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# RESEARCH MEMORANDUM

## AN ANALYSIS OF CONTROL REQUIREMENTS AND CONTROL PARAMETERS FOR DIRECT-COUPLED TURBOJET ENGINES

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RESEARCH MEMORANDUM

# AN ANALYSIS OF CONTROL REQUIREMENTS AND CONTROL PARAMETERS FOR DIRECT-COUPLED TURBOJET ENGINES

By David Novik and Edward W. Otto

## SUMMARY

Requirements of an automatic engine control, as affected by engine characteristics, have been analyzed for a direct-coupled turbojet engine. Control parameters for various conditions of engine operation are discussed. A hypothetical engine control is presented to illustrate the use of these parameters.

An adjustable-speed isochronous governor was found to offer a desirable method of over-all engine control. The selection of a minimum value of fuel flow was found to offer a means of preventing unstable burner operation during steady-state operation.

Until satisfactory high-temperature-measuring devices are developed, air-fuel ratio is considered to be a satisfactory acceleration-control parameter for the attainment of the maximum acceleration rates consistent with safe turbine temperatures. No danger of unstable burner operation exists during acceleration if a temperature-limiting acceleration control is assumed to be effective.

Deceleration was found to be accompanied by the possibility of burner blow-out even if a minimum fuel-flow control that prevents burner blow-out during steady-state operation is assumed to be effective. Burner blow-out during deceleration may be eliminated by varying the value of minimum fuel flow as a function of compressor-discharge pressure, but in no case should the fuel flow be allowed to fall below the value required for steady-state burner operation.

## INTRODUCTION

An analytical investigation is being conducted at the NACA Cleveland laboratory to determine requirements of automatic engine

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controls for turbojet engines. As part of this investigation, the requirements of an automatic engine control for a direct-coupled turbojet engine with a fixed exhaust-nozzle area have been analyzed.

The turbojet engine was originally considered to require only a very simple control system. Experience h&s shown, however, that turbojet engines may encounter difficulties that result from excessive engine speeds, from excessive temperature, and from unstable burner operation. With manual control, the operation of the engine within safe limits of speed, temperature, and burner operation is left to the discretion of the pilot, and the possibilities of engine failure are thereby increased. As au alternative to manual control, the engine design c&n be so restricted that sane of the engine difficulties are eliminated or minimized, but this restriction is usually accomplished at substantial cost in thrust output and efficiency. An automatic engine control is therefore desirable in order to eliminate engine operating hazards, to relieve the pilot of responsibility for functions that may be difficult or impossible to perform under all conditions of operation, and to maintain optimum engine performance.

A prerequisite for the design of an automatic engine control is a knowledge of the engine-control requirements and the control p&r&meters that are indicative of these requirements. The variables of direct-coupled jet-engine operation are discussed and evaluated as p&r&meters upon which the control of the engine operating conditions may be based in order that the full performance potentialities of the engine may be realized without exceeding safe operating limits. The control requirements and oontrol parameters for steady-state operation, acceleration, and deceleration are analyzed, end a hypothetic&l oontrol based on this &n&lysis and suoh other considerations as starting, idling, stopping, and emergency fuel supply is described-in appendix A.

Data from a typic&l direct-coupled turbojet engine installed in a typical high-speed aircraft in level flight are used as a basis for the determination of engine-control requirements.

## STEADY-STATE OPERATION

The desired characteristics of a steady-state control for any type of engine may be summarized as follows:

1. The control should cause the engine to so operate that the desired operating characteristics of the driven m&chine are obtained.

2. The control should limit the engine to safe and stable operating conditions.

3. The oontrol should operate the engine at maximum economy under all conditions when the engine design is such that this type of operation is possible.

763

In a turbojet engine with a direct-coupled turbine and cam-pressor and a fixed exhaust-nozzle area (fig. 1), the required engine thrust at each altitude and airplane speed is obtained from the combustion of a definite amount of fuel. All other engine variables and efficiencies are therefore predetermined when the choice of altitude and airplane speed is made. This characteristic precludes any consideration of engine efficiencies in the design of a steady-state control, and the control problem for the turbojet engine then resolves itself into the most desirable method of controlling the fuel flow to obtain characteristics 1 and 2.

## Basic Steady-State Control Methods

From the foregoing considerations, three general methods of control are possible:

1. The airplane speed may be maintained constant regardless of aircraft altitude or attitude by a variably set airplane-speed-sensitive device controlling the fuel flow.

2. The airplane speed may be maintained constant regardless of aircraft altitude, but only in level flight, by a control calibrated to the level-flight relation of fuel flow and airplane speed of a particular combination of airplane and engine.

3. An engine parsmeter (speed, temperatures, and so forth) may be controlled, which for constant values of the parsmeter results in a substantially constant level-flight airplane speed for all altitudes, if such a parameter exists.

Before any of these methods can be considered feasible control methods, the relation between the controlling parameter, or variable, and the fuel flow must be shown to vary consistently over the power and altitude ranges; that is, no double values of fuel flow should exist for any value of the controlling parameter.

Constant-airplane-speed control for all altitudes and. attitudes. The relation of airplane speed to fuel flow for steady-state operation in level flight is shown in figure 2. The course of variation

of fuel flow with airplane speed is consistent over the power range and at each altitude; therefore, this method of control can be considered feasible by this criterion. An absolute constant-airplane-speed control,. however, would vary the fuel flow until the speed setting was satisfied, which would cause undesirable fluctuations in engine speed during climb end dive maneuvers. These unwanted accelerations and decelerations could materially shorten the life of the engine. A control of this type would also give airplane-speed-control characteristics that are unfamiliar to pilots.

Constant-airplane-speed control for all altitudes in level flight.-- A control to maintain airplane speed constant in level flight only would be so altitude-compensated that at a given control-lever setting the correct amount of fuel would be metered to the engine at each altitude to obtain a given airplane speed according to the relation of fuel flow to airplane speed shown in figure 2. This method of control would not attempt to hold the airplane speed constant during climb and dive maneuvers snd therefore would not cause serious fluctuations in engine speed although some changes in engine speed would result because of the change in ram pressure. Also, because the relation of fuel flow to airplane speed is consistent at each altitude, this method of control can be considered feasible. This method is similar to the compensated-fuel-control method in use on soms of the current turbojet engines.

Engine-parameter control. - The use of an engine parameter as an indirect means of controlling the airplane speed is a direct control of the engine. Engine parameters in general, however, do not necessarily bear a consistent relation to airplane speed. If a parameter is found that results in a substantially constant airplane speed for a given value of the parsmeter, then this parameter would present a more desirable means of control than those previously suggested.

The relations between fuel flow and the parameters, burner-outlet temperature, air-fuel ratio, net thrust, and engine speed, are shown in figures 3 to 6, respectively. The parameters burner-outlet temperature and air-fuel ratio (figs. 3 and 4, respectively) do not bear a consistent relation to fuel flow (acme of the curves have two possible values of fuel flow at a single value of the parameter) and are therefore unsuitable for control. In addition, burner-outlet temperature is very difficult to measure. Net thrust does bear a consistent relation to fuel flow, but at a constant value of net thrust the airplane speed varies widely with changes in altitude (fig. 5). Engine speed (fig. 6) varies consistently with fuel flow and at airplane speeds greater than approximately

350 to 400 miles per hour a constant value of engine speed results in a substantially constant airplane speed for level flight. Therefore, this method can also be considered a feasible method of control.

## Choice of Control Method for Steady-State Control

As indicated previously, the use of a variably set airplane-speed-sensing device controlling fuel flow as a basic steady-state-control method results in undesirable accelerations and decelerations of the engine during climb and dive maneuvers. Each of the other methods of control results in a substantially constant airplane speed regardless of altitude for a given control-lever setting, but only in level flight, and avoids undesirable accelerations and decelerations of the engine. These methods thus achieve the desirable characteristic of constant airplane speed for level flight for each control-lever setting without undesirable fluctuations of engine speed. Level-flight constant-airplane-speed control and engine-speed control are therefore considered more practical than the absolute constant-airplane-speed method. Between these two methods the choice is about equal except for the following reasons, which favor the use of engine speed as a control method:

1. A speed governor is required to limit maximum engine speed regardless of the method used for steady-state control and its use as the basic steady-state control eliminates the need for additional control components.

2. Altitude compensation is unnecessary except that an adjustment of governor sensitivity with altitude would probably be required.

The use of engine speed as a basic steady-state-controlmethod is therefore considered the most satisfactory method.

## Engine Limitations

Limitation on engine speed and burner-outlet temperature by turbine stress. - Control of the turbojet engine requires consideration of the *stress* limitations of the turbine wheel, which are due to the combination of high temperatures and high peripheral velocities to which the turbine is subjected. Inasmuch as the turbine-blade temperature (turbine-blade temperature being assumed proportional to burner-outlet temperature) snd engine speed increase simultaneously at their high values (fig. 7), a condition of simultaneous maximum allowable temperature and maximum allowable

engine speed exists for steady-state operation at maximum airplane speed at sea level. The most obvious method for the prevention of excess turbine stress is by the use of a governor that limits engine speed and coincidentally limits engine temperatures. Such amethodis now commonly used.

Prevention of unstable burner operation. - In addition to the stress limitations of the turbojet engine, a region of unstable burner operation may exist where combustion becomes erratic and blow-out occurs. The parameters that influence burner operation must therefore be investigated. A discussion of the effects of inlet velocity, inlet temperature, inlet static pressure, and burner temperature rise on burner operation is presented in reference 1. The turbojet engine is usually so designed that the adverse effects of high inlet velocities and low inlet temperatures on burner efficiency are avoided. Thus, for a given engine these effects of inlet-air velocity and temperature are small. Furthermore, for an engine in which critical flov exists at the turbine nozzles, the burner velocity and temperature can be expressed as functions of the burner pressure and temperature rise (reference 2) so that a region of stable burner operation similar to that shown in figure 8 (reproduced from reference 3) may be expressed in terms of the temperature rise through the burner and the burner pressure, which may be assumed equal to the compressor-discharge pressure.

If steady-state operating conditions are superimposed on figure 8, as in figure 9, it may be seen that for certain conditions of steady-state operation the limits of stable burner operation can be exceeded. For example, the points at airplane speeds of 200 and 300 miles per hour for an altitude of 35,200 feet and the paint at 200 miles per hour for 25,050 feet are outside the boundaries of the burner-operation curve. A means for preventing attempted engine operation at conditions that could result in burner blow-out must therefore be determined.

Examination of figure 9 reveals that a compressor-discharge pressure maintained above 18 pounds per square inch absolute would eliminate attempted engine operation outside the region of combustion stability. Maintenance of this pressure would, however, also eliminate possible engine operation over a wide range of airplane speeds at the high altitudes in which engine operation would normally be possible. Maintenance of a fixed minimum compressor-discharge pressure is consequently not regarded as a completely satisfactory method of limiting engine operation to the region of stable burner operation.

A study of figures 6 and 9 shows that in the region of operation where burner blow-out occurs low values of fuel flow are used. This relation suggests the possibility of avoiding burner blow-out by setting a minimum value of fuel flow. Fuel flow is plotted against burner temperature rise in figure 10 (for calculations, see appendix B) and the results indicate that for these data a minimum fuel flow of 1025 Rounds per hour would eliminate the points of steady-state operation that fall outside the region of stable burner operation (fig. 9). In the lower right-hand corner of figure 10, the critical region of burner operation is replotted and the dashedcurve shows the approximate limit of the range of burner operation permitted by the selection of a minimum fuel flow of 1025 pounds per hour.

The attainment of engine ceiling depends upon the burner-stability characteristics. As altitude is increased, the selected minimum fuel flow results in increased engine speeds, possibly up to the altitude at which minimum fuel flow would result in maximum allowable engine speed (fig. 6). No definite statement can be made, however, that the altitude at which this maximum allowable engine speed would occur is the operational limit of the engine because before such an altitude is attained the compressor-discharge pressure may very possibly fall below the value required for burner operation. Insufficient data prevent a more complete analysis of the factors that affect engine ceiling.

## ACCELERATION

### Basic Operational Requirements

Acceleration of a direct-coupled turbojet engine is accomplished by an increase in the fuel-flow rate, which increases the temperature of the combustion gases and the speed of the turbine and the compressor. Inasmuch as fuel is added before air consumption is increased, rich air-fuel ratios are obtained until the turbine and the compressor reach the new equilibrium speed. Acceleration therefore produces combustion-gas temperatures that may cause the turbine-stress limitations to be exceeded.

For safe engine operation, the temperature should be limited to some maximum allowable value over the entire period of acceleration. At the same time, the temperature should be maintained at the maximum allowable value in order that maximum acceleration may be obtained. The allowable value of maximum temperature may be somewhat higher than that for steady-state operation because of the relatively short time required for acceleration snd because the final equilibrium engine speed is as yet unattained.

In this analysis, burner-outlet temperature is considered indicative of the limiting engine temperature. In actual practice, the temperature of the turbine blades is usually critical but turbine-blade temperature cannot be practically measured. Some other temperature must therefore be measured that is proportional to turbine-blade temperature during acceleration. Because all other combustion-gas temperatures are functions of the burner-outlet temperature, turbine-blade temperature has been assumed in this analysis to be a function of burner-outlet temperature.

Virtually any method used to determine the temperature of the combustion gases must necessarily assume a uniform temperature distribution through the various components of the engine. Over-all temperature indications cannot take into account local hot spots that could conceivably result in engine failure; consequently, problems of spray uniformity, fuel distribution, air distribution, and so forth, must be solved before any acceleration control csn be expected to function properly.

Direct-temperature measurement. - The operation of a temperature-limiting device for acceleration involves the measurement of the burner-outlet temperature and modulation of the fuel supply to prevent this temperature from exceeding the safe limit. Although a method of direct measurement of the temperatures encountered in turbojet engines is as yet undeveloped, such measurement would permit a straightforward method of acceleration control. The electromotive force from a thermocouple, for instance, could be amplified and used to position a valve in a fuel-bypass line.

Possibly the temperature of the exhaust gas in the tail pipe can be measured as an indication of the limiting temperature for acceleration. At this point, the temperature of the combustion gas is at its lowest value, and measuring devices such as thermocouples or differential-expansion instruments would be quite reliable. The temperature of the exhaust gas in the tail pipe, however, is not proportional to the burner-outlet temperature during acceleration, and engine investigations are required before it can be definitely ascertained whether the exhaust-gas temperature is substantially proportional to the turbine-blade temperature.

Burner heat balance. - Inasmuch as direct measurements of combustion-gas temperatures are as yet considered unsatisfactory, other means of obtaining en indication of burner-discharge temperature have been investigated. If a heat balance is taken across the burner, an equation for burner-outlet temperature can be obtained

in terms of air flow, fuel flow, and compressor-discharge temperature. On the basis of this heat balance, the possibilities of limiting burner-outlet temperature as a function of engine variables or of imposing either a maximum allowable fuel flow or a minimum allowable air-fuel ratio can be analyzed.

The heat added in the burner can be equated to the temperature rise of the masses involved as follows if the heat necessary to vaporize the fuel and to heat it to the inlet-air temperature is neglected (the error is small because the air flow is very large compared with the fuel flow):

$$W_f\, h\, \eta_b = W_a\, c_{p,a}\, (T_4 - T_3) + W_f\, c_{p,f}\, (T_4 - T_3)$$

$$= (T_4 - T_3)(W_a\, c_{p,a} + W_f\, c_{p,f}) \qquad (1)$$

where

$W_f$ weight rate of fuel flow

$h$ lower heating value of fuel

$\eta_b$ efficiency of burner

$W_a$ weight rate of air flow

$c_{p,a}$ average specific heat for air at constant pressure between temperatures $T_4$ and $T_3$

$T_4$ burner-outlet temperature

$T_3$ compressor-discharge (burner-inlet) temperature

$c_{p,f}$ average specific heat for fuel at constant pressure between temperatures T4 and $T_3$

Inasmuch as Wf is small compared with Wa, only a small error is introduced by assuming an over-all value of $c_p$ where $c_p$ is defined as the average specific heat for a mixture of air and fuel at constant pressure between the temperatures $T_4$ and T3. Equation (1) may then be simplified to

$$W_f\, h\, \eta_b = cp\, (T4 - T_3)(W_a + W_f)$$

and if $h/c_p = K$ where K is aconstant

$$W_f K \eta_b = (T_4 - T_3)(W_a + W_f) \tag{2}$$

Equation (2) can be rearranged and solved for burner-outlet temperature, for fuel flow, or for air-fuel ratio. If a maximum allowable value for $T_4$ is assumed, various maximum allowable values of fuel flow or minimum allowable values of air-fuel ratio can be obtained, depending upon engine operating conditions:

$$T_4 = T_3 + \frac{K \eta_b}{\frac{W_a}{W_f} + 1} \tag{3}$$

$$W_f = \frac{W_a}{\frac{K \eta_b}{T_4 - T_3} - 1} \tag{4}$$

$$\frac{W_a}{W_f} = \frac{K \eta_b}{T_4 - T_3} - 1 \tag{5}$$

Each of these equations may be investigated for use as an acceleration-control equation.

Maximum allowable temperature. - For the application of equation (3), the quantities represented by the variables on the right-hand side of the equation must be measured and the summation of these variables balanced against a constant that has been previously determined as the maximum allowable temperature $T_4$ for acceleration. The burner efficiency may be obtained as a function of burner temperature rise and compressor-discharge pressure (assumed equal to burner-inlet pressure) from figure 11 (reproduced from reference 3), and equation (3) can be rewritten as

$$T_4 = T_3 + \frac{K f\left[(T_4 - T_3), P_3\right]}{\frac{W_a}{W_f} + 1} \tag{6}$$

where

763

$P_3$ compressor-discharge pressure

The required number of measurements and integrating mechanisms necessary for an acceleration control based on the relations shown in equation (6) makes such a control one of prohibitive complications.

Maximum allowable fuel flow. - In equation (4), the burner efficiency may again be expressed as a function of compressor-discharge pressure P3 and burner temperature rise $T_4 - T_3$ (fig. 11); and the air flow $W_a$ can be expressed as a function of engine speed N, compressor-inlet pressure $P_2$, and compressor-inlet temperature T2 according to figure 12. Equation (4) then becomes

$$W_f = \frac{f(N, P_2, T2)}{\frac{K\, f\left[(T_4 - T_3),\ P_3\right]}{T_4 - T_3} - 1} \tag{7}$$

Because P3 and $T_3$ are functions of N, $P_2$, and $T_2$ and because $T_4$ may be taken as a constant assumed for the maximum allowable burner-outlet temperature during acceleration, the fuel flow can be expressed as a function of N, $P_2$, and $T_2$. Figures 13 to 15 illustrate these relations. (The calculations are presented in appendix B.) The calculations are based on a maximum allowable burner-outlet temperature of 2000° R, which is assumed to be the limiting temperature over the entire speed range. In figures 13 to 15, the maximum allowable fuel flow is plotted ss a function of two of the parameters for two values of the third parameter. In each case a variation of the third parameter raises or lowers the surface and also changes the shape. This characteristic indicates that the relation of the maximum allowable fuel flow to any combination of the three parameters N, $P_2$, and $T_2$ Is quite complicated and that a control based on these parameters would be virtually impossible to construct.

Minimum air-fuel ratio. - One variable is, in effect, eliminated from equation (2) by solving for air-fuel ratio as a single variable. When $T_4 - T_3$ and $P_3$ are substituted for burner efficiency in equation (5), the minimum allowable air-fuel ratio for the assumed maximum value for $T_4$ becomes a function of only two variables, $P_3$ and $T_3$.

763

$$\frac{W_a}{W_f} = \frac{K\,f\left[(T_4 - T_3),\ P_3\right]}{T_4 - T3} - 1 \tag{8}$$

Thus, for various values of P3 and $T_3$, there are minimum values of $W_a/W_f$ such that the maximum allowable temperature assumed for $T_4$ is attained but unexceeded. The variation of minimum allowable air-fuel ratio with compressor-discharge temperature and pressure is shown in figure 16, which is based on a maximum allowable burner-outlet temperature of 2000° R. (For calculations, see appendix B.)

Equation (8) and figure 16 indicate that an acceleration control based on air-fuel ratio can be considered feasible. Such a control would consist of a device to measure the air-fuel ratio to the engine and balance it against the indication of the minimum allowable air-fuel ratio obtained from the integration of P3 and $T_3$.

### Acceleration as Limited by Burner Operation

As in steady-state operation, the possibility may exist that acceleration can bring the engine into the region of unstable burner operation shown in figure 8. With an assumed maximum allowable burner-outlet temperature of 2000° R, the burner temperature rise at the first instant of acceleration has been calculated for various initial airplane-speed and altitude conditions of steady-state operation. The results of these calculations are shown in figure 17, superimposed on the burner-operation curve of figure 8. For the data used, acceleration would always be within the region of stable burner operation. The trends indicate, however, that for allowable burner temperatures appreciably above the assumed value of 2000° R, the limits of stable burner operation could be exceeded during acceleration. This possibility is precluded by the use of an acceleration control that limits the maximum burner temperature to a suitable value.

## DECELERATION

Analysis of the control requirements for deceleration involves only the limiting conditions of burner operation. The region of unstable burner operation may be encountered during deceleration because a sudden decrease in fuel flow is accompanied by a rapid reduction in burner-outlet temperature such that the

763

temperature rise may be below that required for stable burner operation. The temperature rises that would exist upon instant deceleration to a minimum fuel flow of 1025 pounds per hour (with no instantaneous reduction in compressor-discharge pressure or engine air flow assumed) have been calculated by the method shown in appendix B, and the results are shown in figure 18 together with the burner-operation limits defined by figure 8 and the steady-state burner-operation points.

When the fuel flow is suddenly reduced to the minimum value during operation at high airplane speeds at low altitudes, a strong possibility exists that the temperature rises obtained would be below those required for stable burner operation (fig. 18). (The combustion efficiencies obtained from fig. 11 require extrapolation in this region and are therefore subject to error.) Although a fixed minimum fuel flow is satisfactory for maintaining burner operation during steady-state operation, it is unsatisfactory for deceleration.

If the burner temperature rises are arbitrarily limited to minimum values of 25° F above the boundary line between stable and unstable burner operation (shown in fig. 8), values of fuel flow can be determined below which the temperature rise can be assumed to be too low for stable burner operation. The fuel flows thus obtained would introduce a safety factor of 25° F in the temperature rises required for stable burner operation. These calculations are given in appendix B and the results are plotted. in figure 19. A line starting at a minimum fuel flow of 1025 pounds per hour can be drawn that represents a good approximation of the minimum fuel flow required to insure a temperature rise sufficient for the maintenance of burner stability upon deceleration. An initial minimum fuel flow of 1025 pounds per hour is chosen because this value satisfies the requirements for stable burner operation during steady-state operation, as shown previously. The minimum fuel flow as indicated by the heavy line of figure 19 is always below the normal steady-state operating requirements and therefore deceleration is always possible.

Because the chosen relation between minimum fuel flow and compressor-discharge pressure, as shown by the heavy line of figure 19, provides for the stable-burner-operation requirements of steady-state operation and deceleration, fuel flow as a function of compressor-discharge pressure may be considered the one parameter for prevention of unstable burner operation under any engine condition.

763

## CONCLUSIONS

An analysis was made of the control requirements and control parameters of a direct-coupled turbojet engine. Although specific data were used, the results and methods of analysis are believed to be applicable to any turbojet engine of the direct-coupled type. The following conclusions were reached:

1. An adjustable-speed isochronous governor offers a desirable means of engine control for steady-state operation because: (a) Engine speed varies consistently with fuel flow; (b) at high engine speeds, a substantially constant airplane speed is maintained for a constant engine speed regardless of altitude; (c) altitude compensation is not required; and (d) a governor is required to limit maximum engine speed regardless of the method used for steady-state control. The possibility of burner blow-out at low airplane speeds and high altitudes may be eliminated by setting a suitable minimum fuel flow that eliminates attempted aircraft operation at these points.

2. Limiting the minimum allowable air-fuel ratio as a function of compreseor-discharge pressure and temperature offers a feasible method of acceleration control until satisfactory instruments are developed for directly measuring high temperatures. The temperature limit imposed by an acceleration control also prevents the engine from entering a region of unstable burner operation during acceleration.

3. Deceleration is accompanied by the possibility of unstable burner operation (or possibly blow-out) especially during maximum attempted deceleration from higb airplane speeds at low altitudes. A fixed minimum fuel flow cannot practicably eliminate this possibility, but a minimum fuel-flow setting that is varied as a function of compressor-discharge pressure appears to offer a satisfactory solution. The required minimum fuel flow increases with increasing compressor-discharge pressure and, if the lower limit of fuel flow is fixed at the value required by blow-out limits for steady-state burner operation, compressor-discharge pressure may be used as a control parameter for the prevention of unstable burner operation under any engine condition.

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# APPENDIX A

## DESCRIPTION OF A HYPOTHETICAL CONTROL

In order to clarify and expand the discussion of control parameters, a hypothetical engine control is presented (fig. 20). The analysis has shown that an automatic engine control should perform the following functions:

1. Control fuel flow during steady-state operation for maintenance of constant engine speed

2. Limit maximum allowable engine speed

3. Prevent excessive burner-outlet temperatures during acceleration and permit attainment of maximum acceleration

4. Eliminate possibility of engine operation in regions of unstable burner operation

5. Provide for starting, idling, and stopping the engine

6. Provide emergency fuel control

Speed control. - Requirement 1 is fulfilled by an adjustable-speed isochronous governor x (fig. 20) that operates a balanced bypsss valve l by which fuel effectively bypasses the fuel pump. The governor is set for various speeds by setting a linkage p that determines the engine speed at which a pilot valve m covers the pilot-valve ports. Amodulating piston n causes the governor to so anticipate its setting during changes in speed that, as the engine approaches the set speed, the governor starts changing the fuel flow toward the value required for the new set speed. A small slot o causes the modulating piston to return to the same position at equilibrium conditions and thus keeps the governor linkage in calibration. The function of the modulating piston is to prevent overshooting and hunting.

Requirement 2 is fulfilled by a stop k on the pilot's control lever to prevent the pilot from setting a speed that might cause overstress of rotating parts.

Acceleration control. - A control that maintains and limits burner-outlet temperature at the maximum allowable value provides the maximum permissible acceleration of the engine. As shown in

figure 16, the burner-outlet temperature msy be maintained at any chosen value of maximum allowable temperature by providing the proper air-fuel ratios, which depend on the compressor-discharge temperature and pressure. Equation (8) may be used as the control equation and with a value for $T_4$ assumed at 2000° R is

$$\frac{W_a}{W_f} = \frac{K\ f\left[(2000 - T_3),\ P_3\right]}{2000 - T3} - 1$$

If it is assumed that the air flow is measured by a pitot-static tube inserted in a compressor-discharge passage and the fuel flow is measured by an orifice in the fuel line, the preceding equation becomes

$$\frac{C\ A_a\sqrt{C_1\ P_3/T_3\ \Delta P_a}}{C_2\ A_f\ \sqrt{\rho_f\ \Delta P_f}} = \frac{K\ f\left[(2000 - T_3),\ P_3\right]}{2000 - T_3} - 1$$

where

$C, C_1, C_2$ constants

$A_a$ total. area of air-flow passages in one of which pitot tube is installed

$A_f$ area of fuel orifice

$\rho_f$ fuel density

$\Delta P_a, \Delta P_f$ pressure differentials from air- and fuel-measuring elements, respectively

If $A_a$ and $\rho_f$ are combined with the constants $C, C_1, C_2,$ and $K$ to form one constant $K_1$, this equation may be expressed as

$$\frac{\sqrt{P_3/T_3\ \Delta P_a}}{A_f\sqrt{\Delta P_f}} = \frac{K_1\ f\left[(2000 - T_3),\ P_3\right]}{2000 - T_3} - 1 \qquad \text{(A1)}$$

Because the excess fuel must be bypassed back to the pump inlet in order to provide a feasible method of control, the pressure differentials AD, and $\Delta P_f$ may be equated by a set of balanced diaphragms

(with $\Delta P_a$ Imposed across one diaphragm and $\Delta P_f$ imposed across an opposing diaphragm), which operate a balanced bypass valve. The only remaining variable In equation (Al) capable of being varied as a function of P3 and $T_3$ is the area $A_f$ and equation (Al) becomes

$$A_f = \frac{\sqrt{P_3/T_3}}{\dfrac{K_1 \; f\left[(2000 - T_3), P_3\right]}{2000 - T_3} - 1} \qquad \text{(A2)}$$

which gives the required variation of the area $A_f$ with the pressure $P_3$ and temperature $T_3$ to obtain a burner-outlet temperature of 2000° R. This variation may be obtained by the same method used to obtain figure 16 (see appendix B), that is, by assuming values of $P_3$ and $T_3$ and solving for $A_f$. The term $f\left[(2000 - T_3), P_3\right]$ is the burner efficiency $\eta_b$ and requires the use of a burner-calibration curve similar to figure 11.

The acceleration control (fig. 20), which limits the burner-discharge temperature, consists of the following: (1) a balanced-diaphragm assembly b (subjected to the air- and fuel-pressure differentials) that operates a balanced bypass valve c; and (2) a pressure-sensitive bellows f subjected to the pressure P3 and a temperature-sensitive bellows d subjected to the temperature $T_3$ that operate a drum cm e, which in turn varies the area of valve h. The pilot valve g and the servopiston i are required only if power amplification is necessary. The drum cam embodies the required relation of area $A_f$ to $P_3$ and $T_3$ shown in equation (AZ). The necessary control of fuel flow is obtained by imposing the fuel-pressure differential. from the fuel-metering valve h across the fuel diaphragm of the balanced-diaphragm assembly b.

The acceleration control acts to maintain the temperature at the maximum allowable value for acceleration. When the governor has control of the engine, the temperature is below this maximum value and the force on diaphragm assembly b is unbalanced in a direction that keeps bypass valve c closed. If the governor is set for a higher speed, it causes a sudden increase in fuel flow. When the fuel flow increases to a value sufficient to obtain the maximum allowable burner-outlet temperature, the diaphragms are balanced and any further increase in fuel flow causes sn unbalanced

force on the diaphragms, tending to open bypsss valve c. The governor thus has control of the engine at all times when the speed of the engine is close to the set speed and when the burner-outlet temperature is below the maximum allowable value. These devices fulfill requirement 3.

Minimum-fuel-flow control. - The minimum values of fuel flow that are necessary to prevent unstable burner operation during steady-state operation snd deceleration are shown in figure 19 as a function of compressor-discharge pressure. A control that would prevent the fuel flow from falling below the curve of figure 19 would fulfill requirement 4. The minimum-fuel-flow control consists of a diaphragm assembly v subjected to the pressure differential from a venturi r in the fuel line and to the force of a spring u, whose datum plane is varied by a bellows assembly z subjected to compressor-dischsrg pressure. When the fuel-pressure differential from the venturi r is at a value corresponding to the minimum fuel flow for the particular value of compressor-discharge pressure, the spring u is compressed sufficiently to center the pilot valve w. Whenever the fuel flow is above or below this value, the pilot valve operates bypass valve q, which is in series with the governor bypass valve 2, to adjust the fuel flow to the required value. This control is ineffective as long as the governor requires a fuel flow in excess of the specified minimum amount, but when the governor requires a fuel flow less than the specified minimum amount this control comes into operation to control the fuel flow at the minimum amount and the governor is out of control. A stop t provides for the minimum fuel flow at the low values of compressor-discharge pressure. (See fig. 19.) A cam s controlling the datum plane of spring u is necessary because the relation of pressure differential to weight flow from a venturi is a second-parer function rather than a linear function.

Visual extrapolation of figure 6 shows that an altitude exists at which the minimum fuel flow of 1025 pounds per hour selected for these data causes the engine to run at maximum speed. This statement assumes that the compressor-discharge pressure remains above the limiting value for safe burner operation. (See fig. 8.) At this point there is a choice in method of control: to allow the engine speed to increase beyond the maximum allowable value (the governor being out of control), or to keep the engine speed at the maximum allowable value and allow the engine to enter the region of unstable burner operation. The second alternative is preferable because overspeed may cause failure of rotating parts. The control function may be accomplished by causing the governor to

763

contact the pilot valve w when the governor reaches the maximum allowable speed and thus open the by-pass valve q and prevent the speed from exceeding the maximum allowable value. The engine speed at which the governor contacts the pilot valve w, however, must be slightly higher than the maximum speed determined by the stop k on the governor-setting lever in order that, when set for maximum speed during normal operating conditions, the governor does not attempt to control by-pass valves 2 and q simultaneously. The maximum speed as determined by the point at which the governor contacts the pilot valve w would then be the maximum allowable engine speed end would be obtained only when an altitude is reached at which the minimum fuel flow would cause the engine to run at this maximum speed.

Starting, idling, and stoppingcontrols. - The engine may be started by setting valve a to the manual position (fig. 20), advancing the governor-setting lever upon the attainment of starting speed, end then reducing the setting to the idle position after the engine starts.

The control shown in figure 20 is based on the assumption that the minimum fuel flow as regulated by the minimum-fuel-flow control will correspond to the idling fuel flow of the engine at sea level. For engines in which the minimum fuel flow does not correspond to the idling fuel flow, a linkage must be provided on the governor-setting lever so that, when the governor-setting lever is against the idle stop, the linkage positions the datum plane of spring u to obtain the idling fuel flow. This linkage should be so designed that it is effective only when the pilot's control lever is set to the idle position.

The engine is stopped by turning valve a to the shutoff position.

Emergency control. - Emergency control &the engine is provided by a bypass line controlled by valves a end j end check valve y. In the event of failure of the normal fuel-control system, the emergency system is put into operation by valve a. The emergency control valve j is then operated by the same lever used to control the engine with the normal fuel control.

## APPENDIX B

## TYPICAL CALCULATIONS

763

Steady-state operating characteristics. - The data used for plotting figures 2 to 7 were obtained from typical operating data for a direct-coupled turbojet engine installed in a high-speed airplane, typical operating data for a turbojet burner (reference 3), and typical engine static data (reference 4). These data are presented as curves in figures 8, 11, 12, and 21 to 24. In some cases the curves had to be extrapolated to extend the range of calculations. These extrapolations are shown by dotted lines.

Engine speed, air flow, and fuel flow for various flight conditions. - In the calculations for figures 2 to 6, altitude and airplane speed were considered the main parameters effecting engine performance. The pressure and the temperature ahead of the compressor were determined for various flight speeds end altitudes. (NACA standard atmosphere end 100-percent rem-pressure recovery were used.) The equations used for total pressure and temperature at the Inlet to the compressor were

$$P_2 = P_1 + \frac{\rho_1 V_1^2}{2g}\left(1 + \frac{V_1^2}{4a^2}\right)$$

and

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

where

$P_1$ atmospheric pressure

$\rho_1$ atmospheric density

$V_1$ airplane speed

$g$ acceleration of gravity

$a$ local velocity of sound

$T_1$ atmospheric temperature

$\gamma$ ratio of specific heats of air at constant pressure and constant volume

The required thrust (drag = net thrust) for each flight condition was determined from figure 21. Then the engine speed to give that net thrust was found from figure 22. When the engine speed and the compressor-inlet conditions were known, the air flow and the fuel flow were read from figures 12 end 23.

Burner-outlet temperature and temperature rise for various flight conditions. - The conditions at the compressor discharge were determined from the relation of compressor pressure ratio and engine speed shown in figure 24. When compressor pressure ratio was corrected for compressor-inlet temperature variation and an adiabatic compressor efficiency of 73.3 percent was used. (reference 4), the temperature after compression was determined from

$$T_3 = T_2 + T_2 \left[ \frac{\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_c} \right] \tag{B1}$$

where

$\eta_c$ compressor efficiency

Burner-outlet temperature was then found by adding to the burner-inlet temperature the temperature rise in the burner, which was calculated by

$$T_4 - T_3 = \frac{h\,\eta_b}{c_p\left(1 + \frac{W_a}{W_f}\right)} \tag{B2}$$

The value for h was assumed to be 18,400 Btu per pound and the value of the over-all $c_p$ was assumed to be 0.26 Btu per pound °R.

Inasmuch as the burner efficiency is a function of $T_4 - T_3$, a trial-and-error method of solution of equation (B2) was used. The burner-outlet temperature for various flight conditions is first used in figure 3 and the burner temperature rise is first used in figure 9.

Acceleration characteristics. - The maximum allowable fuel flow for acceleration as a function of N, $P_2$, and T2 for figures 13 to 15 was obtained by calculations made with the assumption that during acceleration the burner-outlet temperature was maintained at 2000° R.

At the assumed value of N, the pressure ratio $P_3/P_2$ is determined for the assumed value of $T_2$ by correcting figure 24 according to the method previously described. The value of $P_3$ may then be determined for the assumed conditions of N, $P_2$, and T2. The value of $T_3$ that corresponds to the assumed inlet conditions is then calculated by equation (B1). The air flow that corresponds to the assumed inlet condition is determined by us8 of figure 12. The fuel flow necessary to obtain the assumed burner-outlet temperature is given by equation (5), *rearranged* as

$$W_f = \frac{W_a\ (2000 - T_3)}{70,800\ \eta_b - 2000 + T_3} \tag{B3}$$

The term $\eta_b$ may be determined from the burner pressure $P_3$ and the temperature rise 2000 - $T_3$ by use of figure 11. The computed values of $W_a$ and $T_3$ and the efficiency $\eta_b$ are then substituted in equation (B3) to obtain the fuel flow necessary to obtain a burner-outlet temperature of 2000° R for the assumed conditions of N, $P_2$, end $T_2$. Figures 13 to 15 were plotted by using the values of fuel flow obtained by this method for a series of values of N, $P_2$, end T2.

Figure 16 was plotted for calculations made when equation (B3) is rearranged in the following manner:

$$\frac{W_a}{W_f} = \frac{70,800\ \eta_b}{2000 - T_3} - 1 \tag{B4}$$

where $W_a/W_f$ is the afr-fuel ratio required to maintain a burner-outlet temperature of 2000° R. When values of $T_3$ for constant values of $P_3$ are assumed, the air-fuel ratio can be obtained f rom equation (B4) and figure 11.

Deceleration characteristics. - In order to determine whether establishing a minimum fuel flow for steady-stat8 conditions would

also serve to prevent unstable burner operation during deceleration, calculations were mad8 to determine the probable values of burner temperature rise when the fuel flow was instantaneously reduced from a steady-state value to the minimum value of 1025 pounds per hour. These calculations were as follows: At each of the steady-state points of altitude end airplane speed, the value of burner temperature rise was determined by a trial-and-error solution of equation (B2) end from figure 11, with values of compressor-discharge pressure and air flow corresponding to the steady-state values. The accuracy of the values of burner efficiency and temperature rise so obtained is doubtful because of the necessity of extreme extrapolation of the burner-efficiency curve. However, in some cases, the assumption of a burner efficiency of 100 percent would still result in a burner temperature rise below the burner-stability limits of figure 8. The required extrapolation indicates the need for complete burner data and. flight correlation data es a prerequi-Sit8 to the design of an automatic engine control.

Because the results of these calculations indicate that a minimum fuel flow of 1025 pounds per hour would not prevent unstable burner operation during deceleration from low-altitude end high-airplane-speed conditions, calculations were mad8 to determine the minimum allowable value of fuel flow during deceleration from each of the steady-stat8 conditions. For these calculations, the lower allowable limit of burner-temperature rise was taken as 25° F above the curve of figure 8. (This assumption gives a safety factor of 25° F,) At each steady-state condition the values of air flow, compressor-discharge pressure, and the value of burner temperature rise (from fig. 8) plus 25° F were substituted in equation (B2) and the equation was solved for the fuel flow. The results were used to plot figure 19.

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2. Pierce, L. J.: A Method of Valuing Combustion Chambers for Aircraft Gas Turbines. Data Folder No. 81467, General Electric co., Aircraft Gas Turbine Eng. Div., April 9, 1946.

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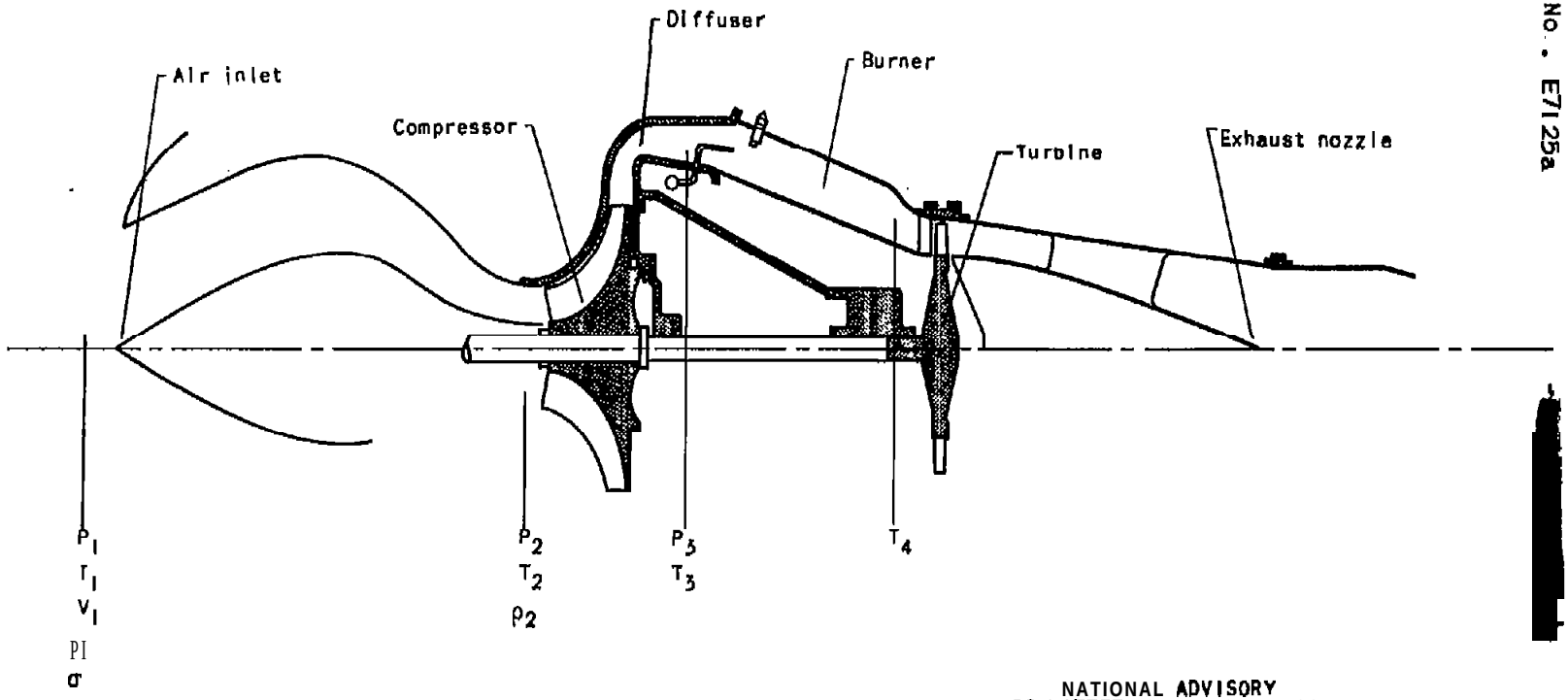


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Figure 1. - Typical configuration of direct-coupled turbojet engine.

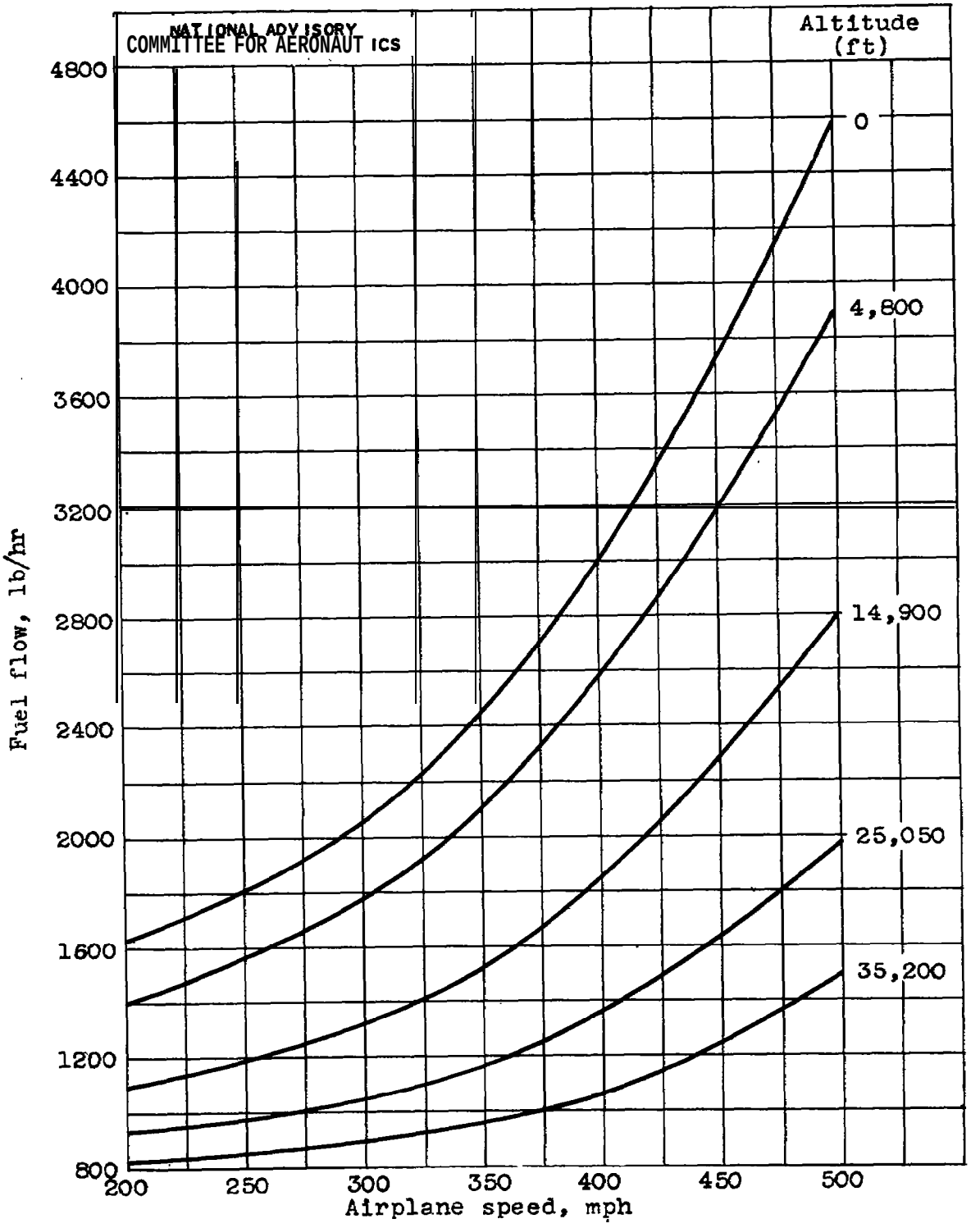
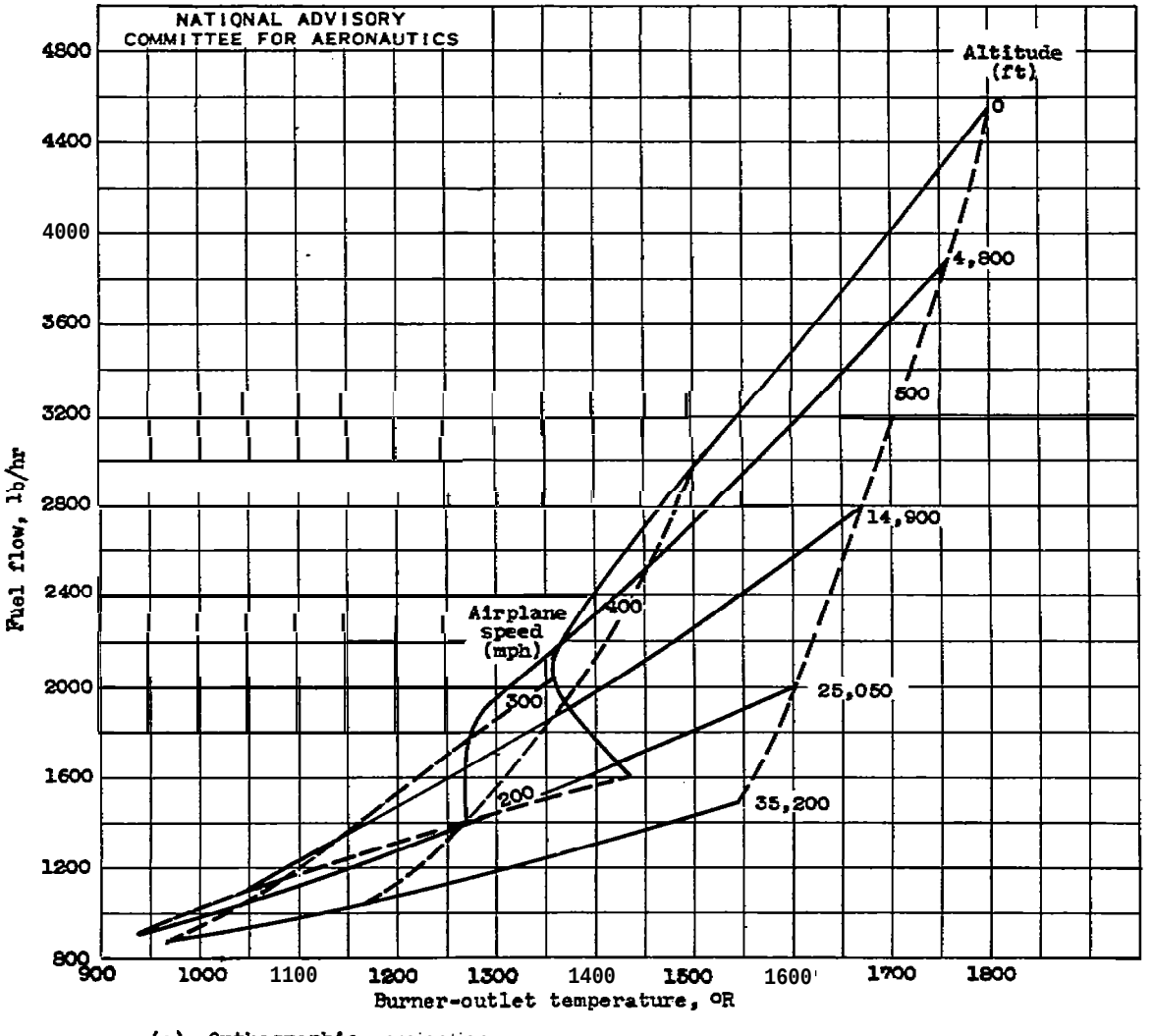



Figure 2. - Variation of fuel flow with airplane speed for turbojet engine under steady-state conditions at various altitudes with a[redacted]evel flight.

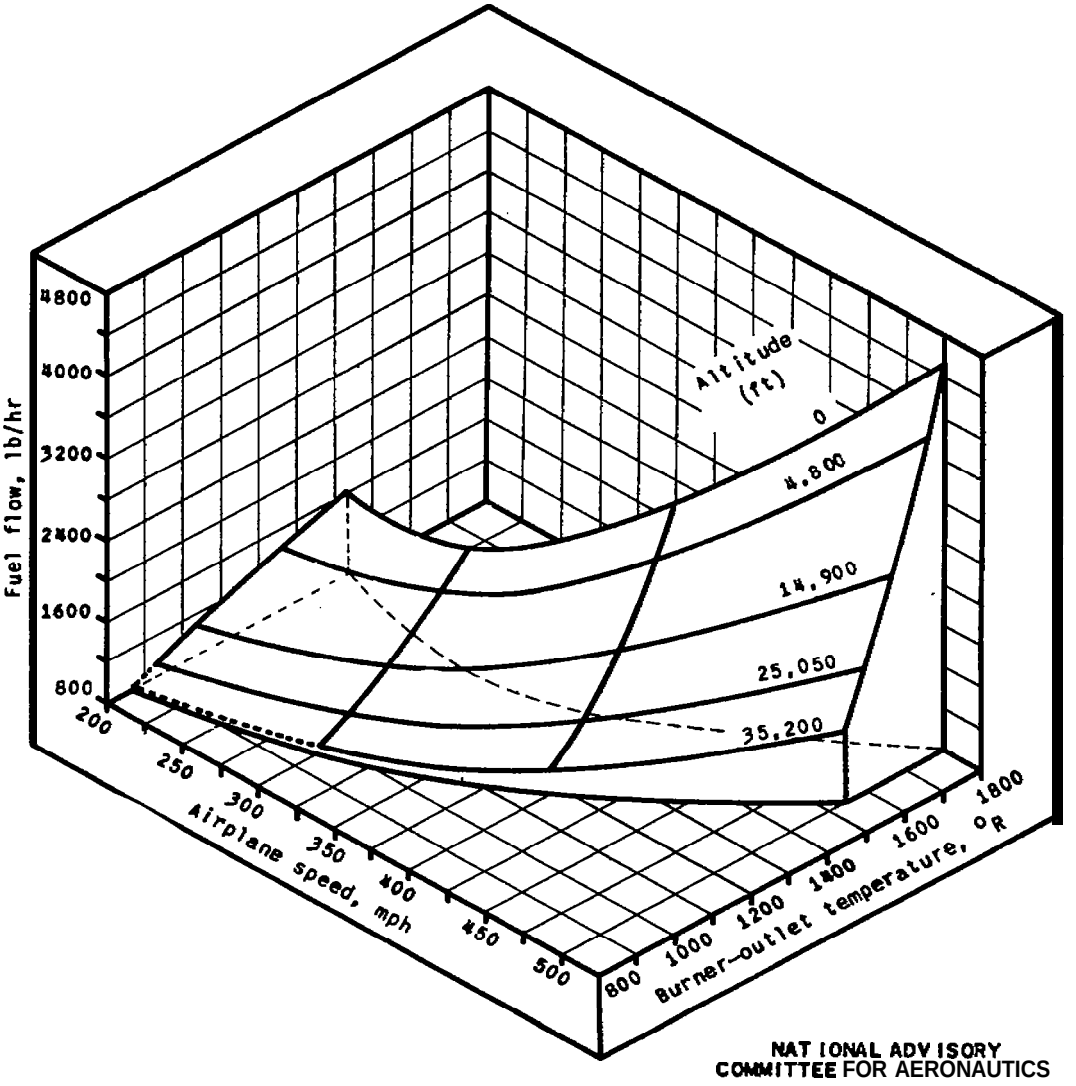
763




(a) Orthographic projection.

Figure 3. - Variation of fuel flow with burner-outlet temperature for turbojet engine under steady-state conditions at various airplane speeds and altitudes.

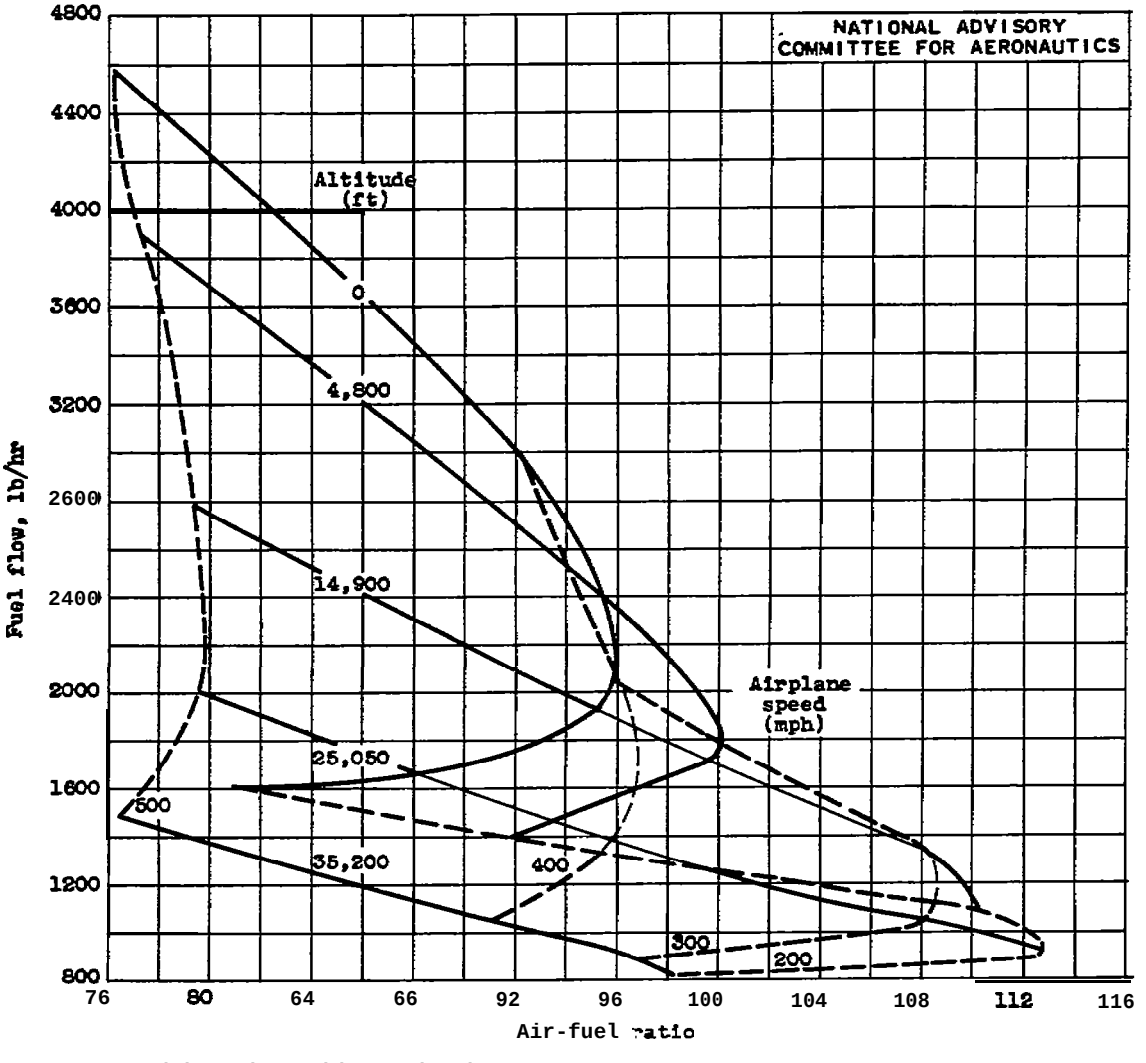
763




(b) Isometric projection.

Figure 3. – Concluded. Variation of fuel flow with burner-outlet temperature for turbojet engine under steady-state conditions at various airplane speeds and altitudes.

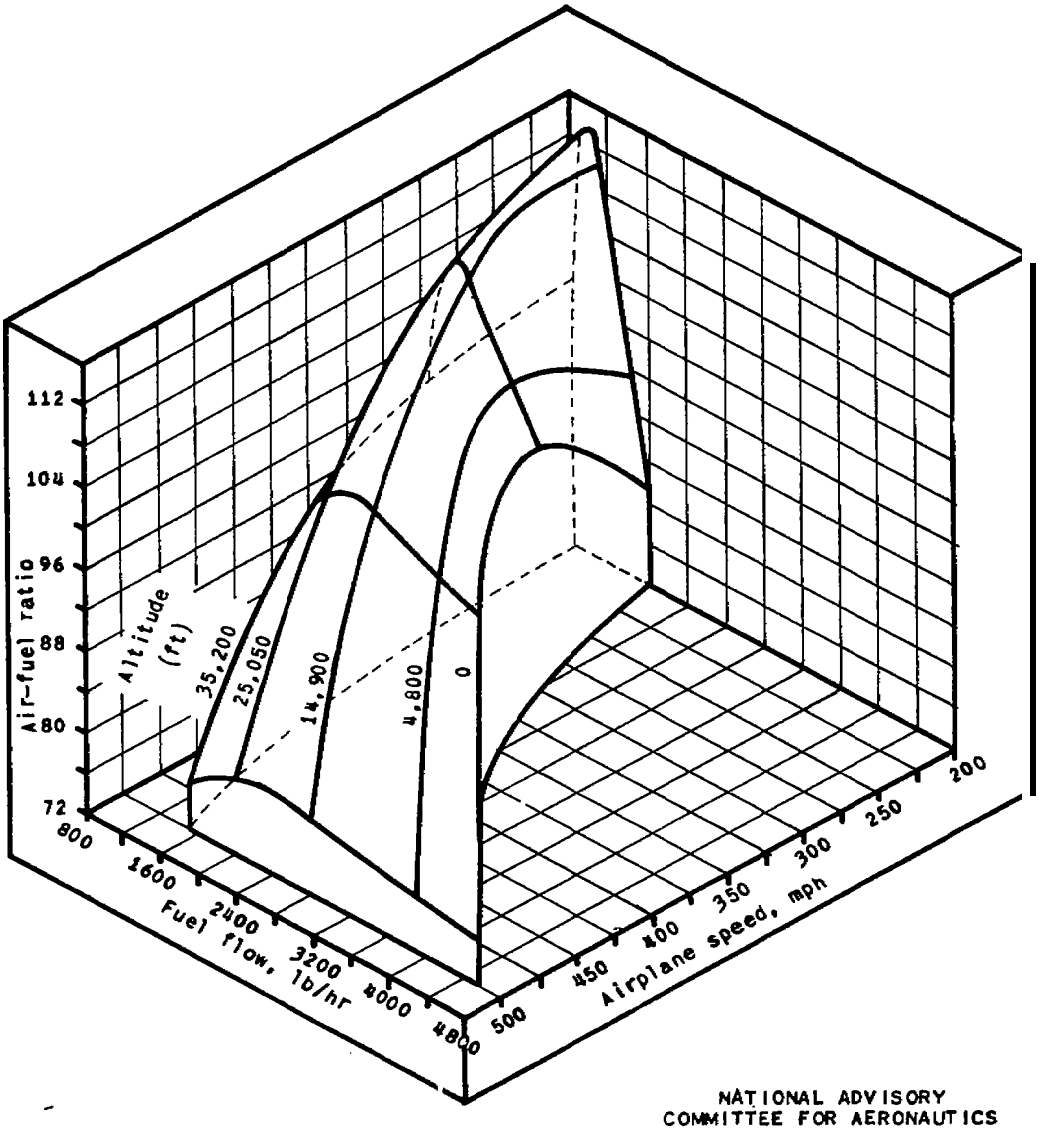
763




(a) Orthographic projection.

Figure 4. - Variation of fuel flow with air-fuel ratio for turbojet engine under steady-state conditions at various airplane speeds and altitudes.

763




(b) Isometric projection.

Figure 4. - Concluded. Variation of fuel flow with air-fuel ratio for turbojet engine under steady-state conditions at various airplane speeds and altitudes.

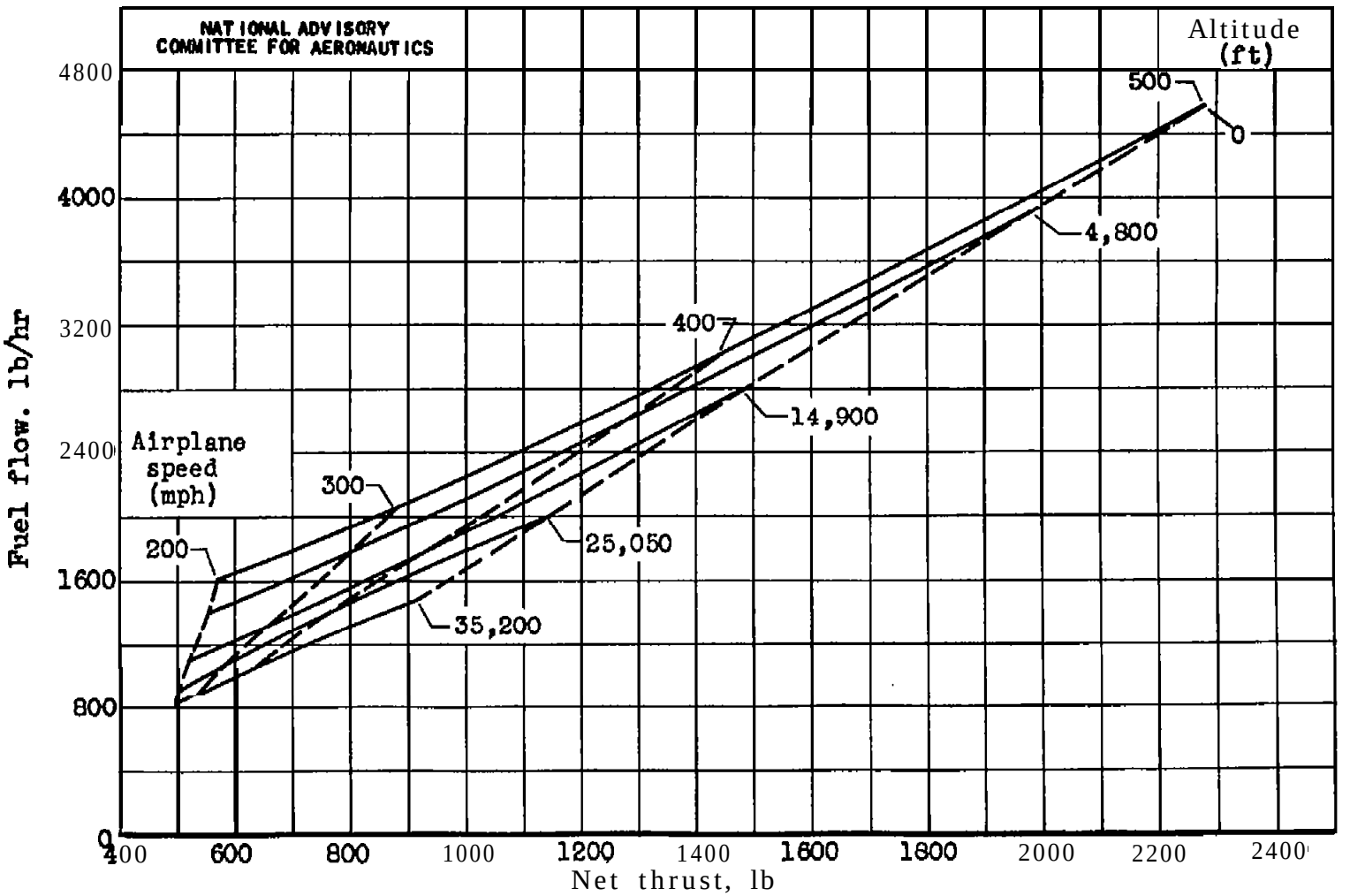



Figure 5. - Variation of fuel flow with net thrust for turbojet engine under steacly-state conditions at varlous airplane speeds and altitudes.

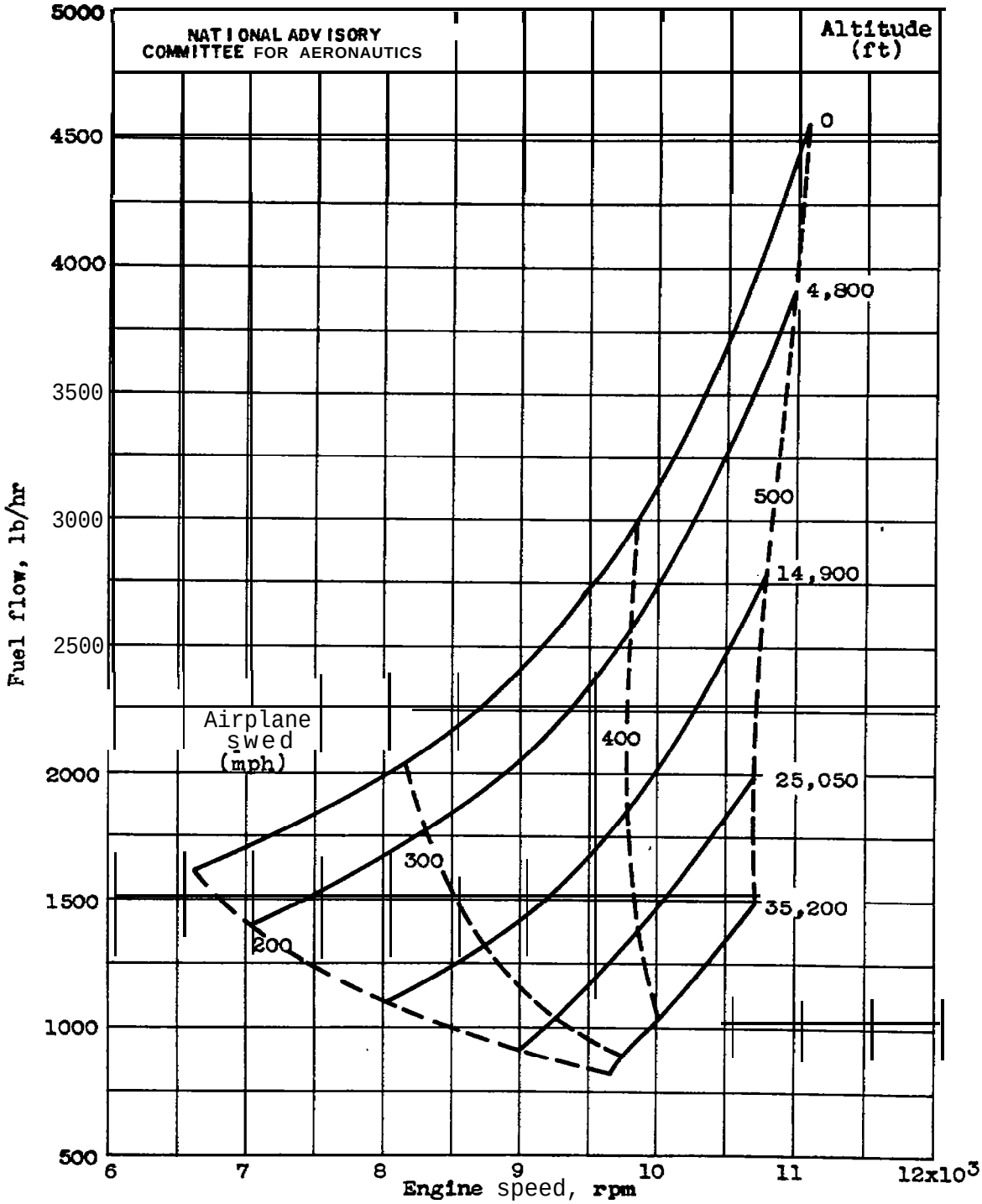



Figure 6. - Variation of fuel flow with engine speed for turbojet engine under steady-state conditions at various airplane speeds and altitudes.

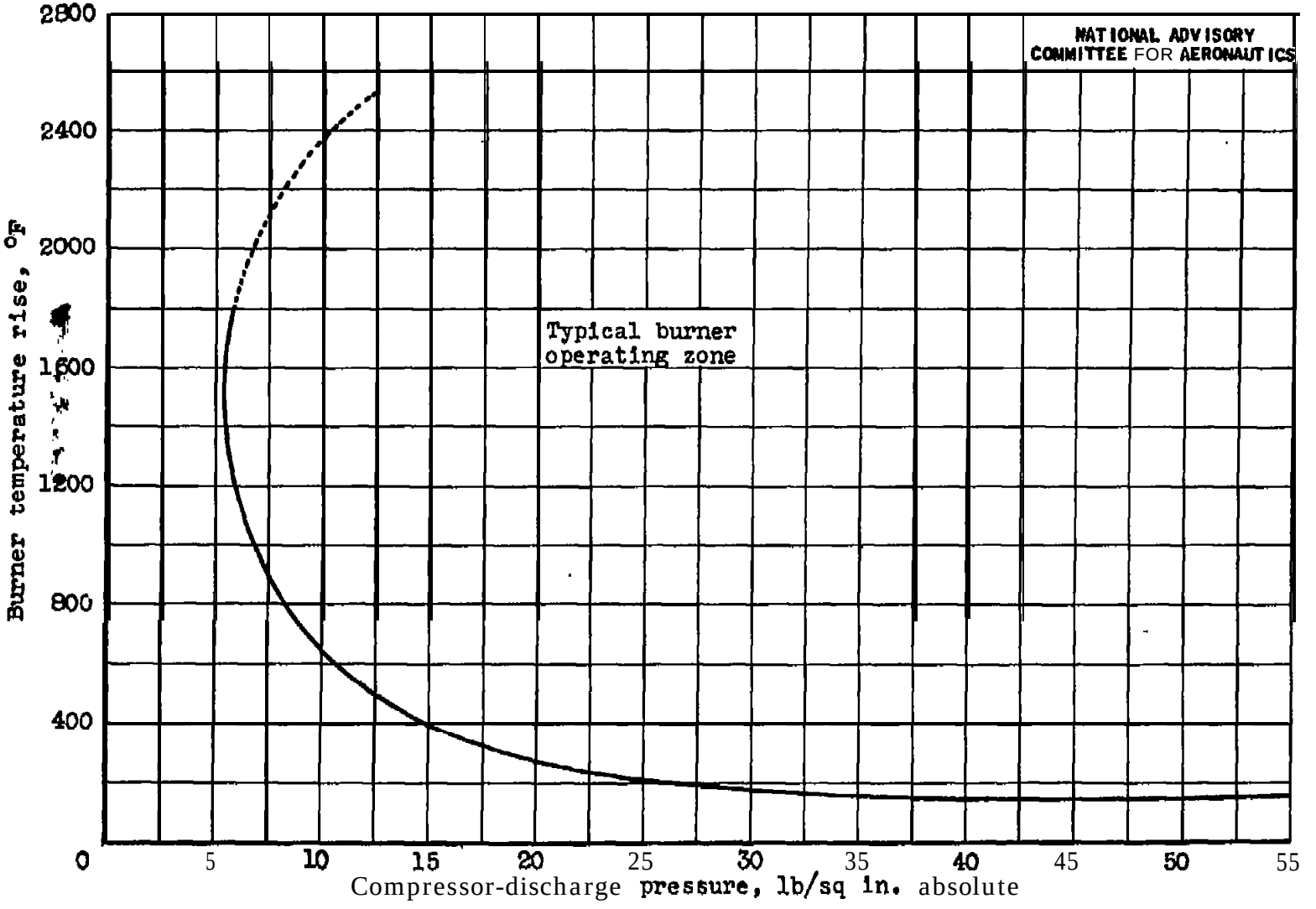



Figure 8. - Burner operation as function of burner temperature rise and compressor-discharge pressure showing burner operating zone. (Curve taken from fig. 3 of reference 3.)

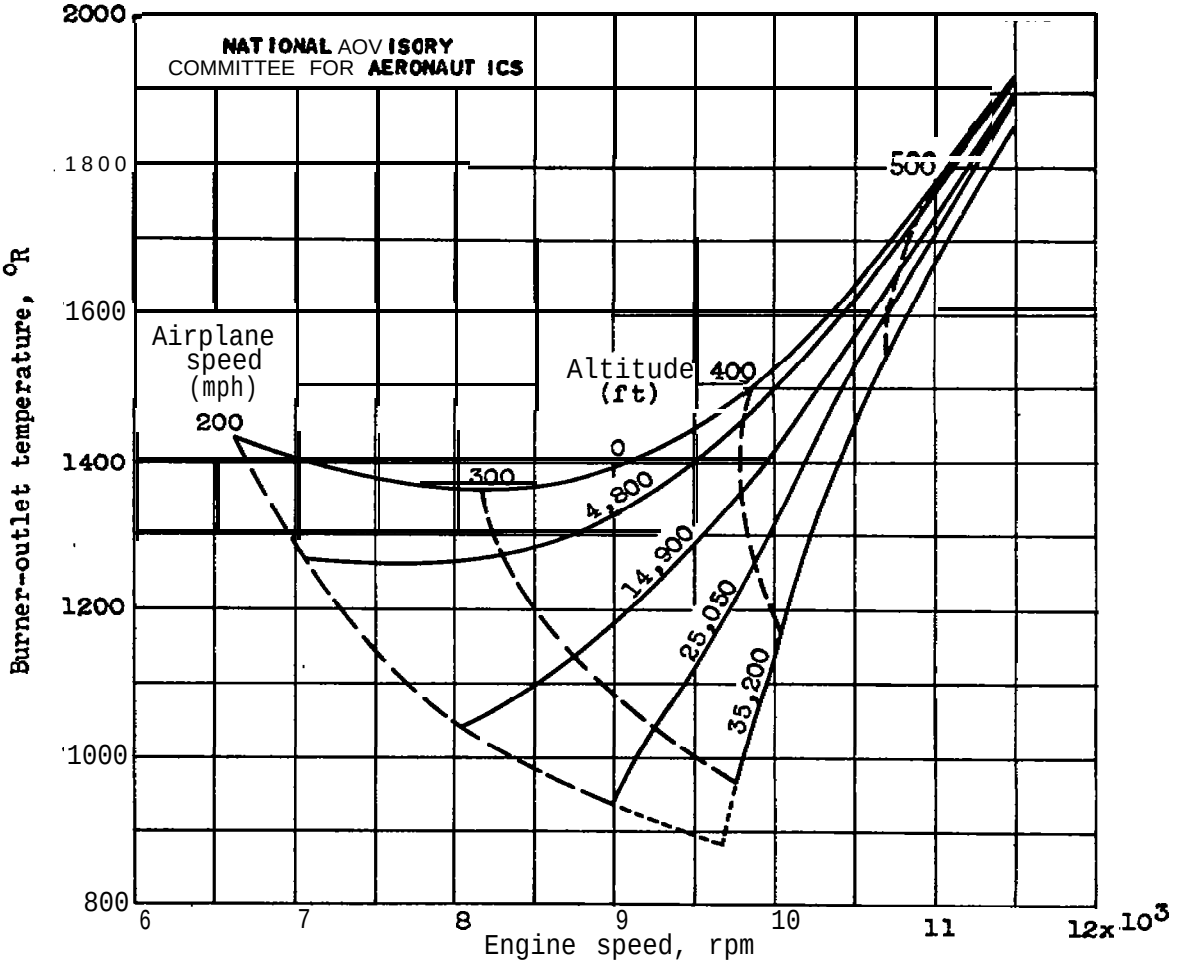



**Figure 7.** - Variation of burner-outlet temperature with engine speed for turbojet engine under steady-state conditions at various airplane speeds and altitudes.

763

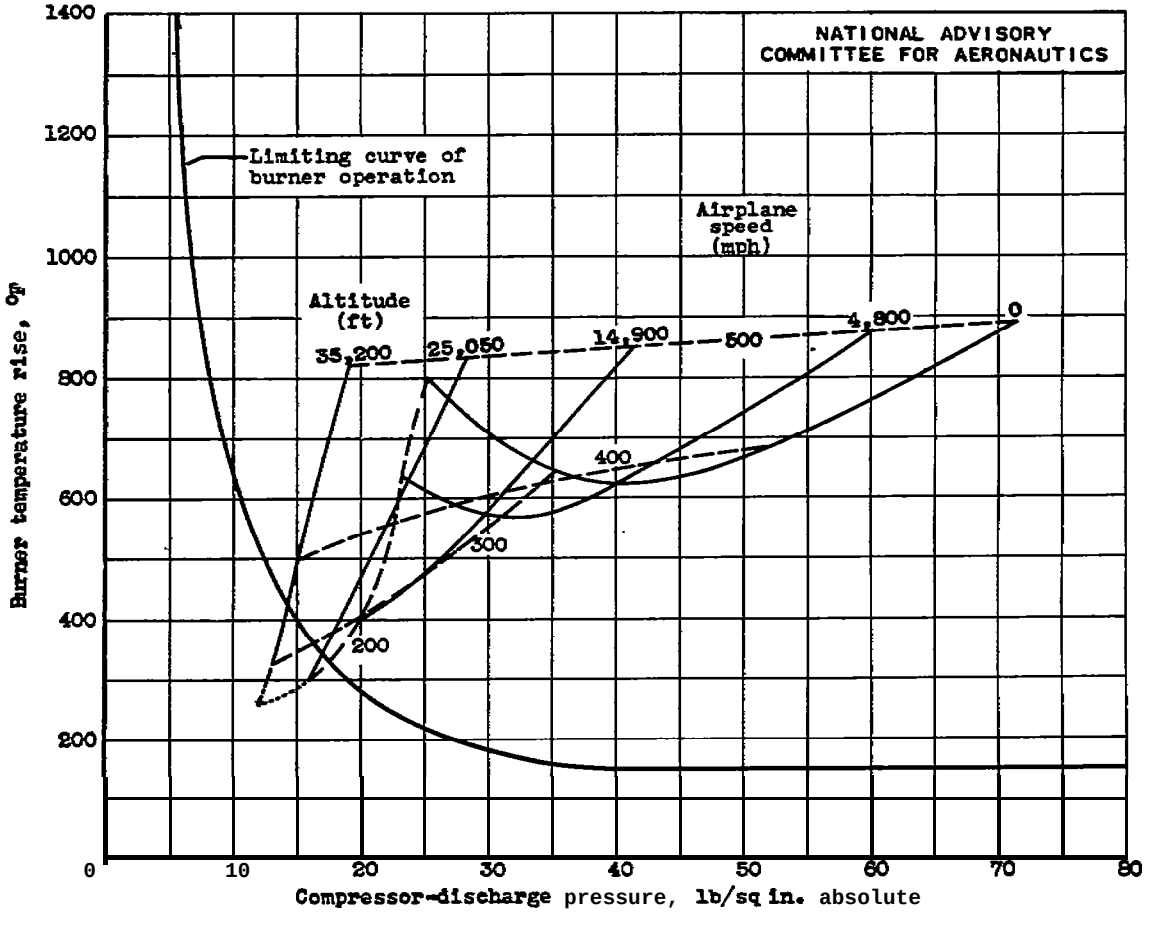



Figure 9. - Burner characteristics obtained during steady-state operation superimposed on limiting curve of burner operation. (Limiting curve of burner operation taken from fig. 3 of reference 3.)

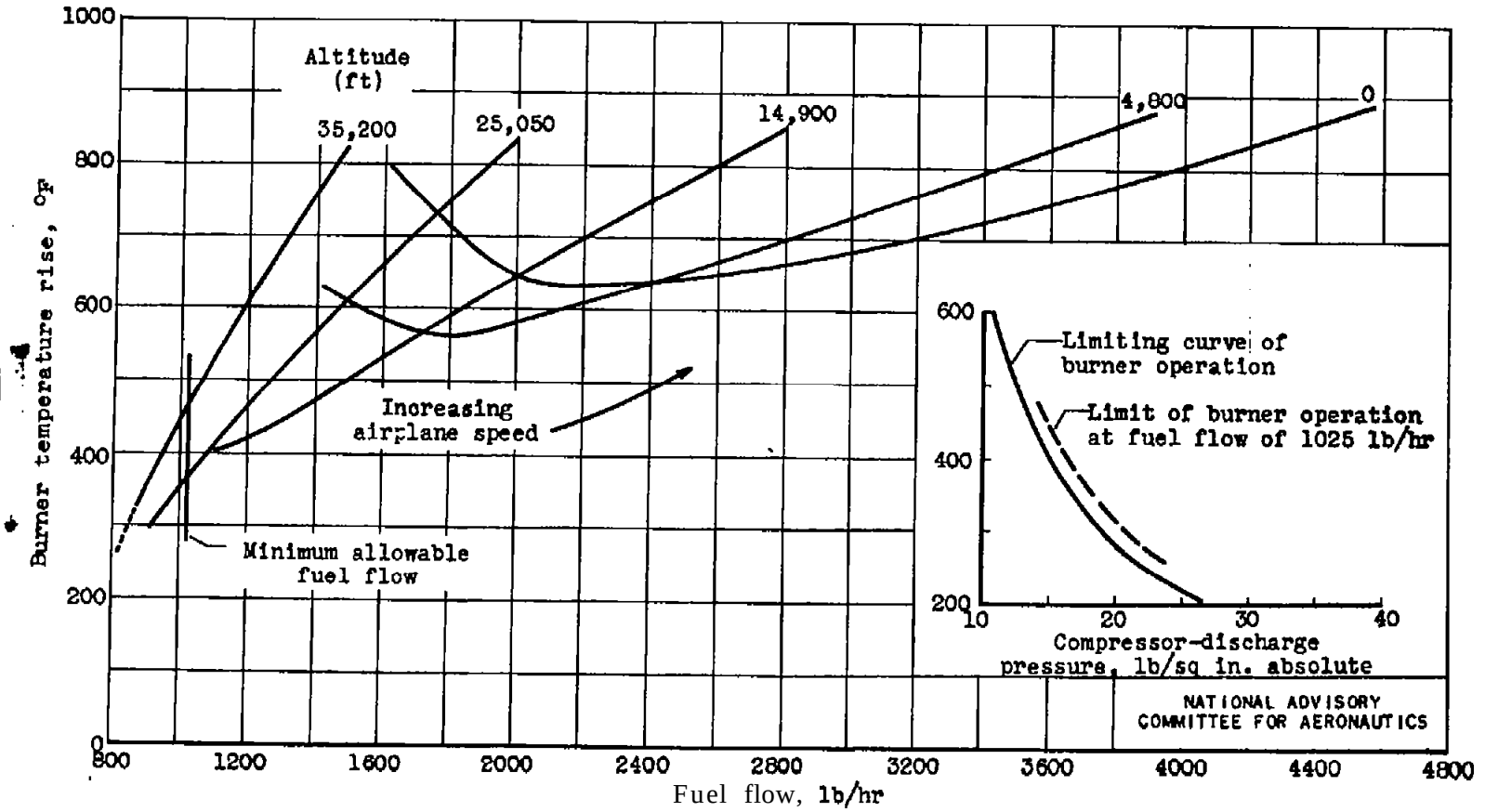



Figure 10. - Determination of minimum allowable fuel flow required for burner stability during steady-state operation. (Limiting curve of burner operation taken from fig. 3 of reference 3.)

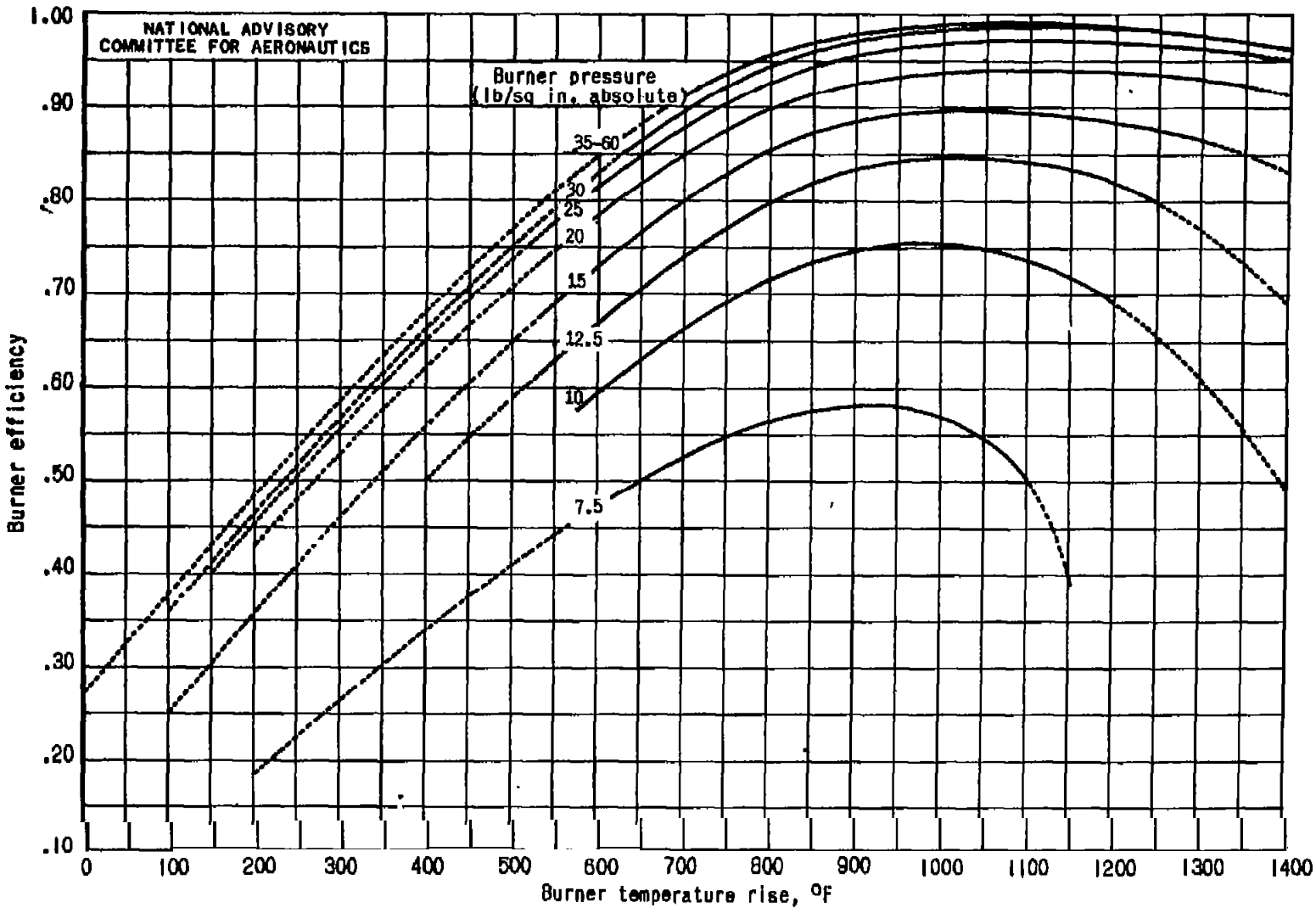



Figure 11. - Effect of burner pressure and burner temperature rise on burner efficiency. (Taken from fig. 5 of reference 3.)

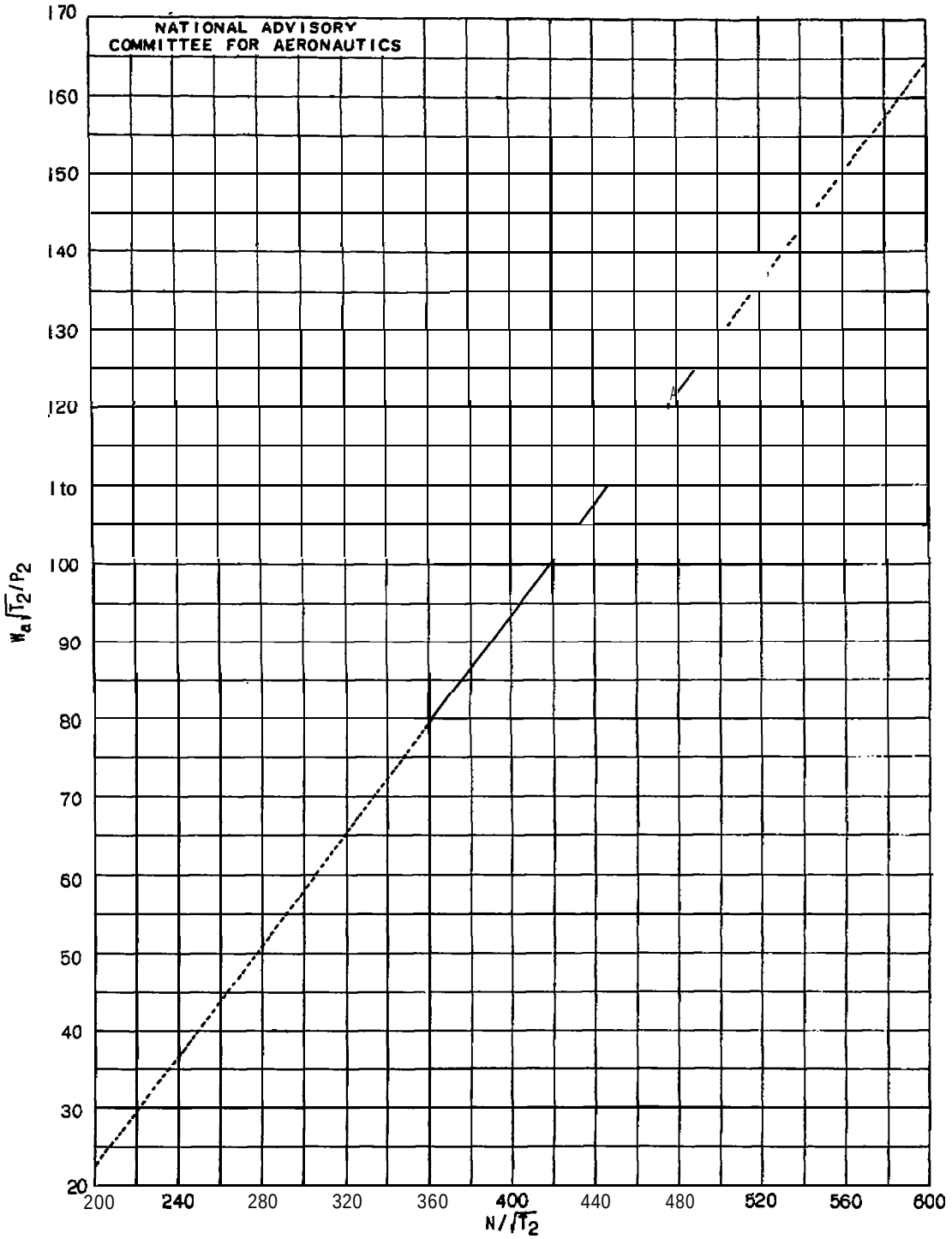
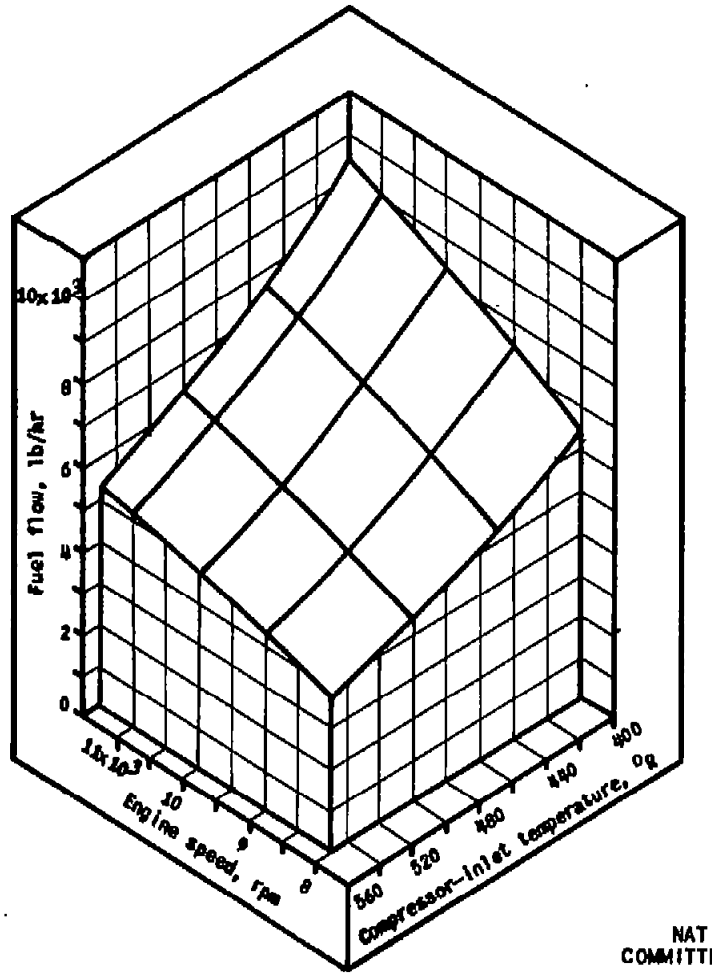
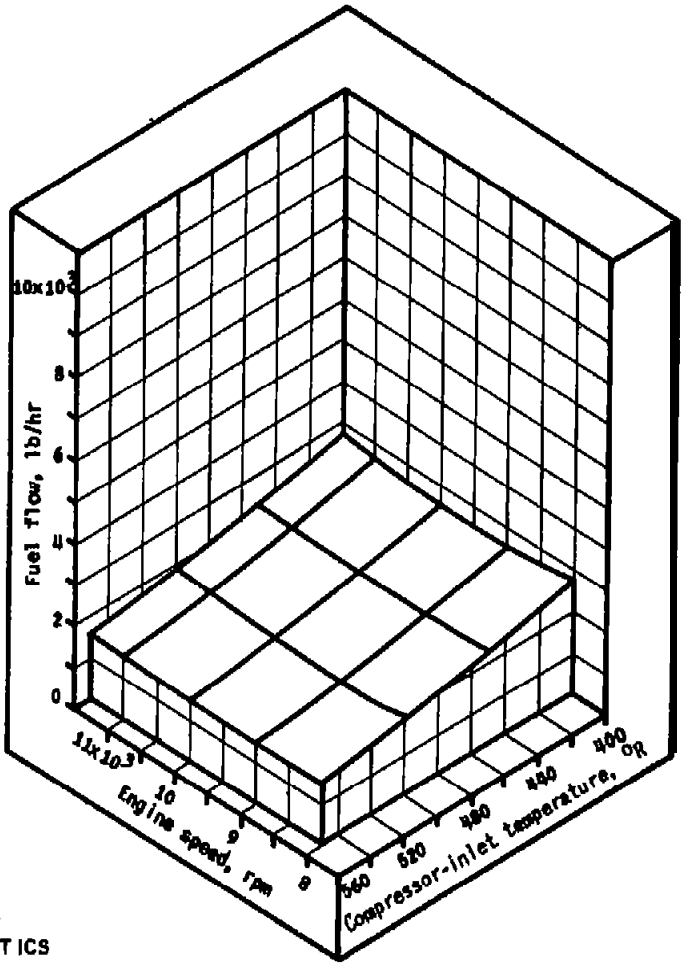



Figure 12 - Air flow as function of engine speed. Compressor-inlet pressure and

763

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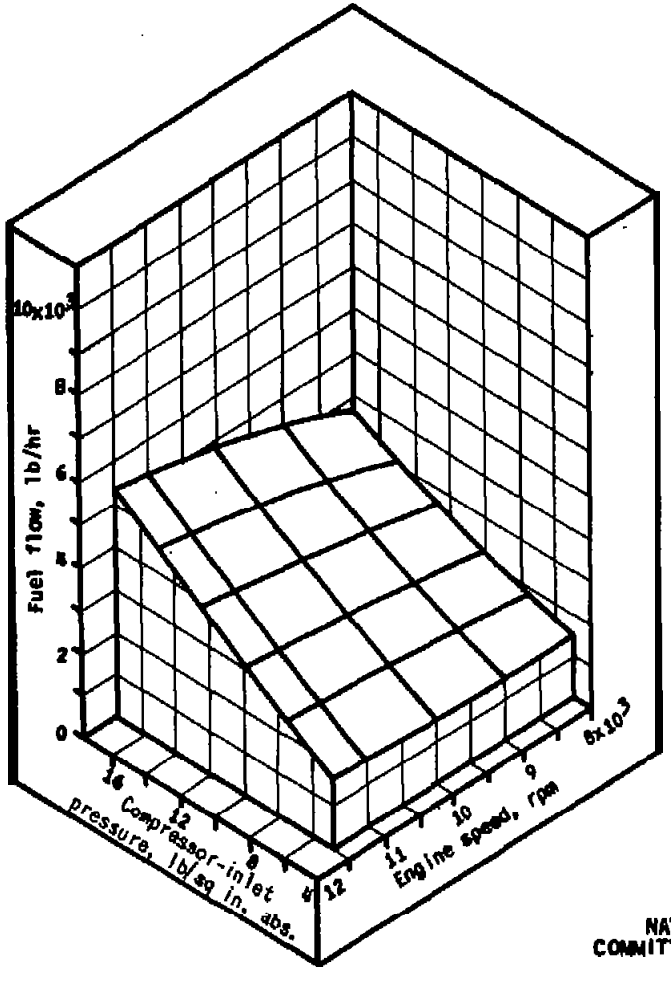
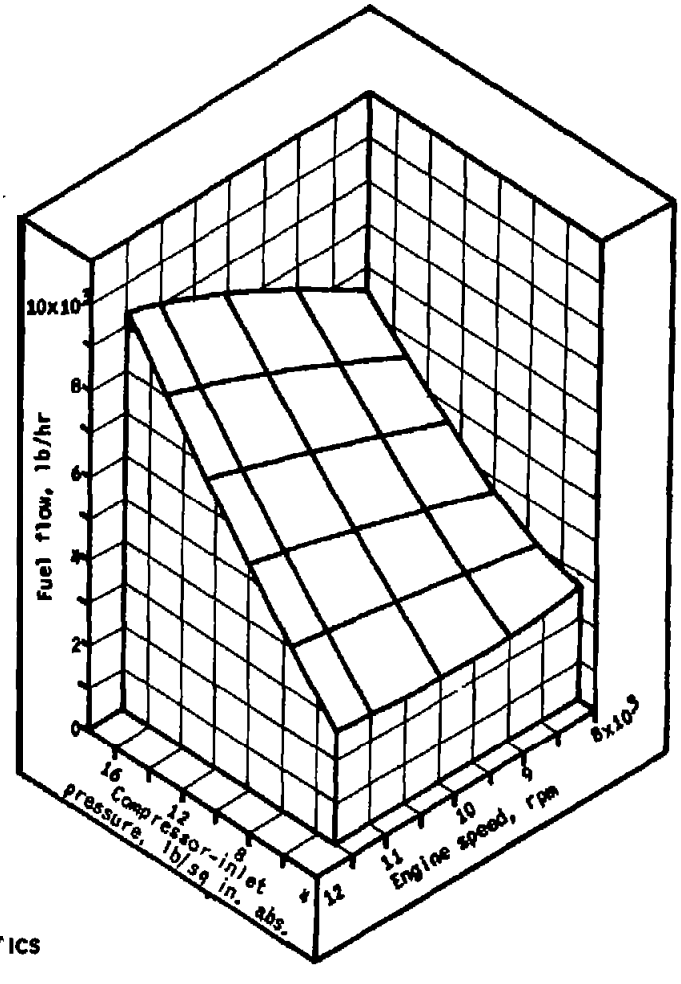
(a) Compressor-inlet pressure, 17.5 pounds per square inch absolute.

(b) Compressor-inlet pressure, 5 pounds per square inch absolute.

Figure 13. - Variation of fuel flow with engine speed and compressor-inlet temperature for two conditions of compressor-inlet pressure, based on maximum allowable burner-outlet temperature of 2000° R.

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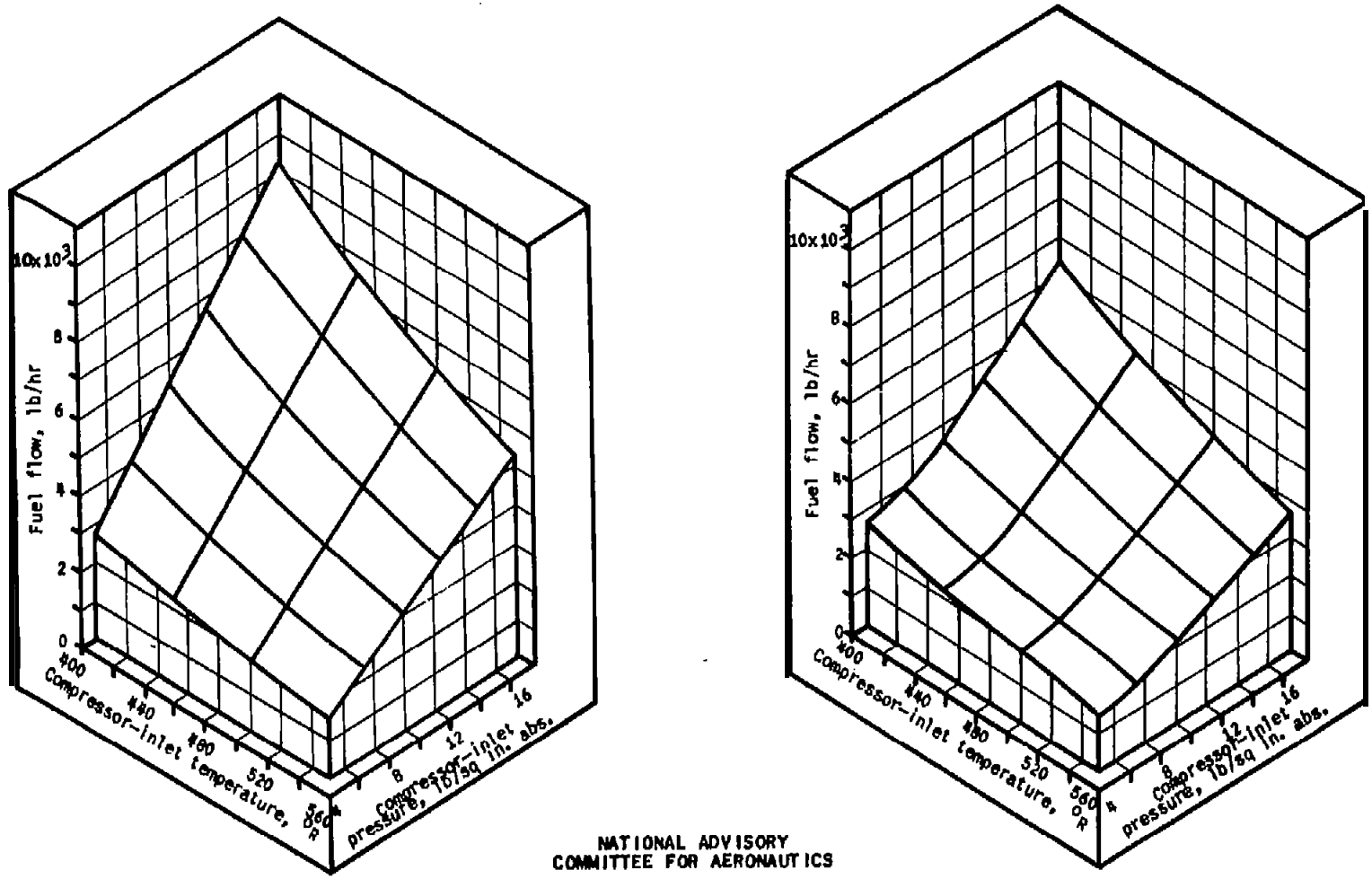
(a) Compressor-inlet temperature, 550° R.

(b) Compressor-inlet temperature, 400° R.

Figure 14. - Variation of fuel flow with compressor-inlet pressure and engine speed for two conditions of compressor-inlet temperature, based on maximum allowable burner-outlet temperature of 2000° R.

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(a) Engine speed, 11,500 rpm.

(b) Engine speed, 8000 rpm.

Figure 15. - Variation of fuel flow with compressor-inlet temperature and compressor-inlet pressure for two conditions of engine speed, based on maximum allowable burner-outlet temperature of 2000° R.

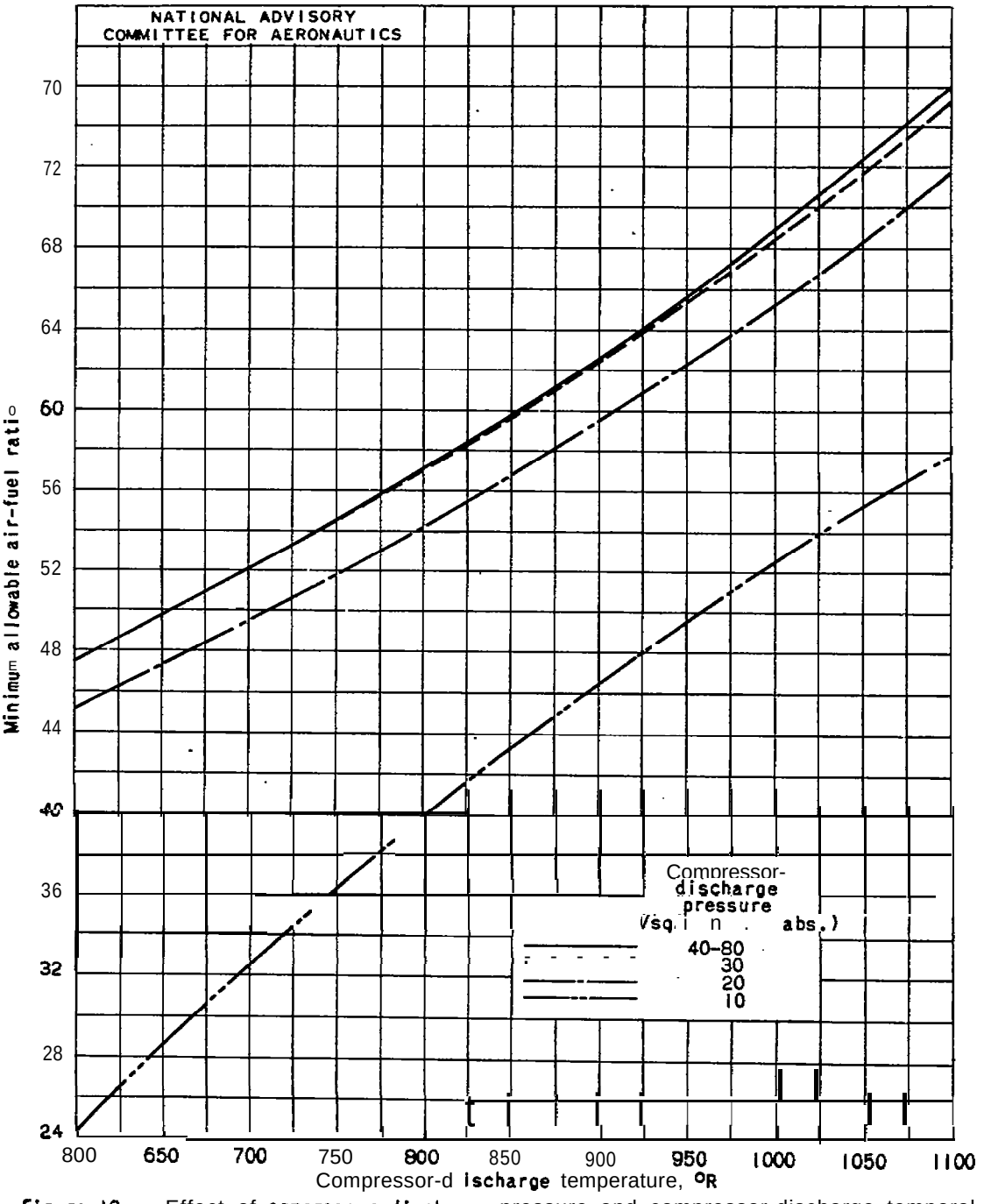


Figure 16. - Effect of compressor-discharge pressure and compressor-discharge temperature on minimum allowable air-fuel ratio, based on maximum allowable burner-outlet temperature of 2000° R.

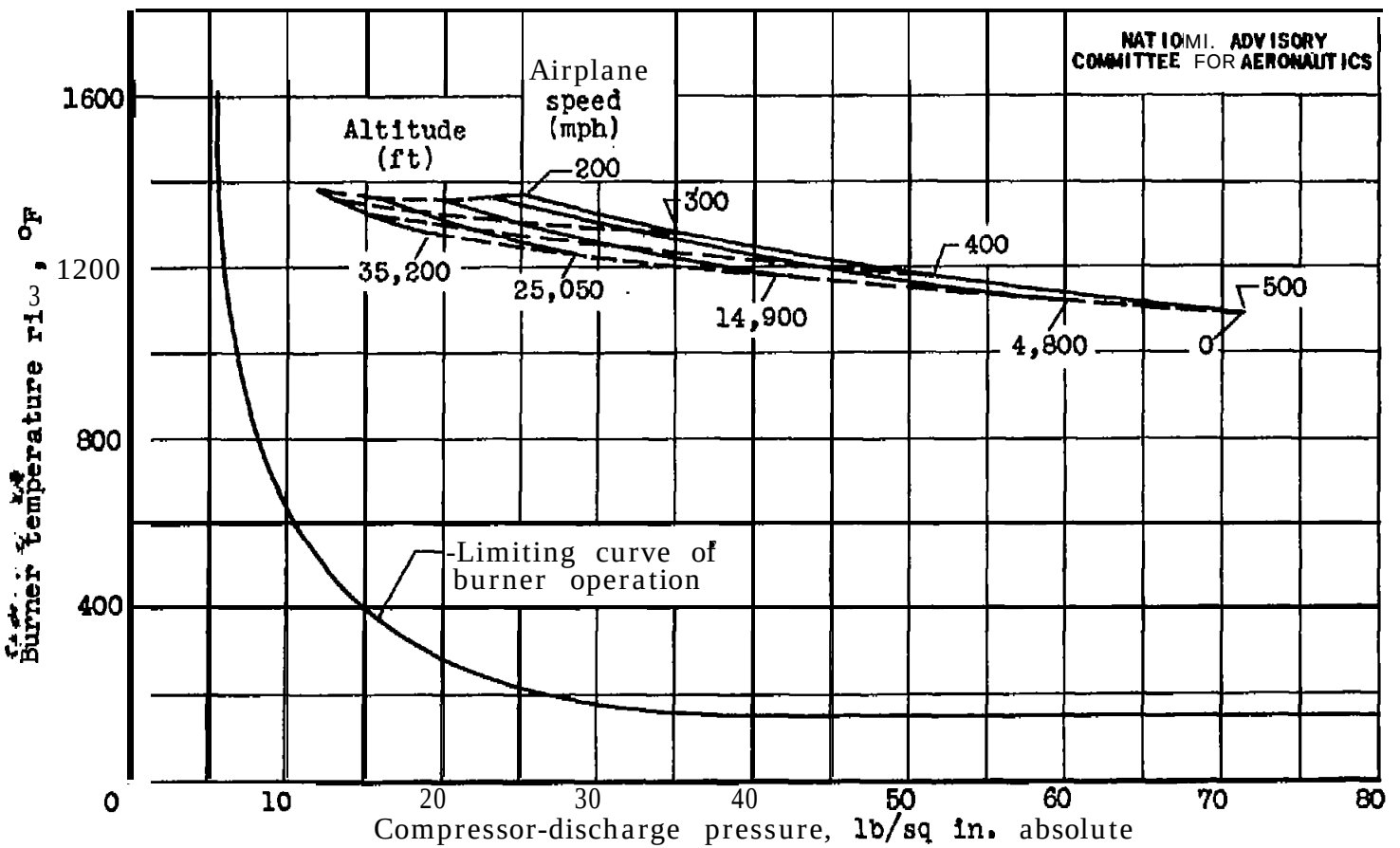


Figure 17. - Burner characteristics obtained when accelerating to burner-outlet temperature of 2000° R from steady-state conditions superimposed on limiting curve of burner operation. (Limiting curve of burner operation taken from fig. 3 of reference 3.)

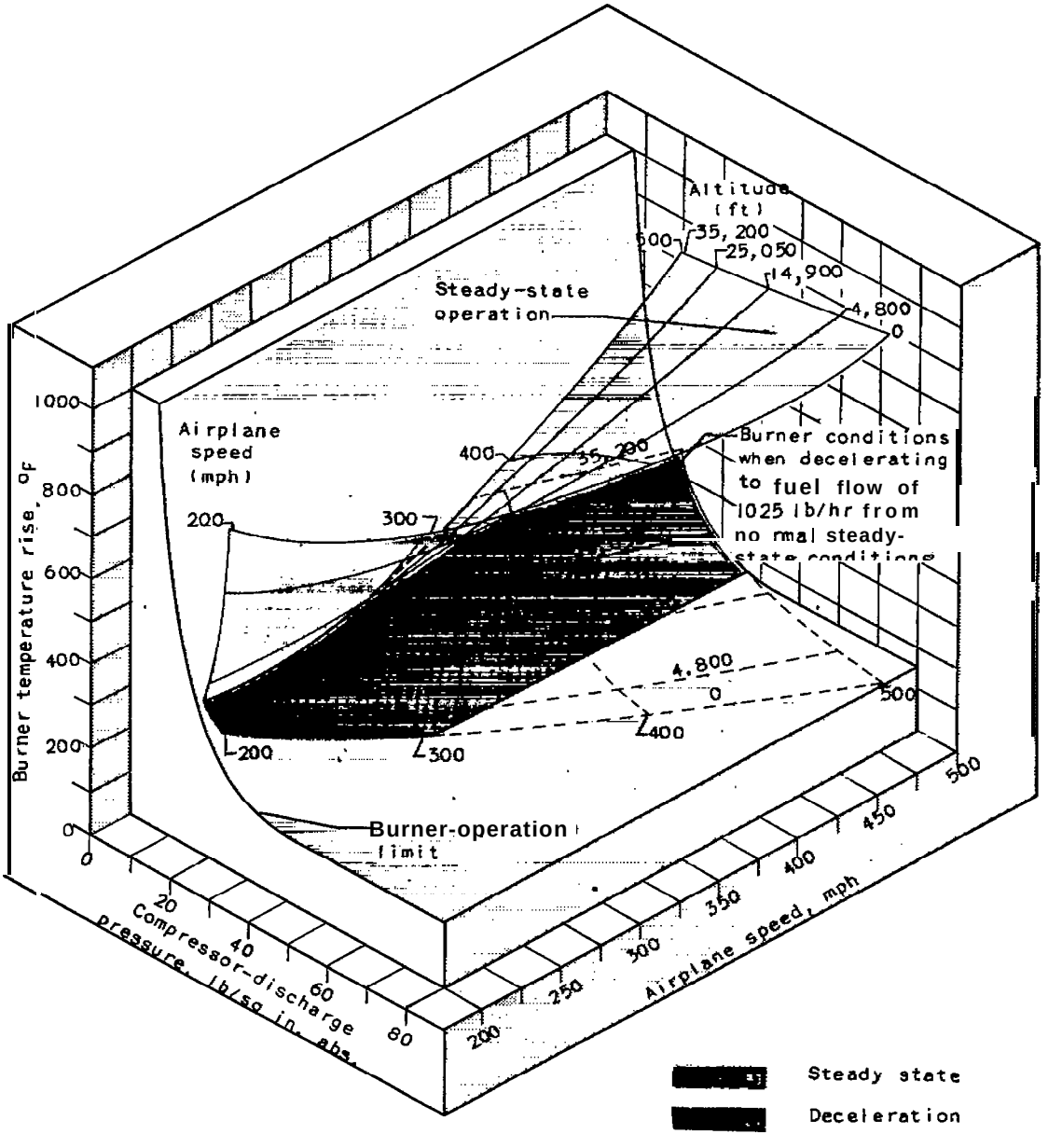


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Figure 18. - Burner characteristics obtained when decelerating to fuel flow of 1025 pounds per hour from steady-state conditions showing burner-operation limits. (Limiting curve of burner operation taken from fig. 3 of reference 3.)

763

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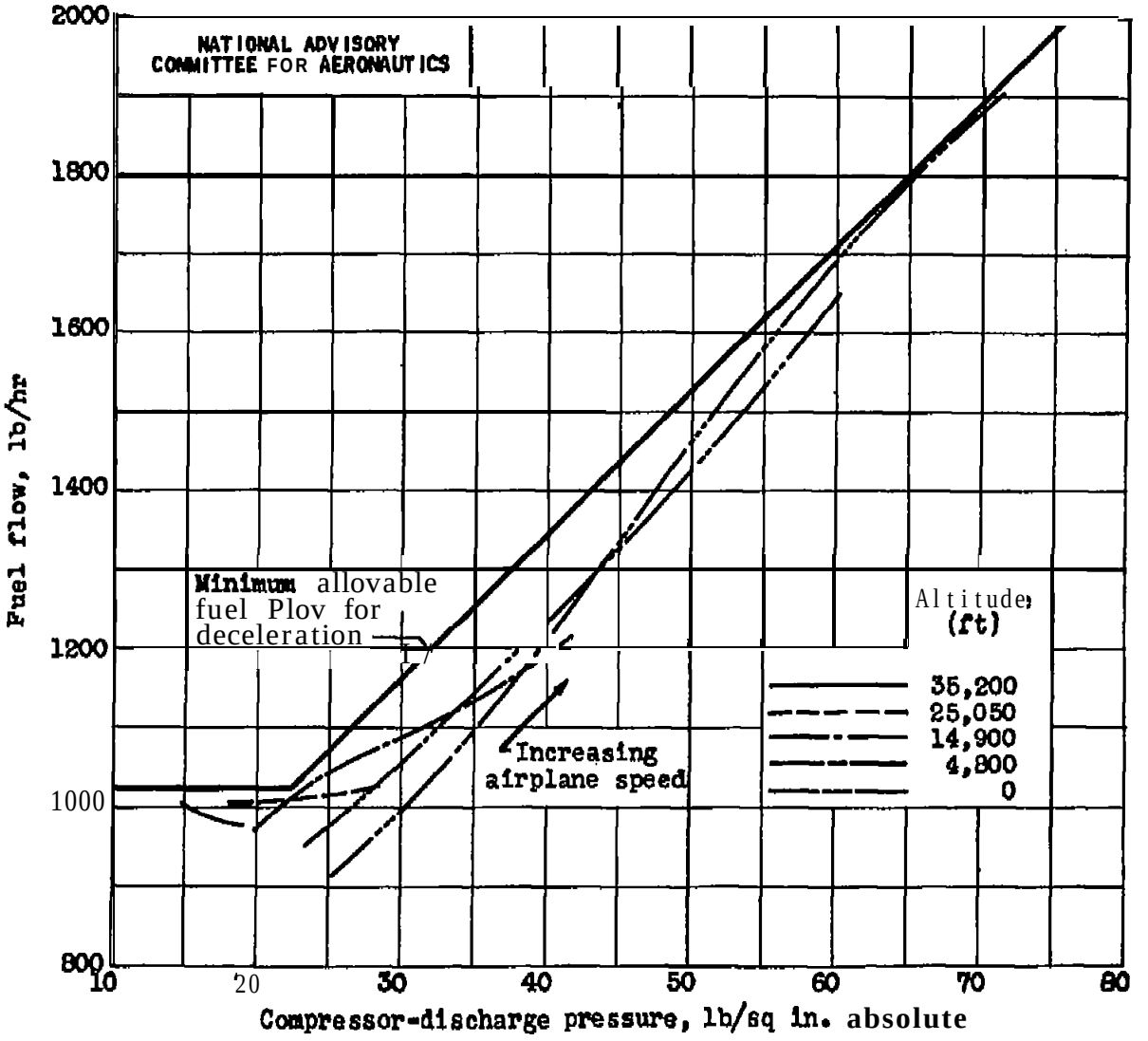


Figure 19. - Minimum allowable fuel flow for deoeleratlon as function of compressor-discharge pressure.

a System selection and shut-off valve
b Balanced-diaphragm assembly
c Acceleration-control balanced bypass valve
d Acceleration-control temperature-sensitive bellows
e Drum cam
f Acceleration-control pressure-sensitive bellows
g Pilot valve
h Fuel-metering valve
i Acceleration-control servopiston
j Emergency control valve
k Maximum-speed stop
Governor balanced bypass valve
Governor pilot valve
n Modulating piston
Slot in cylinder of modulating-piston assembly
p Governor-setting linkage
Minimum-fuel-flora-contml balanced bypass valve
r Venturi
s Cam
t Minimum-fuel-flow stop
u Spring
v Diaphragm assembly
w Minimum-fuel-flow-control pilot valve
x Governor
y Check valve
z Minimum-fuel-flow-control pressure-sensitive bellows

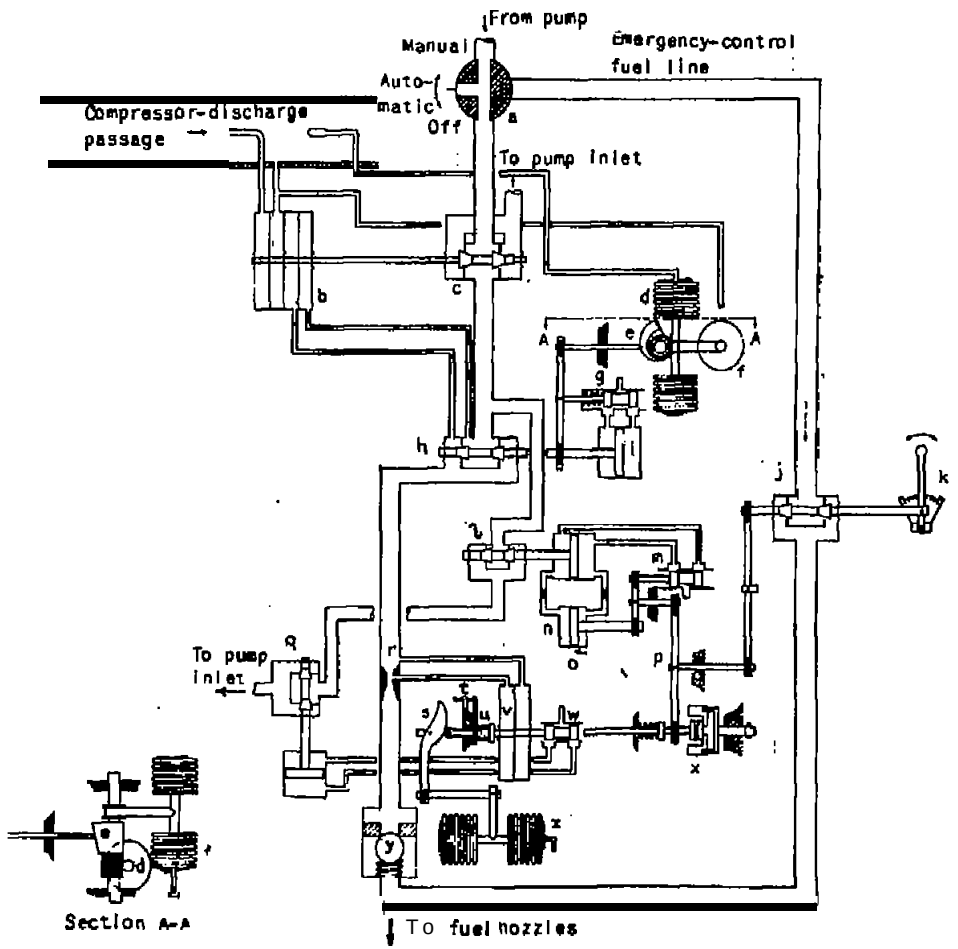


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Figure 20. - Schematic diagram of hypothetical engine control.

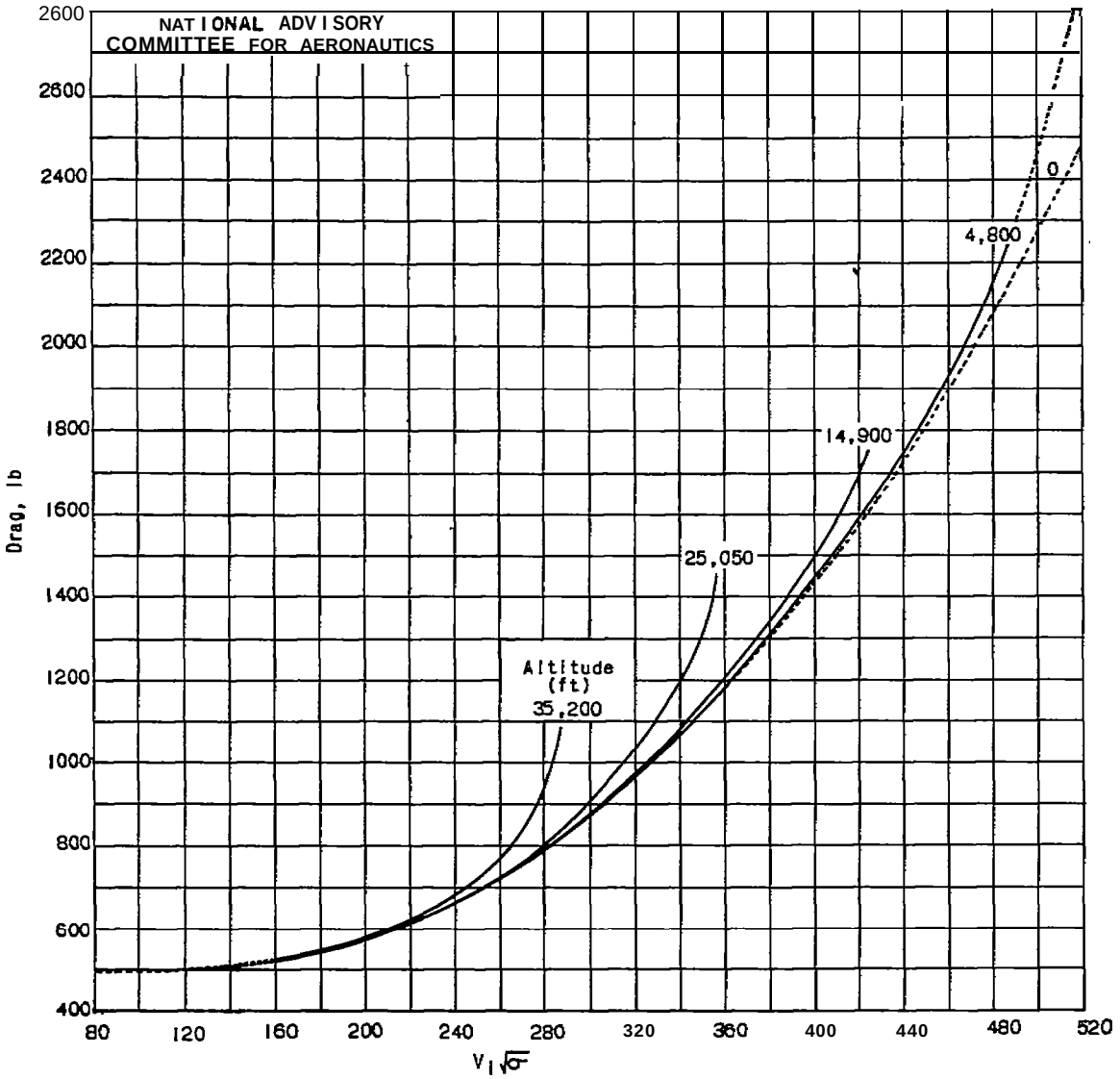


Figure 21. - Drag as function of indicated airplane speed and altitude. True airplane speed $V_i$, mites per hour; altitude-density ratio $\sigma$; Indicated airplane speed $V_i\sqrt{\sigma}$, miles per hour. (Taken from Lockheed Aircraft Corporation data.)

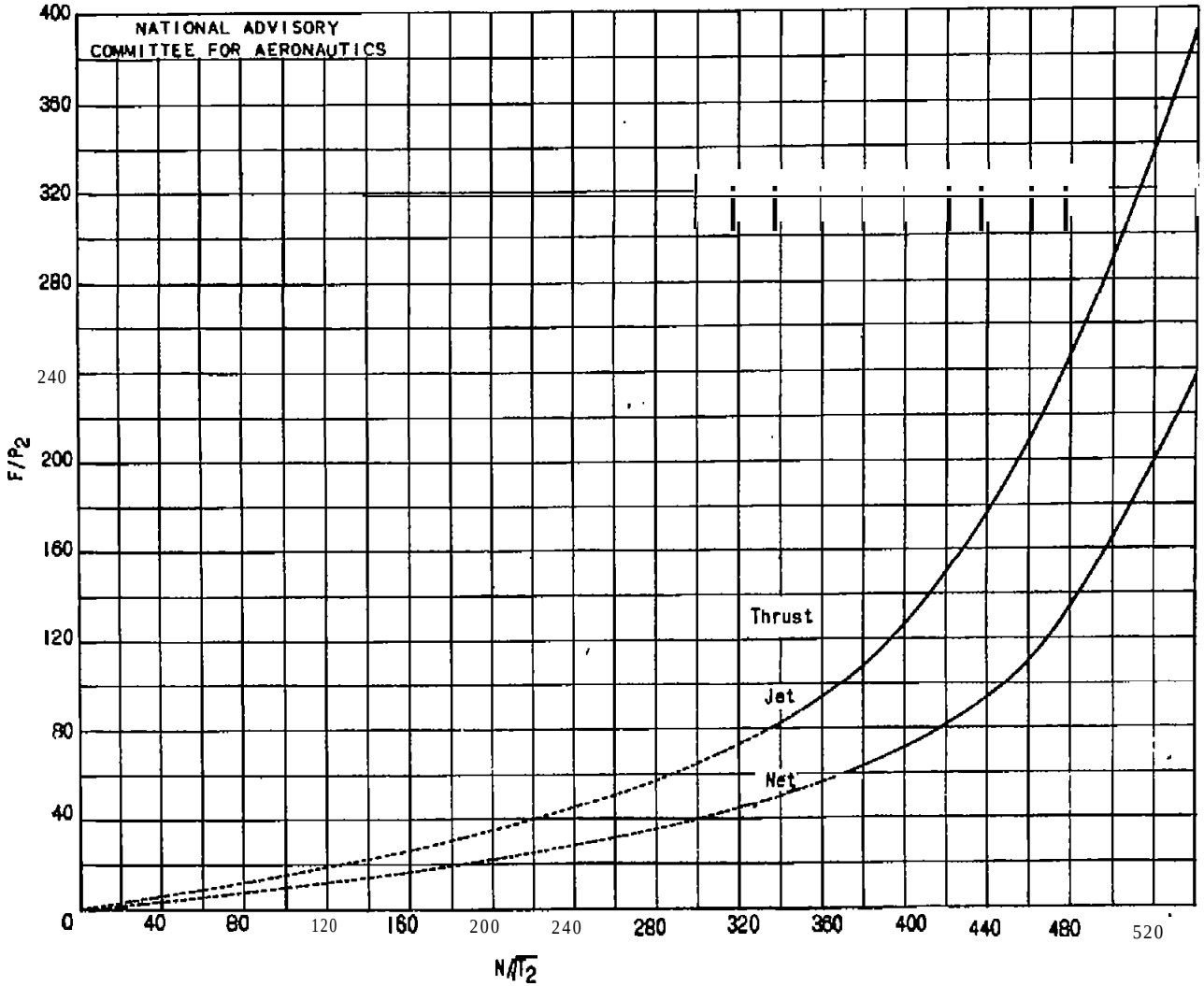


Figure 22. - Engine thrust as function of compressor-inlet pressure, compressor-inlet temperature, and engine speed. Engine thrust F, pounds; engine speed N, rpm; empressor-inlet pressure $P_2$, pounds per square Inch absolute; compressor-inlet temperature $T_2$, °R. (Taken from Lockheed Aircraft Corporation data.)

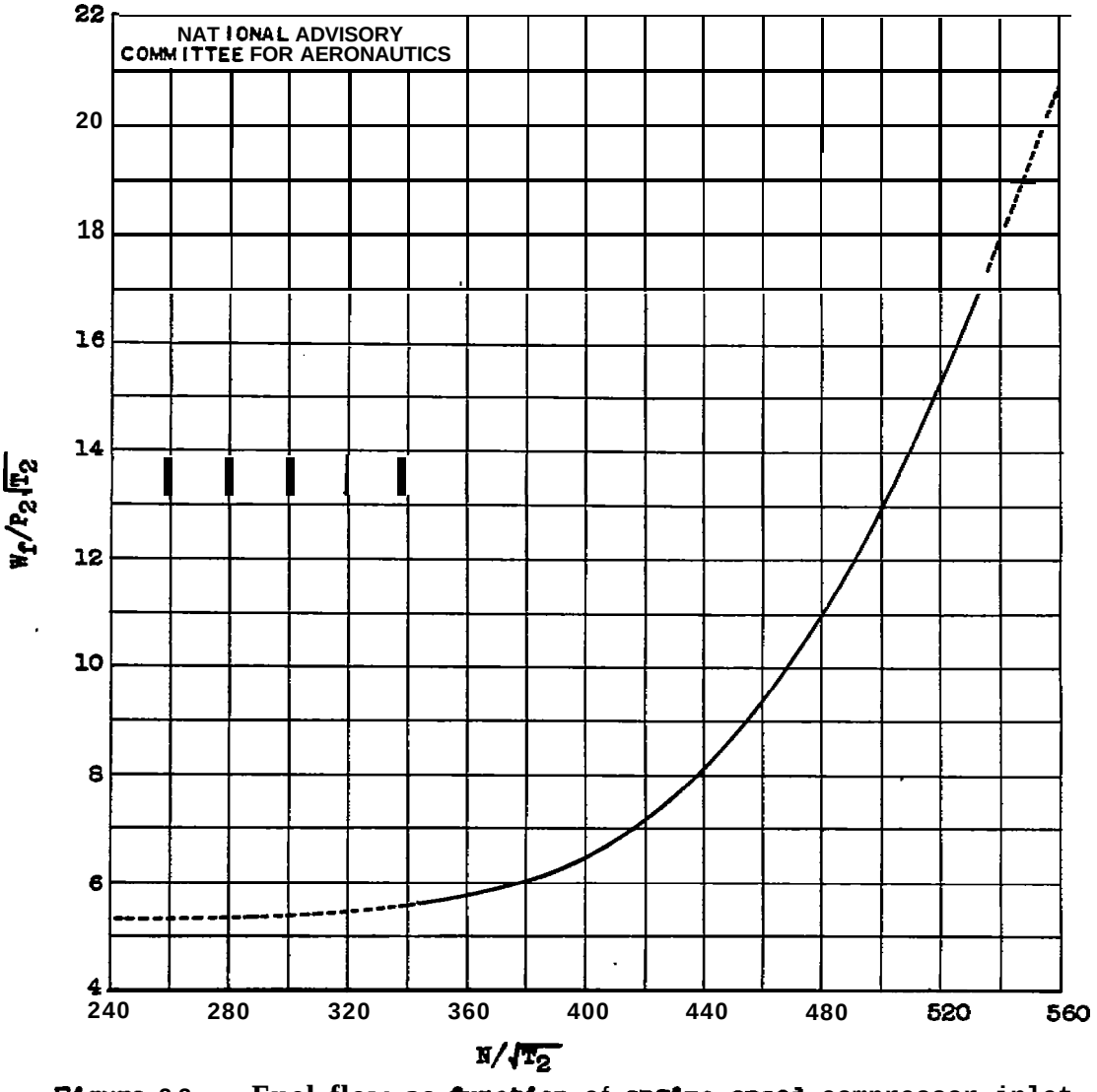


Figure 23. - Fuel flow as function of engine speed, compressor-inlet pressure, and compressor-inlet temperature. Engine speed I, rpm; compressor-inlet pressure $P_2$, pounds per square inch absolute; compressor-inlet temperature $T_2$, °R; fuel flow $W_f$, pounds per hour. (Curve taken from Lockheed Aircraft Corporation data.)

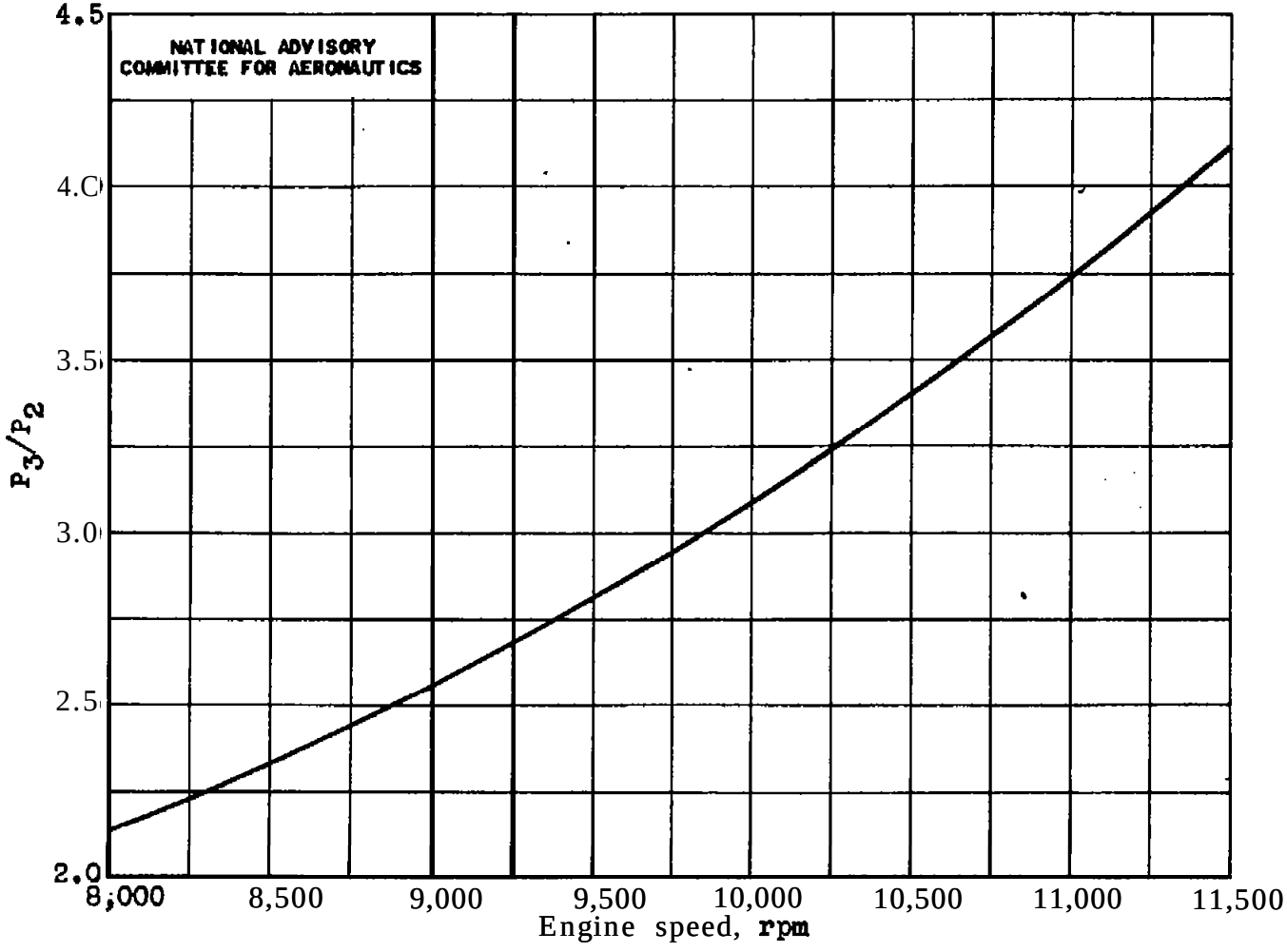


Figure 24. - Effect of engine speed on compressor pressure ratio at standard atmospheric conditions. Compressor-inlet pressure P2, pounds per square inch absolute; compressor-discharge pressure $P_3$, pounds per square inch absolute. (Data taken from reference 4.)

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