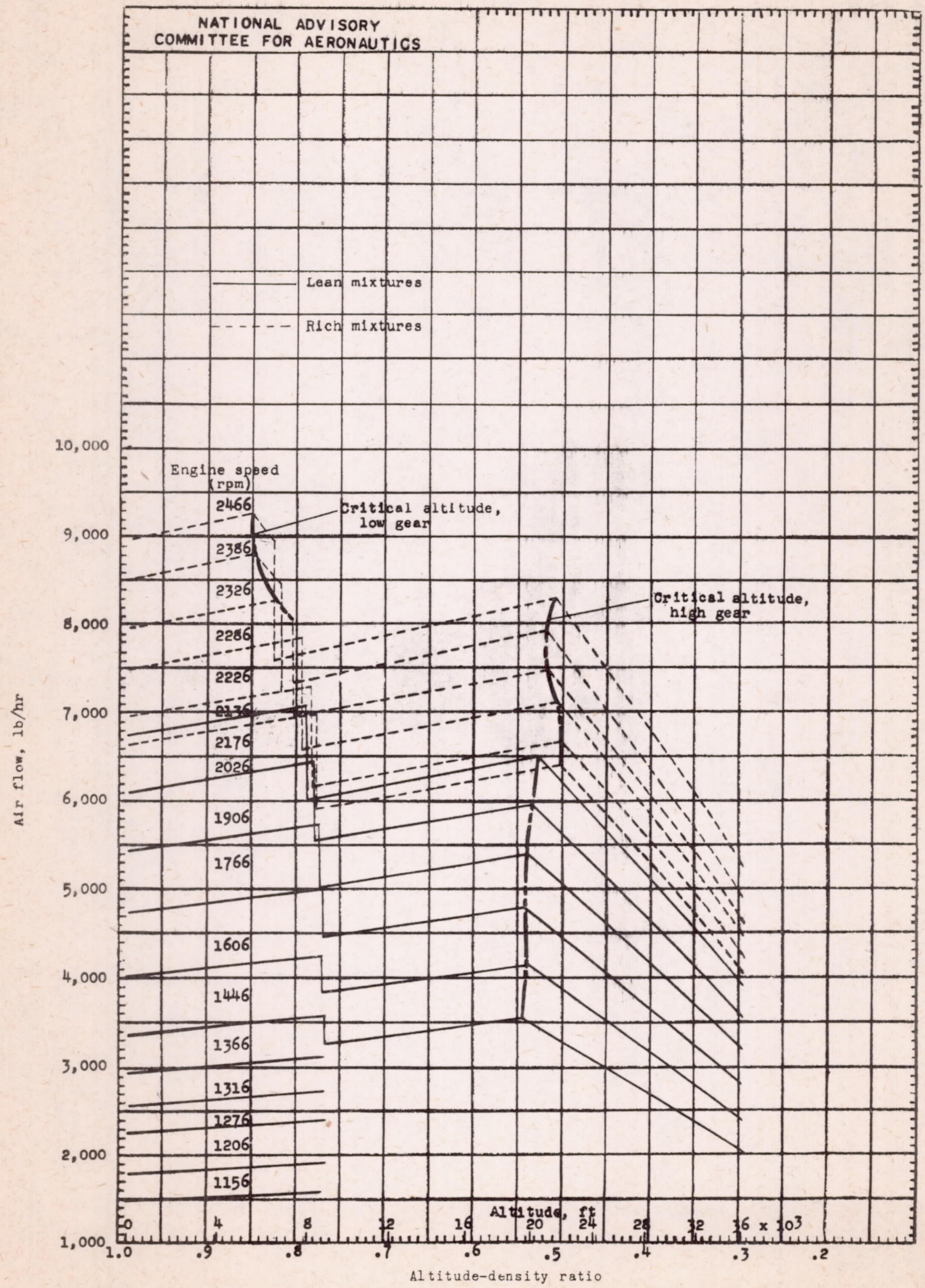
E-192



(a) Increasing altitude.

Figure 12. - The effect of altitude-density ratio on calculated air flow.

E-192



(b) Decreasing altitude.

Figure 12. - Concluded. The effect of altitude-density ratio on calculated air flow.

E-192

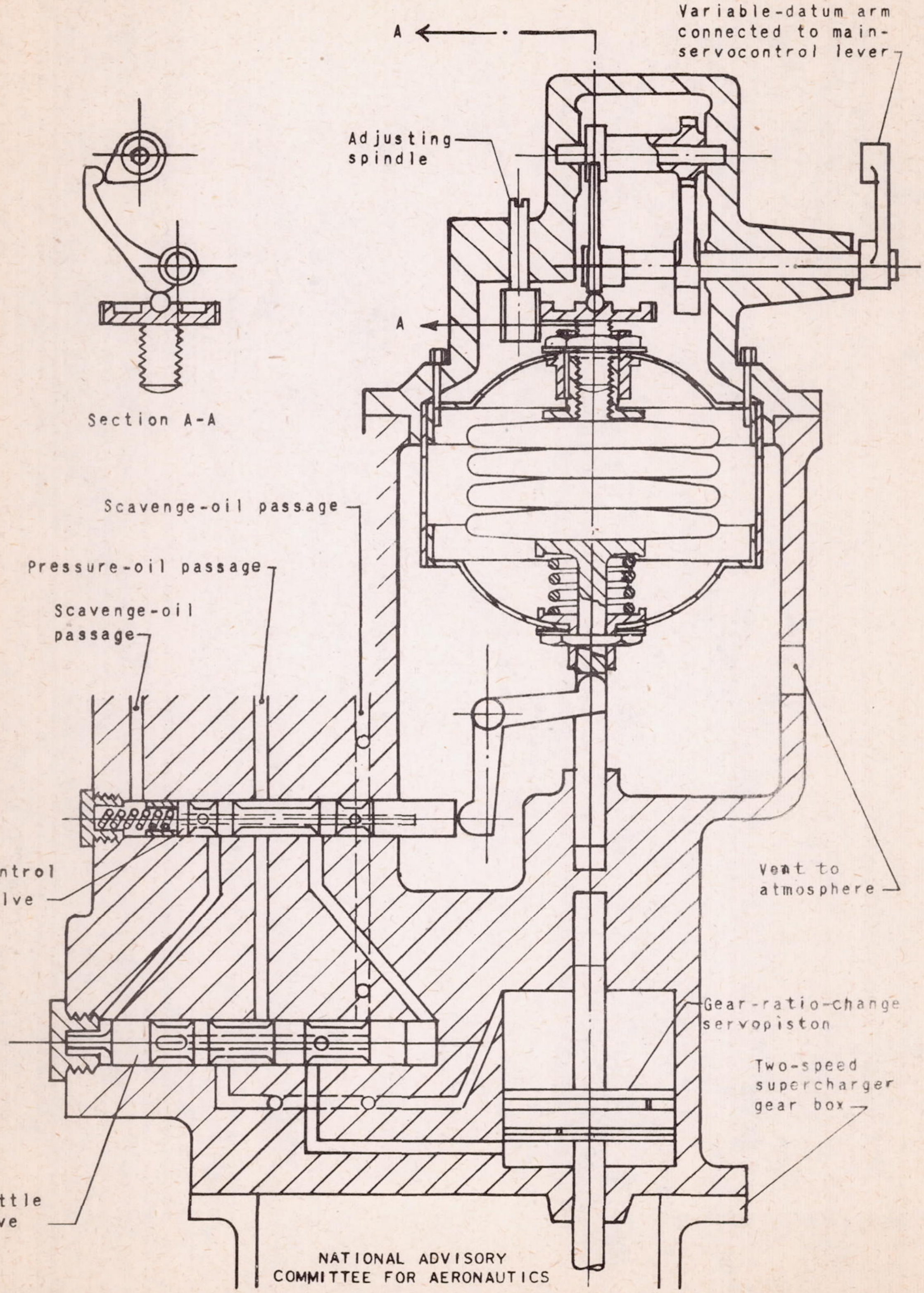


Figure 13. - Diagram of the mechanism for changing the gear ratio of the supercharger.

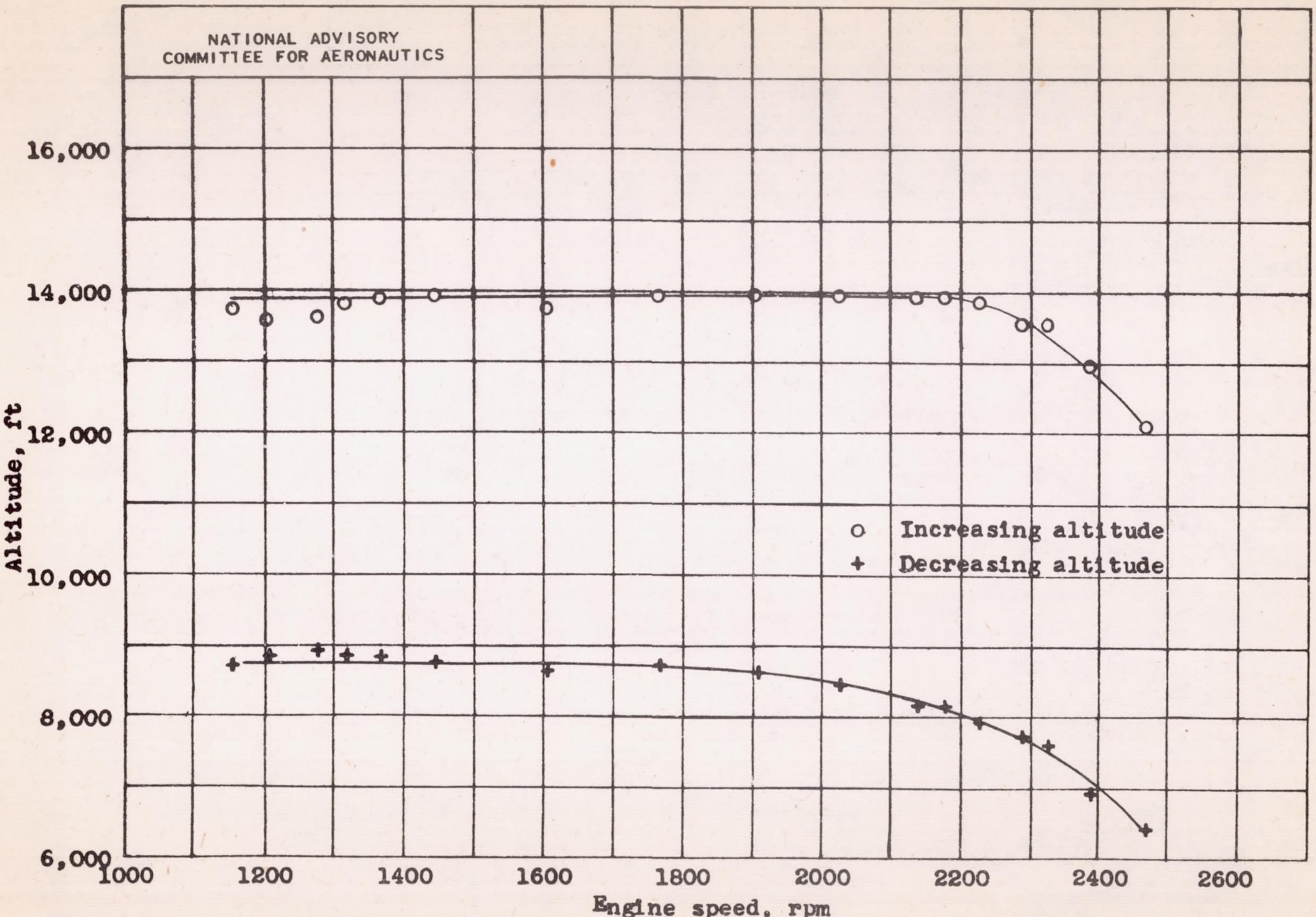


Figure 14. - The effect of engine speed on the altitude at which the change in gear ratio of the supercharger occurs.

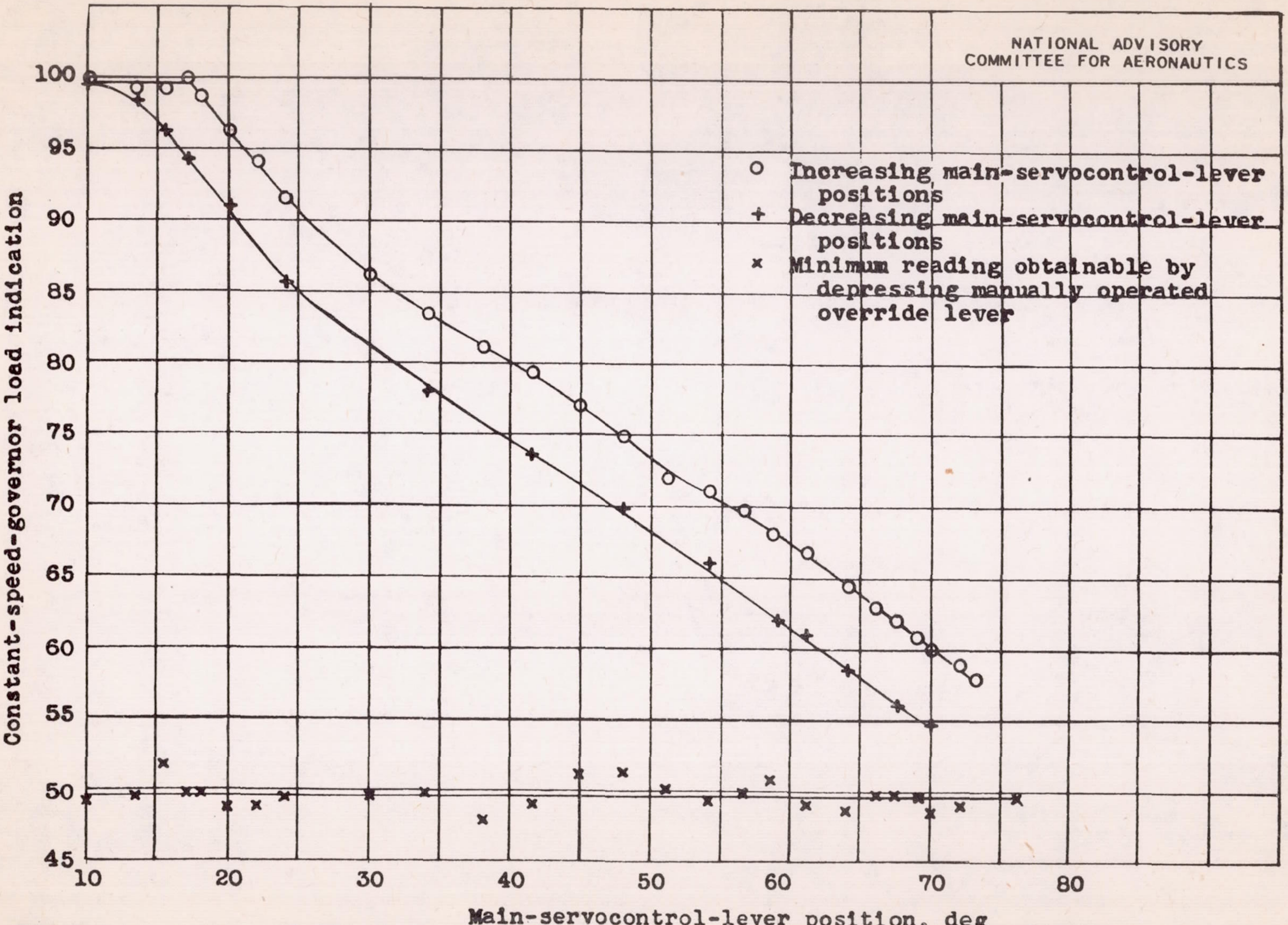


Figure 15. - The effect of the position of the main-servocontrol lever on load indication of the propeller constant-speed governor.

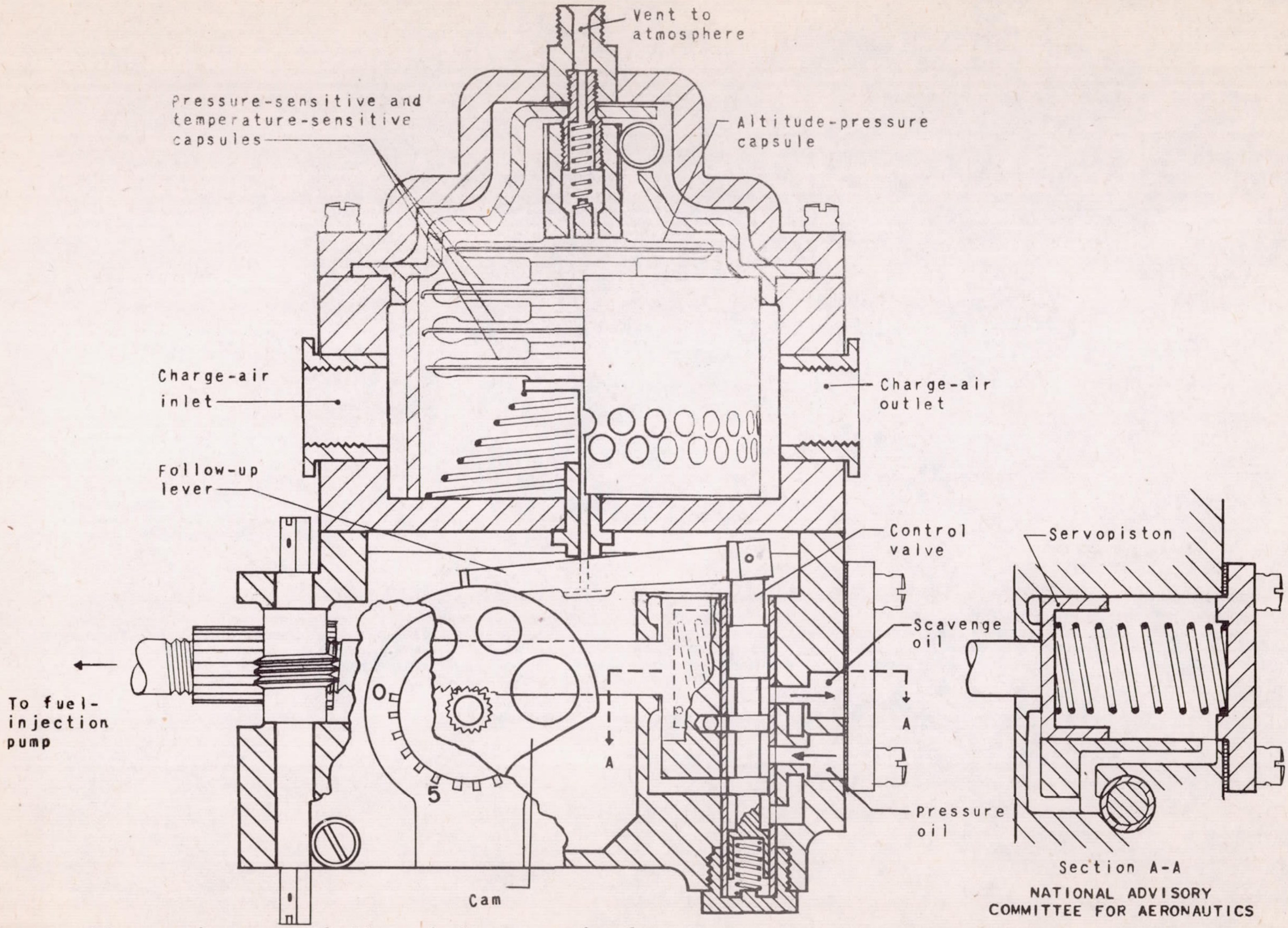
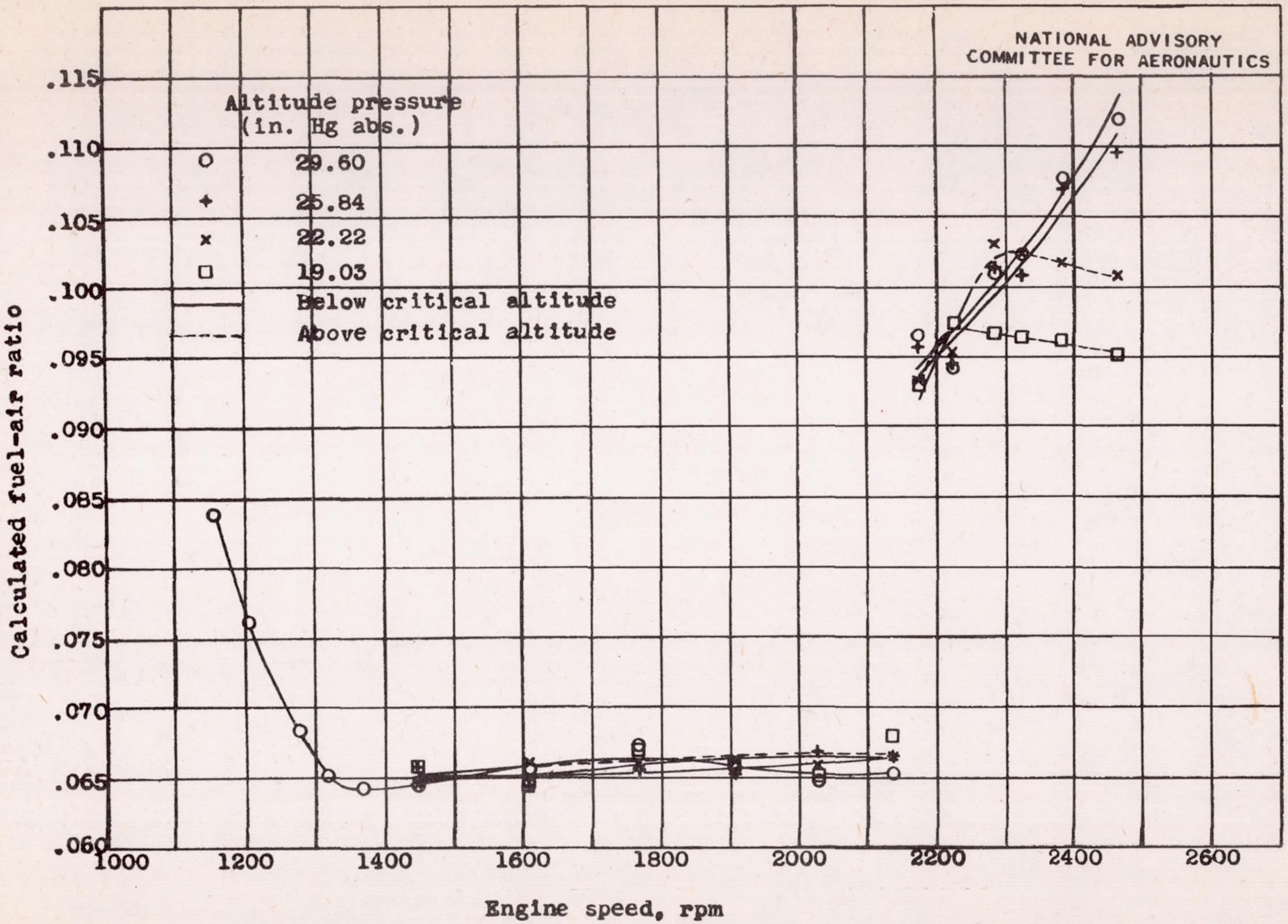
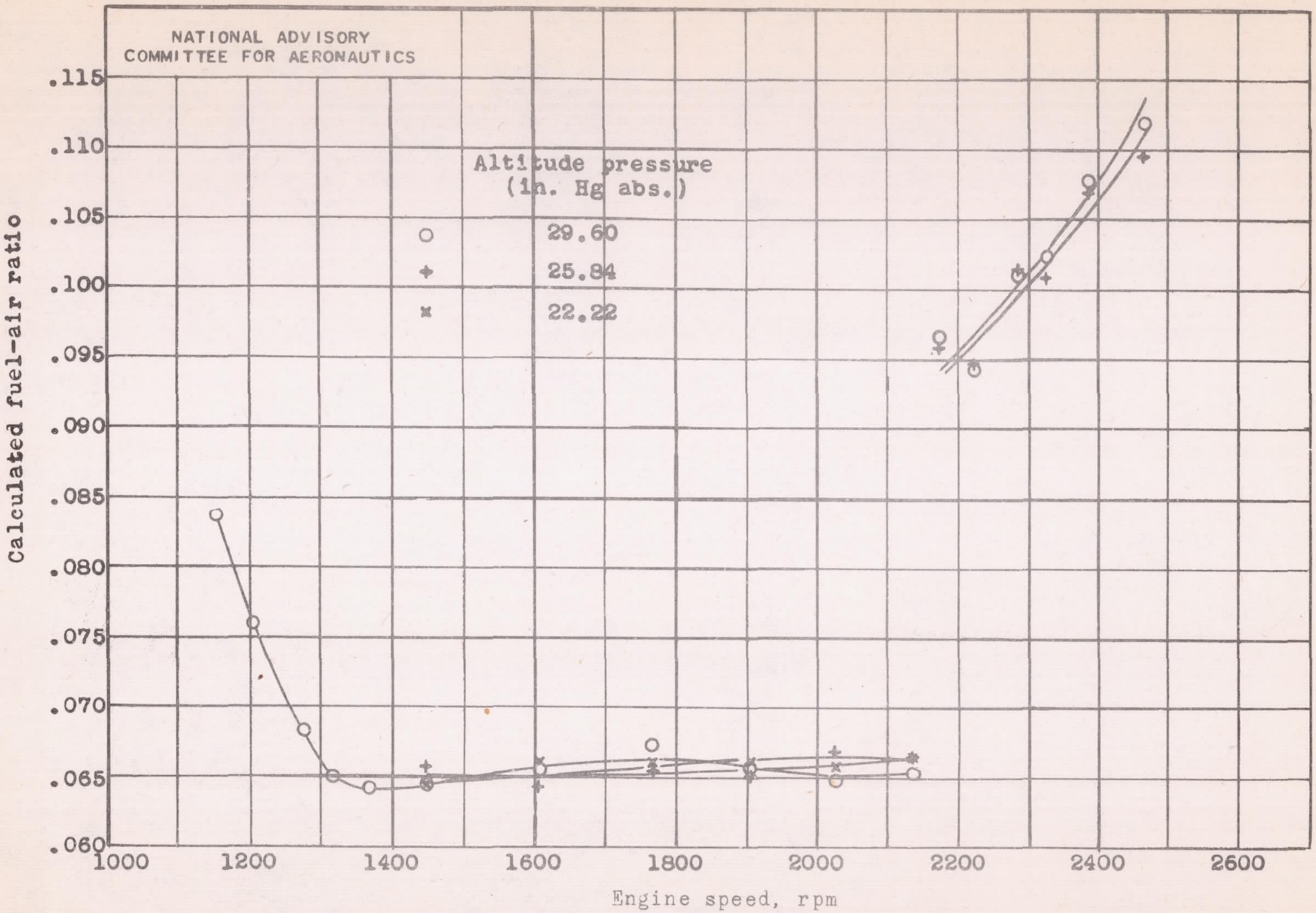


Figure 16. - Diagram of the mixture control.



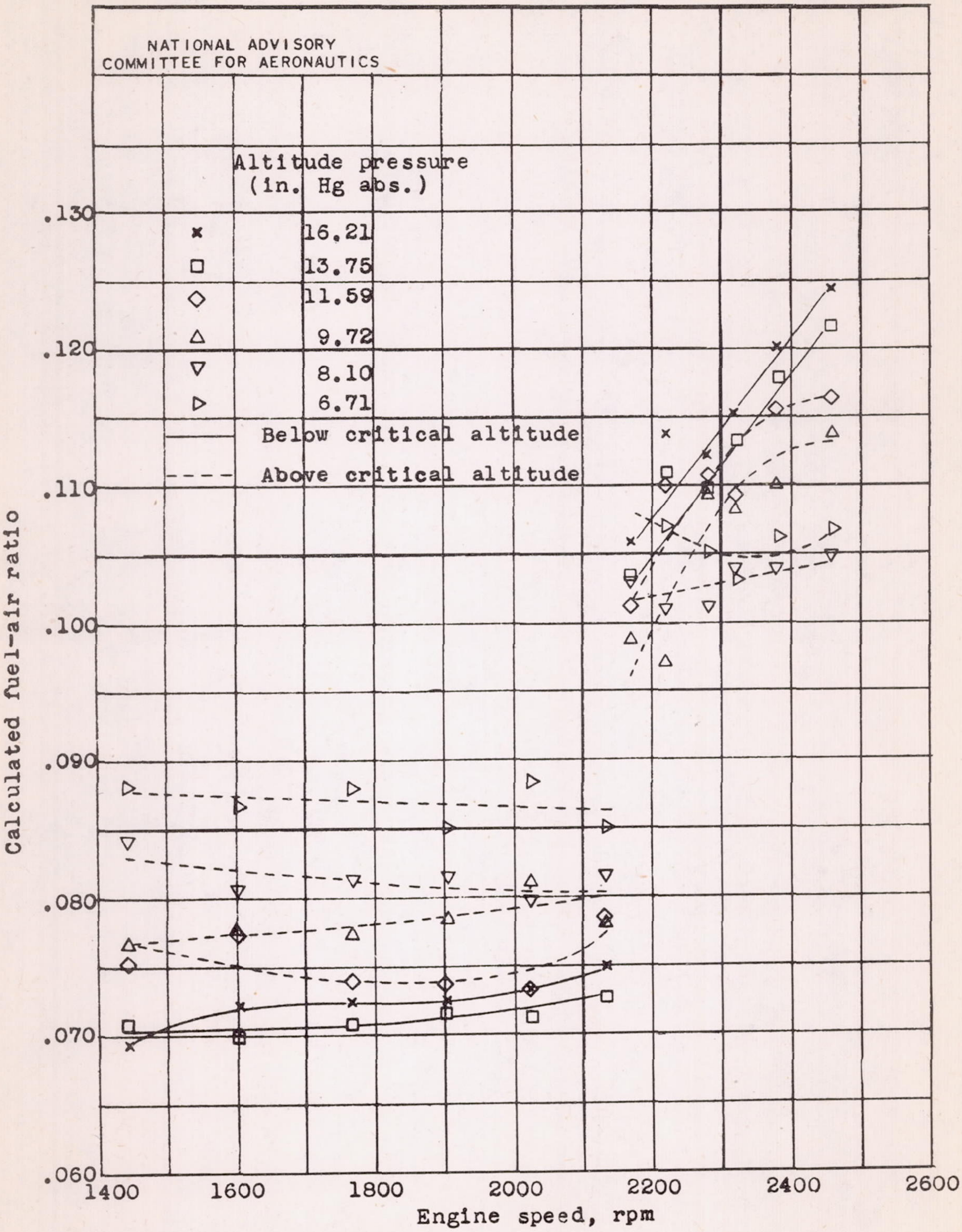
(a) Increasing altitude.

Figure 17. - The relation between engine speed and calculated fuel-air ratio with supercharger in low gear.



(b) Decreasing altitude.

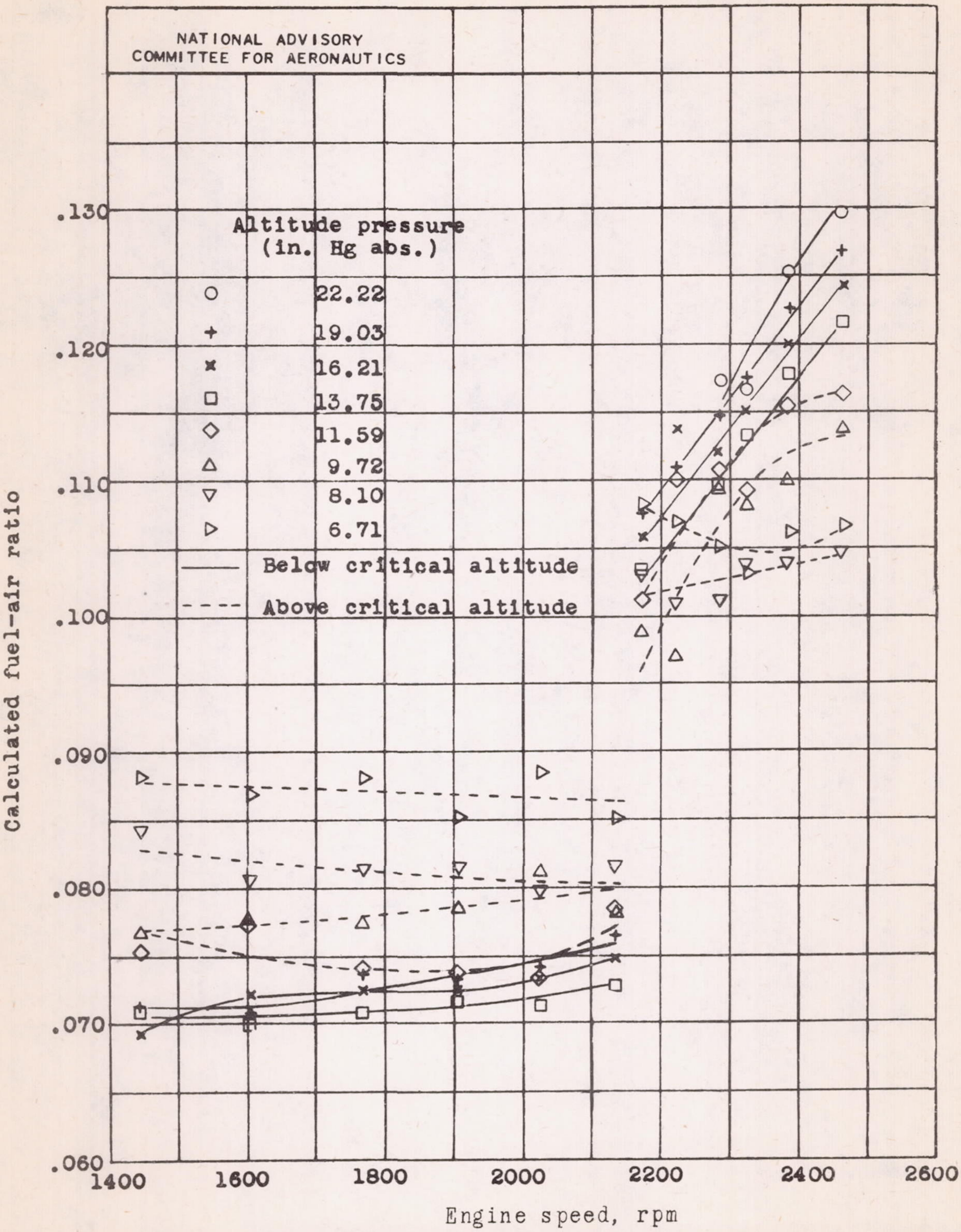
Figure 17. - Concluded. The relation between engine speed and calculated fuel-air ratio with supercharger in low gear.



(a) Increasing altitude.

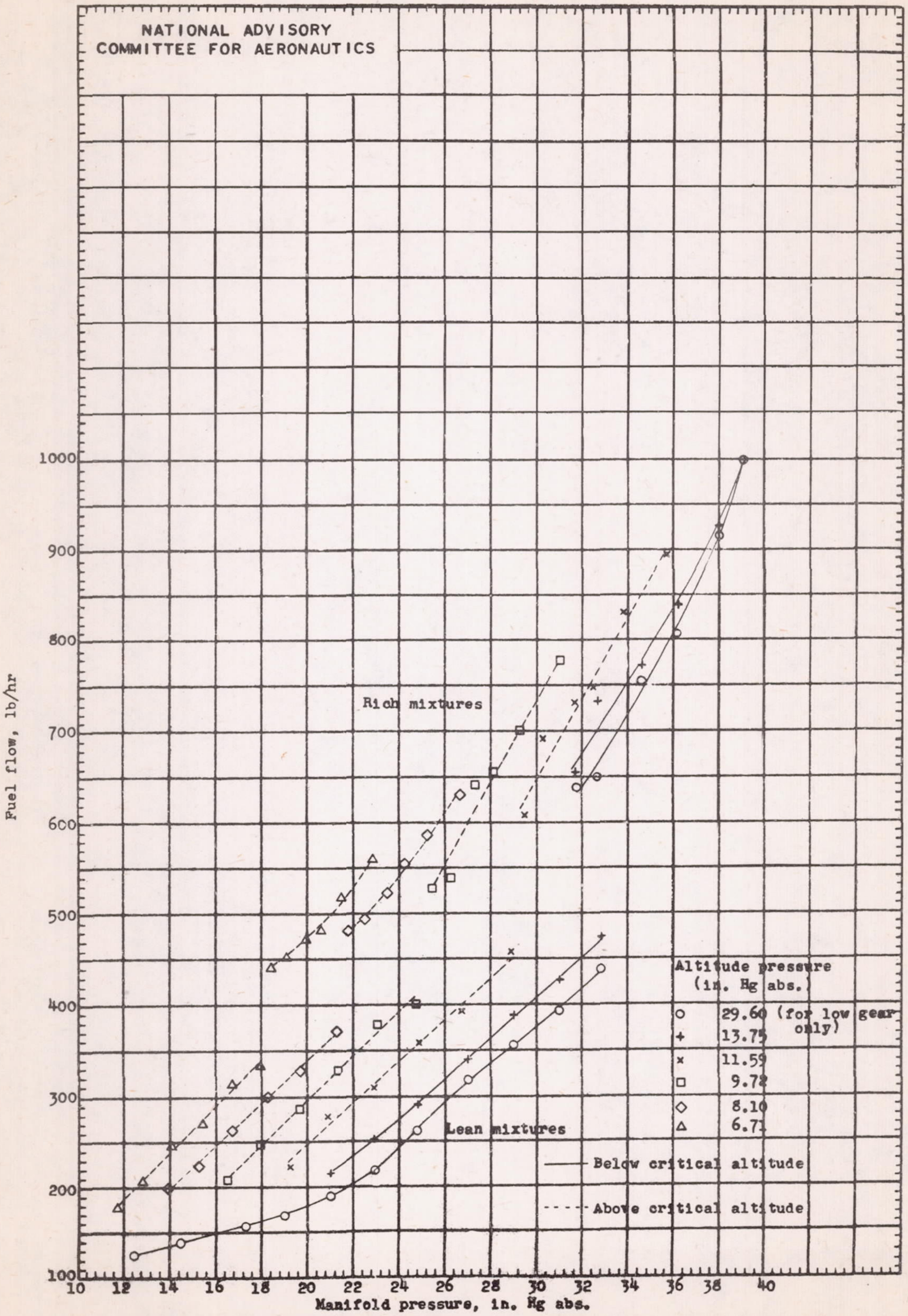
Figure 18. - The relation between engine speed and calculated fuel-air ratio with supercharger in high gear.

E-192



(b) Decreasing altitude.

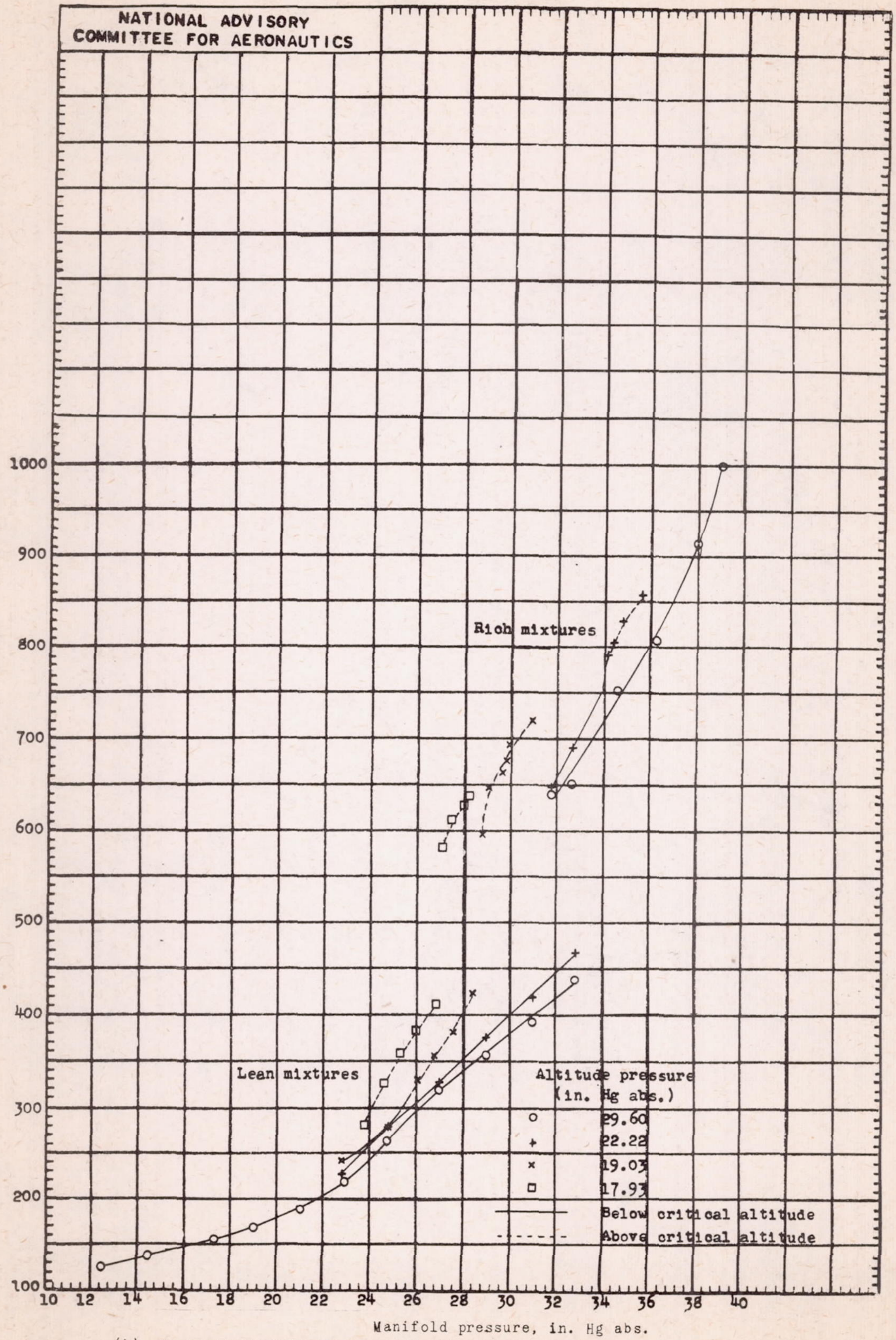
Figure 18. - Concluded. The relation between engine speed and calculated fuel-air ratio with supercharger in high gear.



(a) Increasing altitude with supercharger in high gear or decreasing altitude with supercharger in high or low gear.

Figure 19. - The effect of manifold pressure on fuel flow.

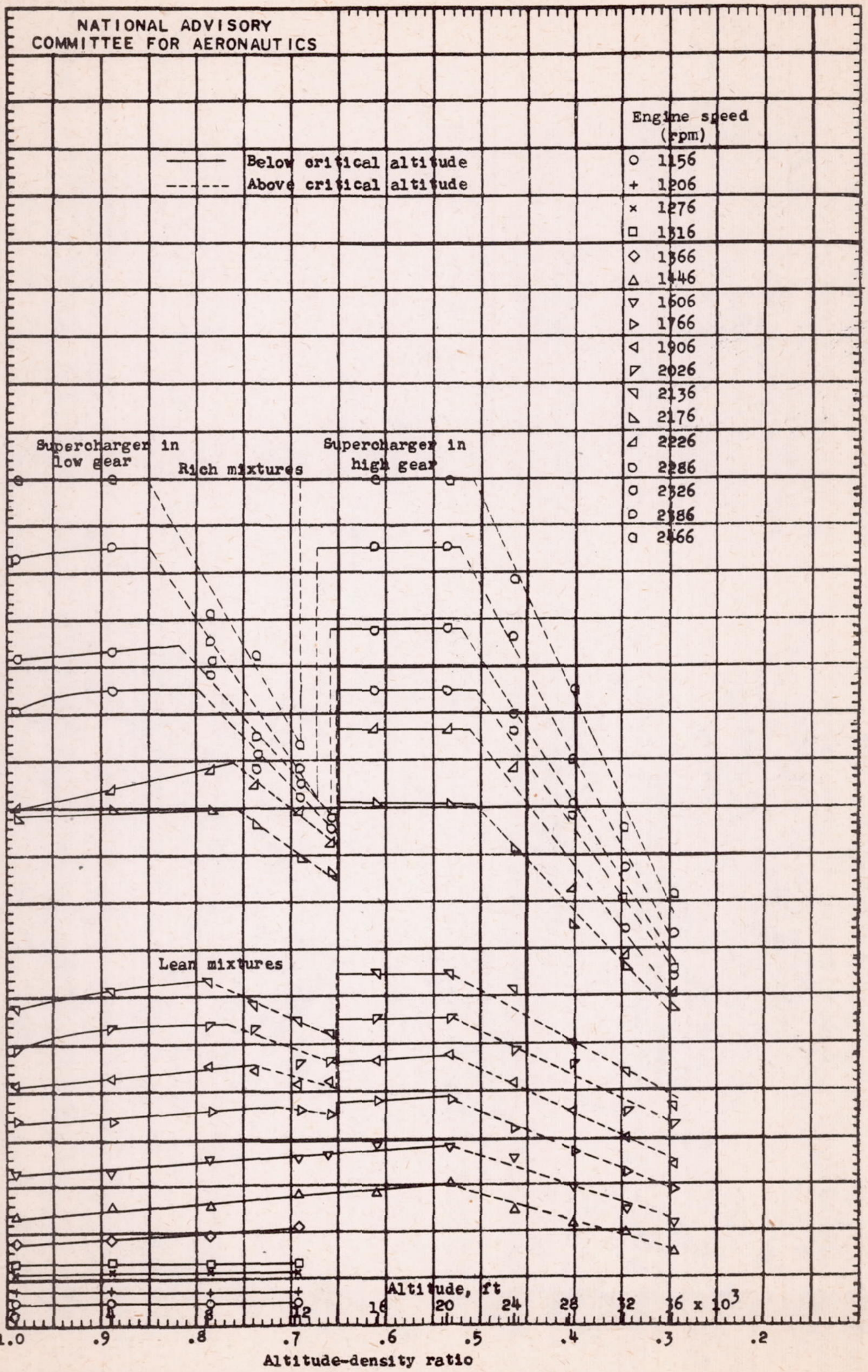
E-192



(b) Increasing altitude with supercharger in low gear.

Figure 19. - Concluded. The effect of manifold pressure on fuel flow.

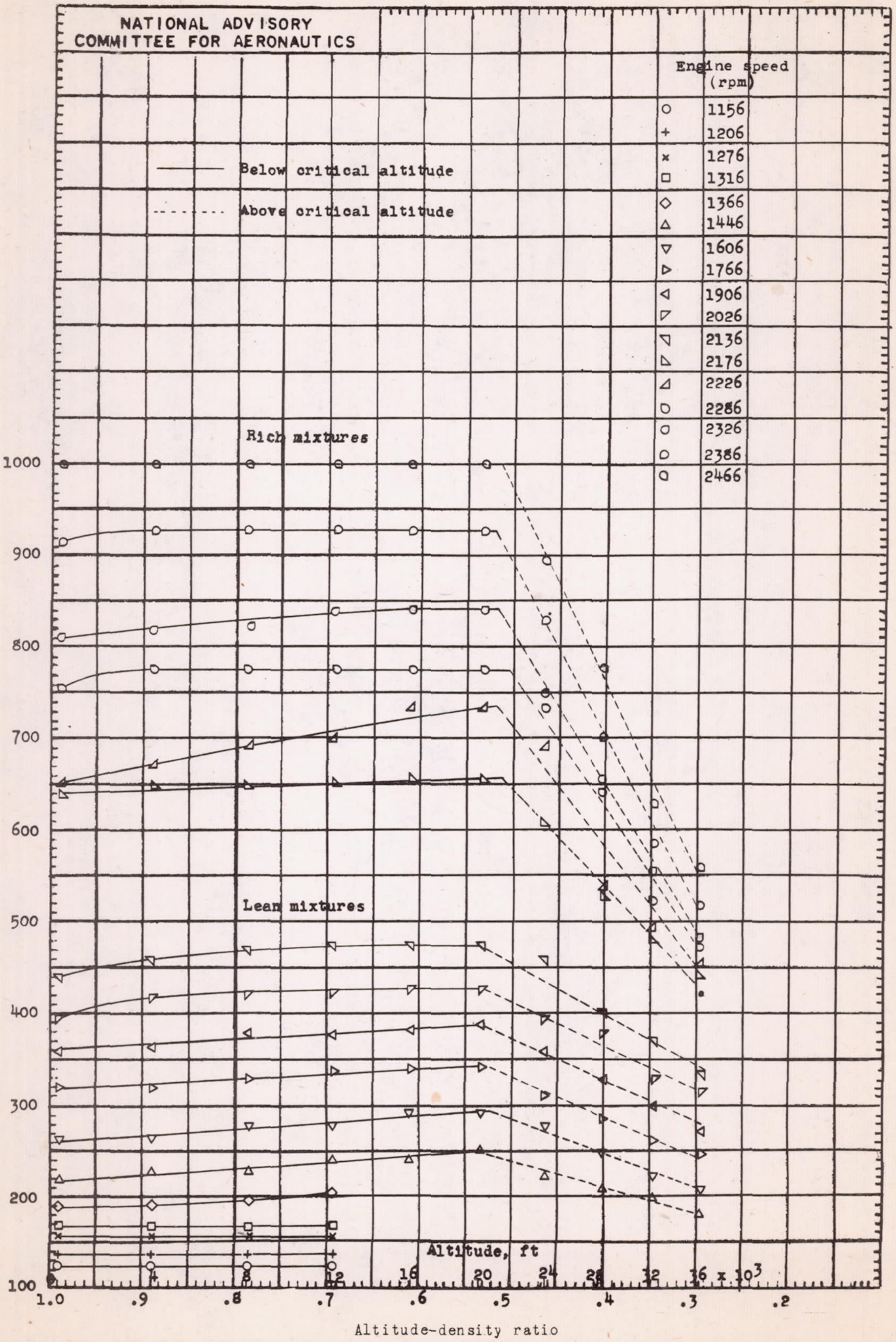
E-192



(a) Increasing altitude.

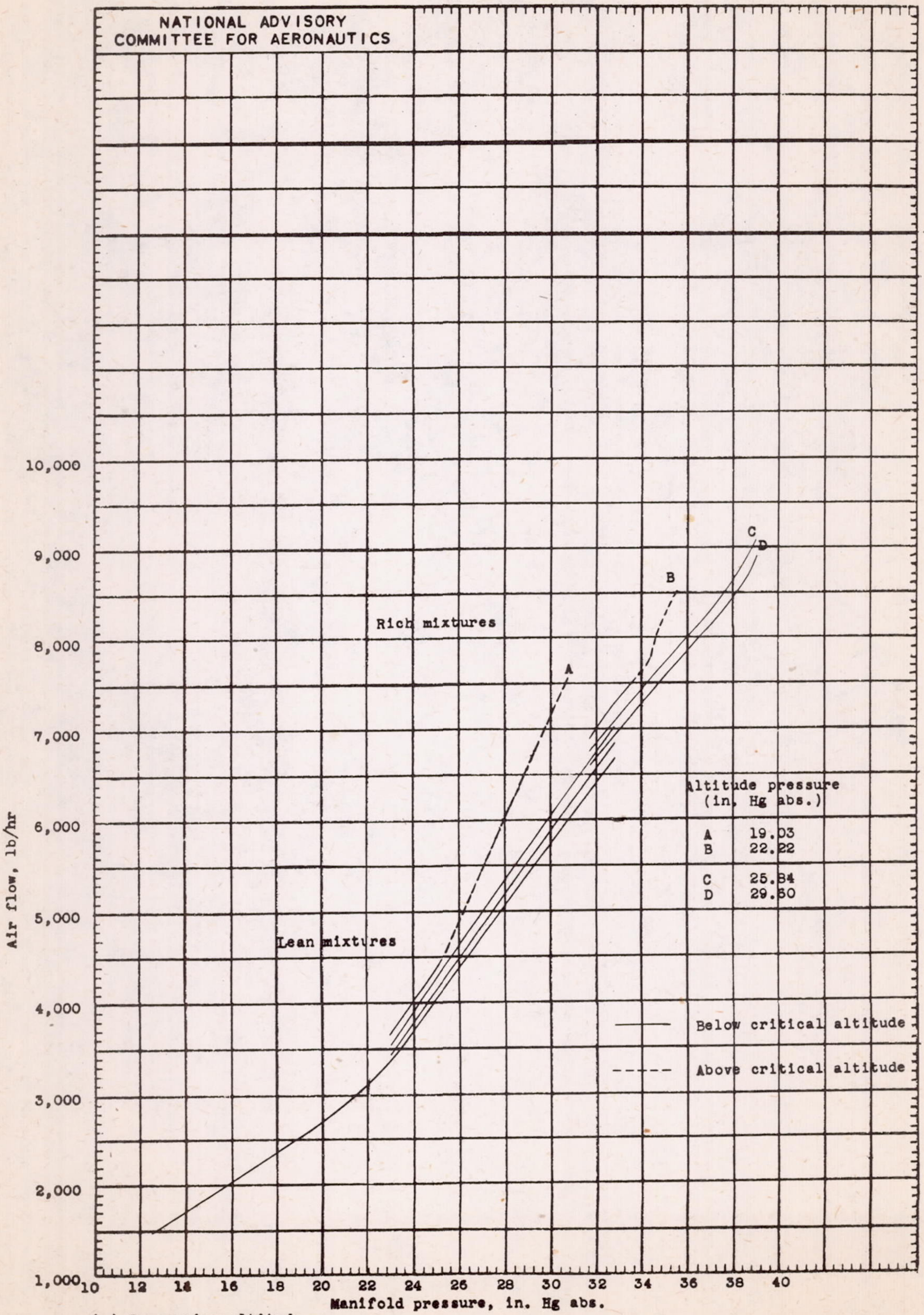
Figure 20. - The effect of altitude-density ratio on fuel flow.

E-192



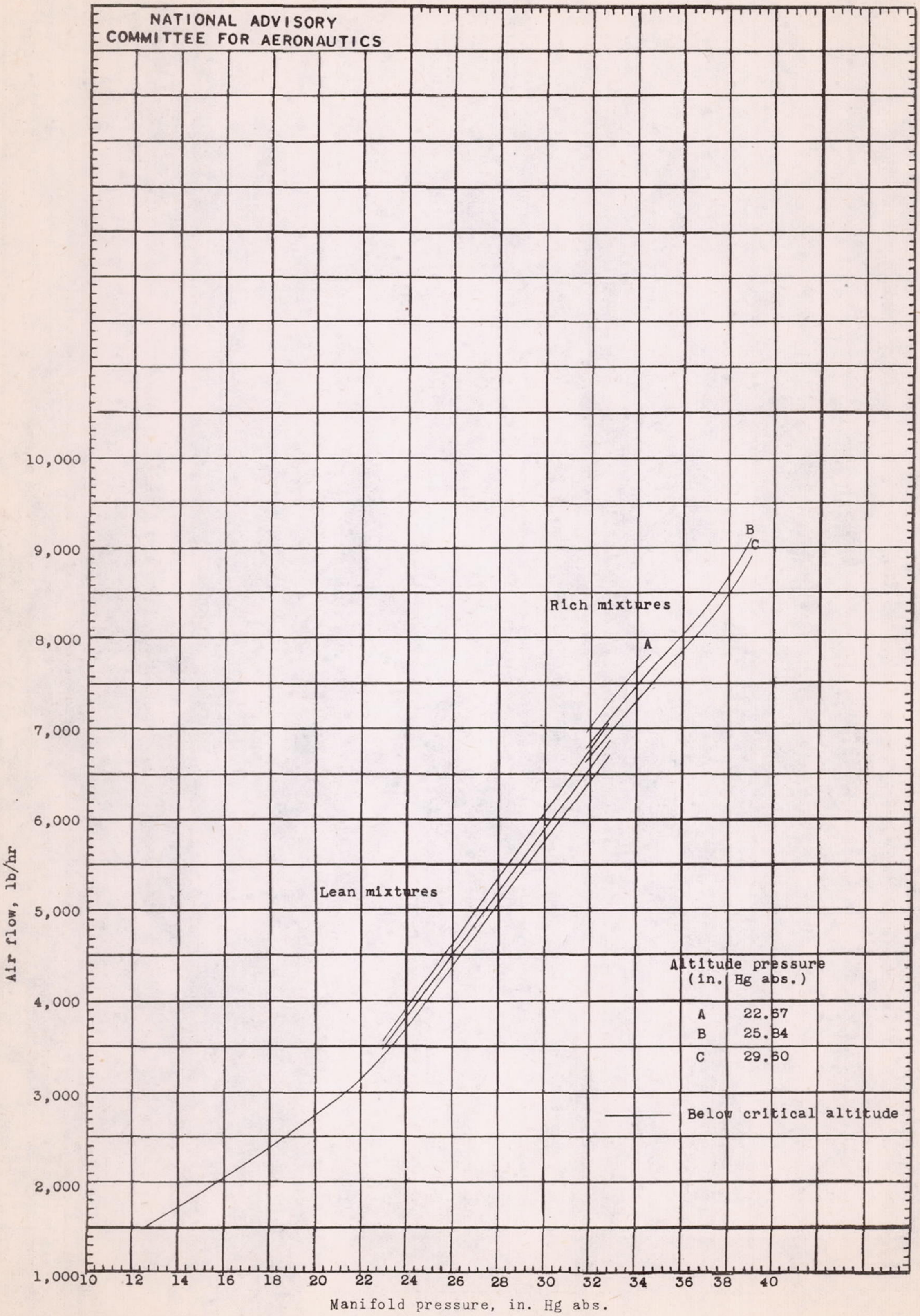
(b) Decreasing altitude.

Figure 20. - Concluded. The effect of altitude-density ratio on fuel flow.



(a) Increasing altitude.

Figure 21. - The effect of manifold pressure on calculated air flow with supercharger in low gear.



(b) Decreasing altitude.
Figure 21. - Concluded. The effect of manifold pressure on calculated air flow with supercharger in low gear.

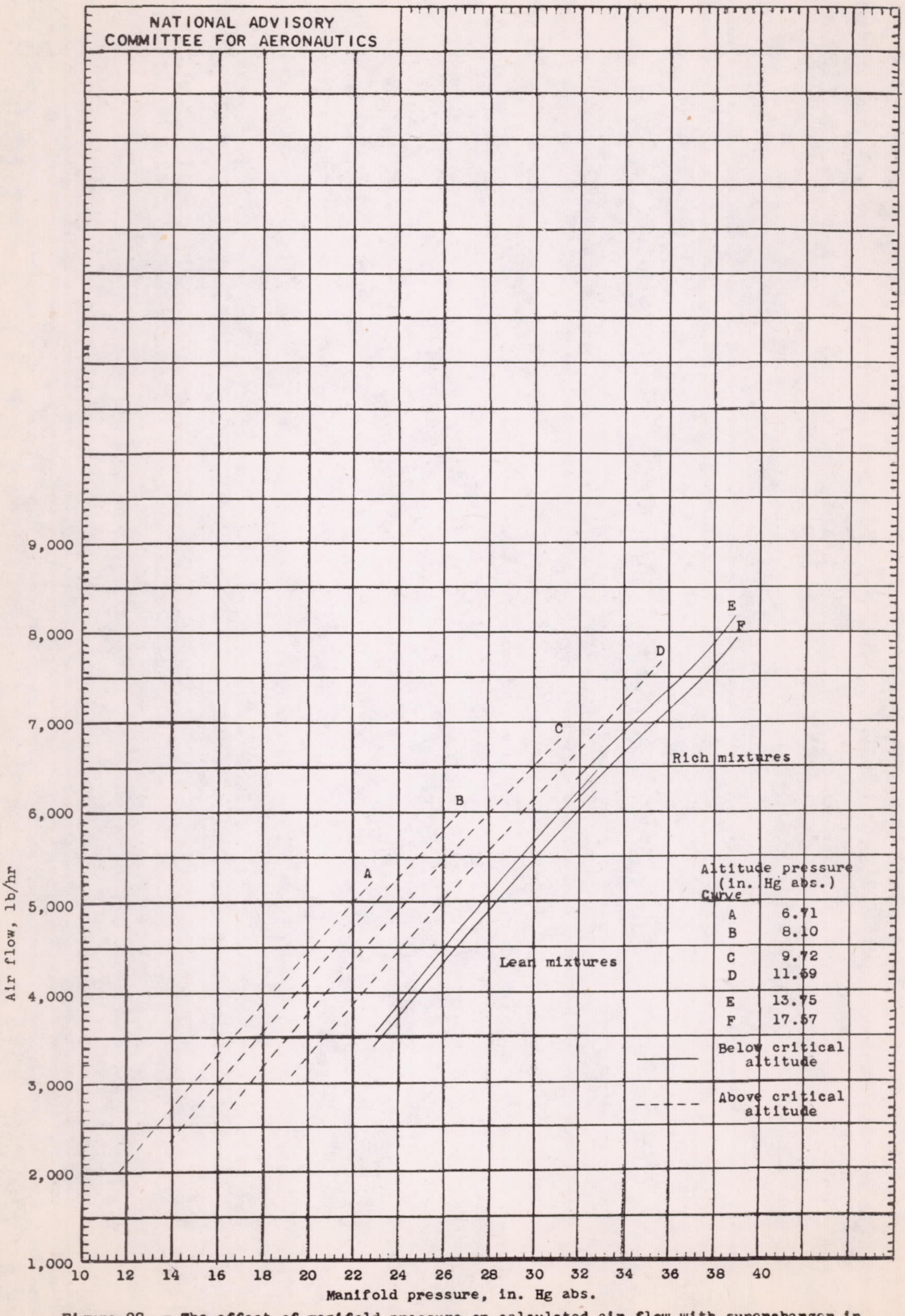


Figure 22. - The effect of manifold pressure on calculated air flow with supercharger in high gear. Increasing or decreasing altitude.

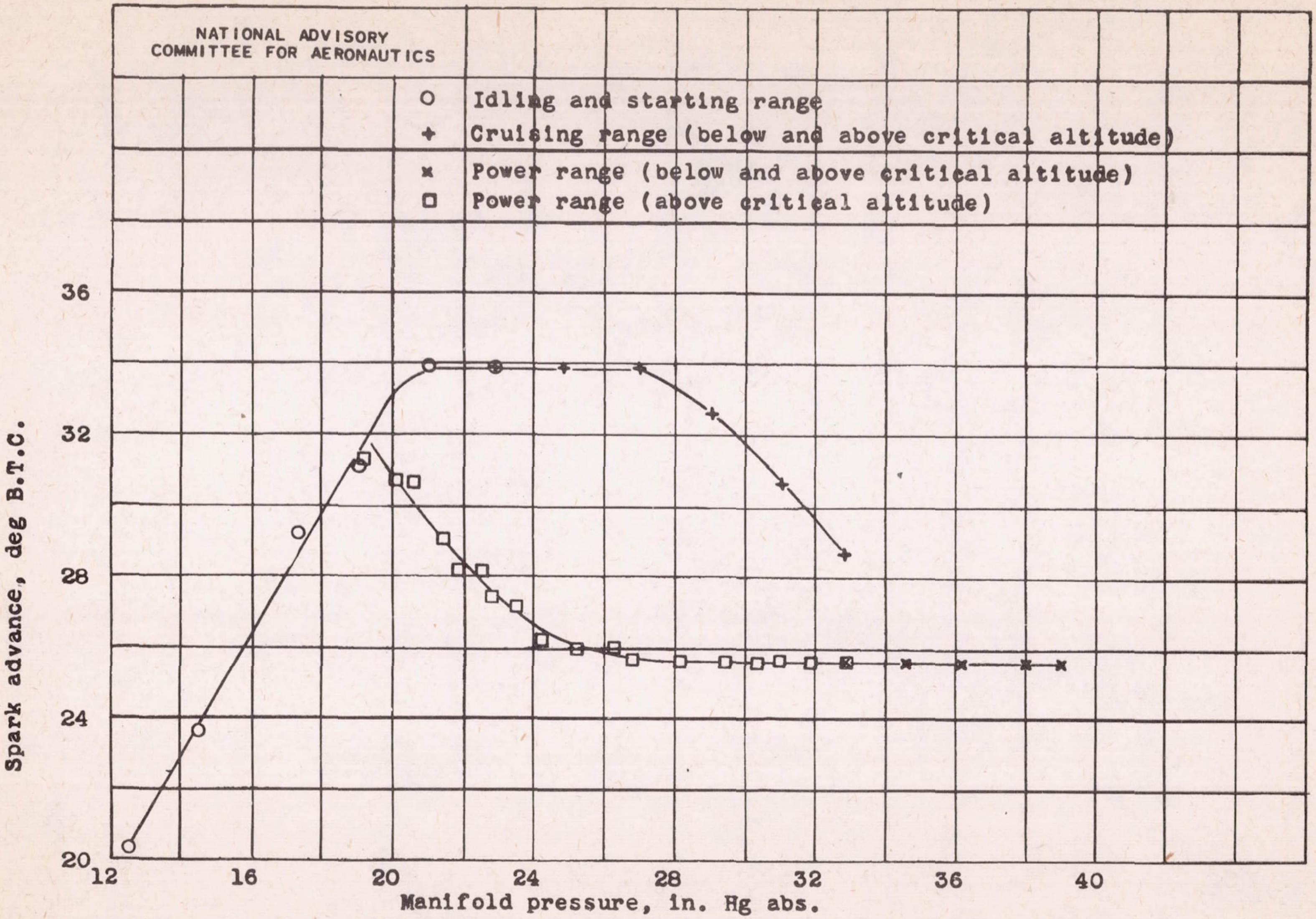


Figure 23. - The effect of manifold pressure on spark advance.

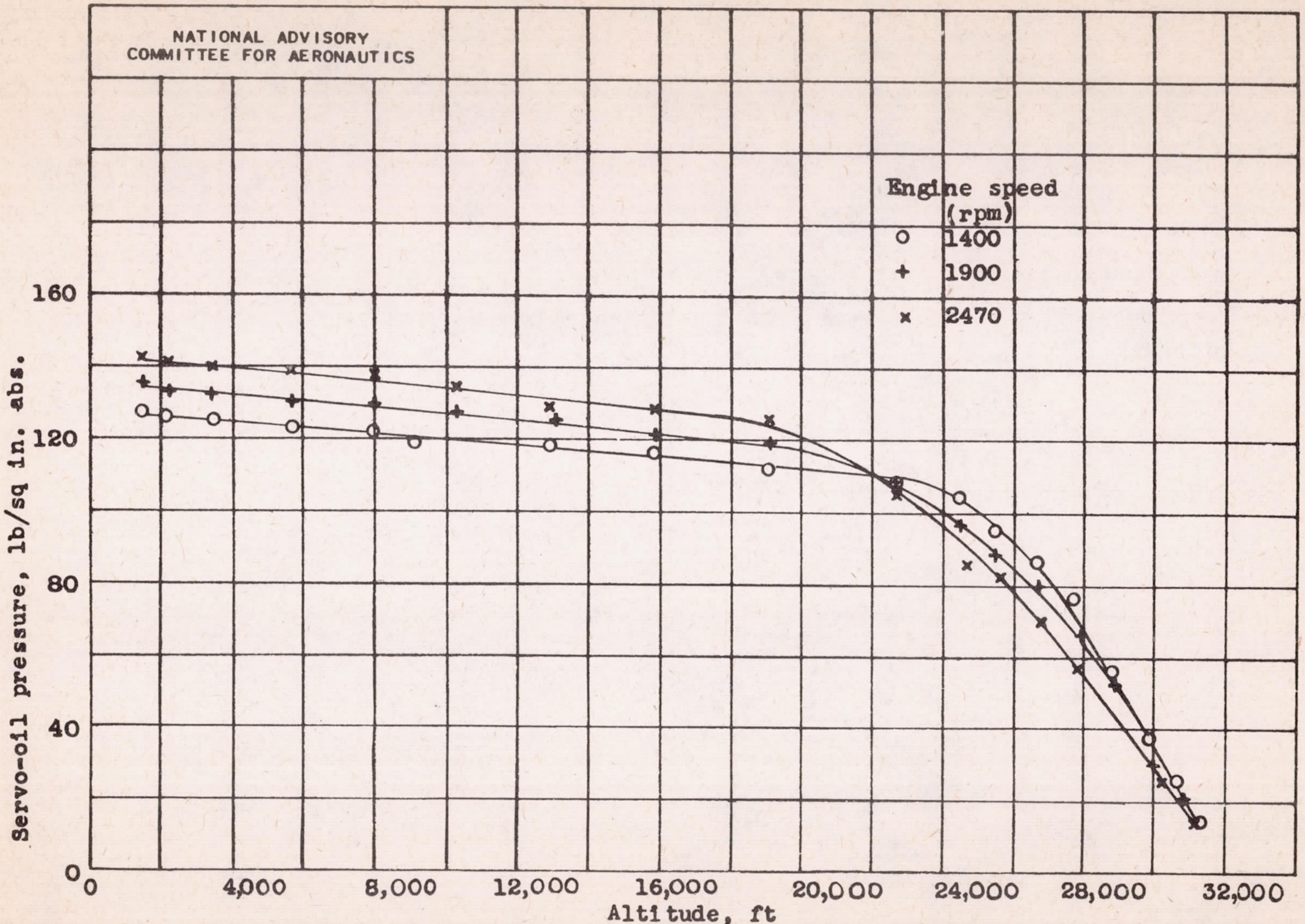


Figure 24. - The effect of altitude on the discharge pressure of the servo oil-pressure pump.

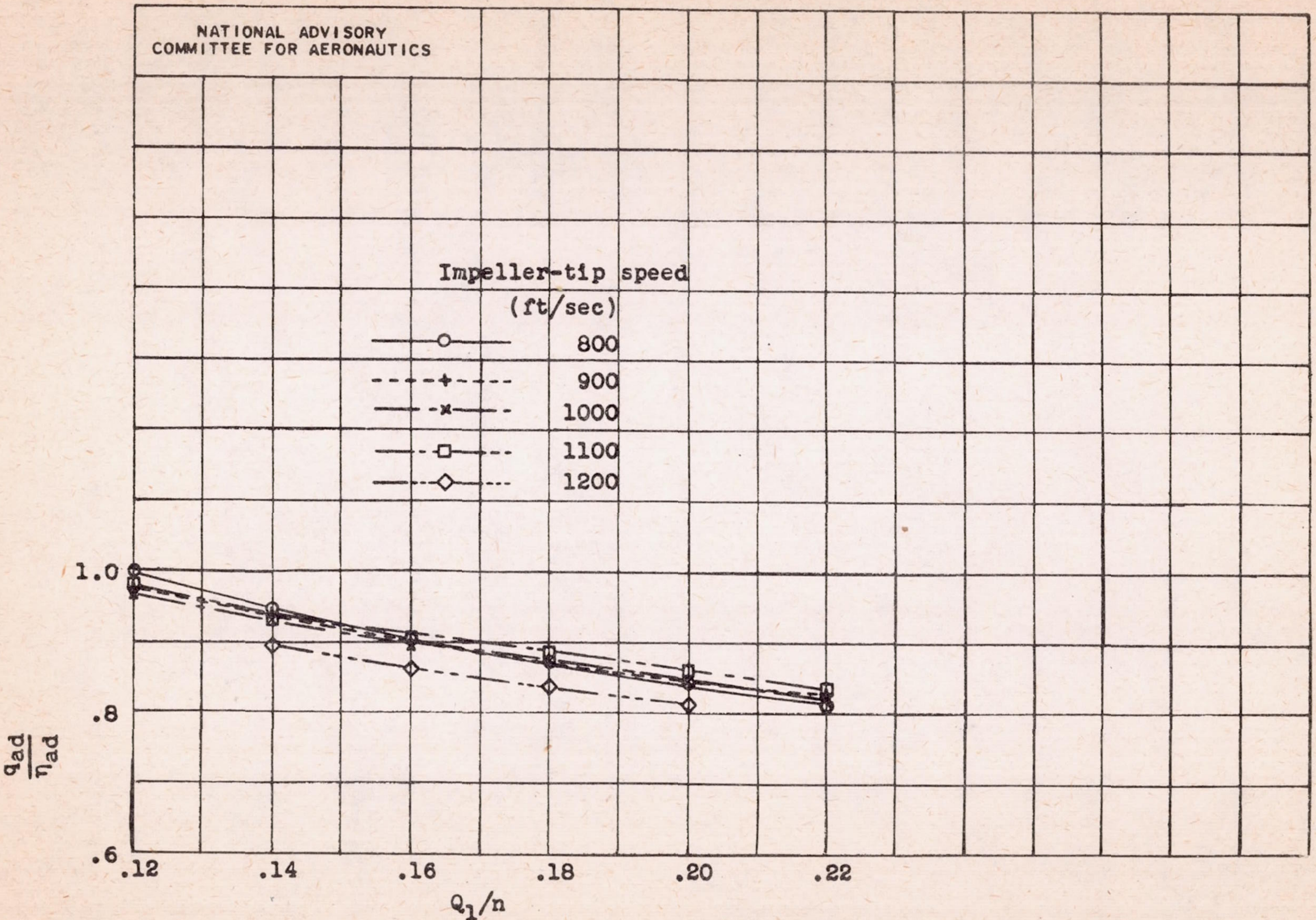


Figure 25. - The relation between the load coefficient Q_1/n and the ratio q_{ad}/η_{ad}