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RESEARCH MEMORANDUMANALYSIS OF PARAMETERS FOR THRUST CONTROL OF A TURBOJET ENGINE
EQUIPPED WITH AIR-INLET THROTTLE AND VARIABLE-AREA
EXHAUST NOZZLE

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SUMMARY

The rate of thrust change of a turbojet engine can be increased over that obtained by controlling only fuel flow by the addition to the standard configuration of an air-inlet throttle, a variable-area exhaust nozzle, or a combination of the two. Engine performance characteristics with an air-inlet throttle and a variable-area exhaust nozzle were predicted and control-parameter curves were chosen for each of these thrust-control methods.

A typical direct-coupled turbojet engine with a centrifugal-flow compressor which was installed in a fighter airplane and controlled by use of an air-inlet throttle system, can, at sea level and an airplane velocity of 200 miles per hour, deliver an increase in thrust of approximately 39 percent without a change in engine speed; at an altitude of 35,200 feet such an engine can be operated over its complete range of thrust at constant engine speed. The engine controlled by use of a variable-area exhaust-nozzle system can, at sea level and an airplane velocity of 200 miles per hour, deliver an increase in thrust of approximately 176 percent without a change in engine speed; at an altitude of 35,200 feet such an engine can be operated over its complete range of thrust at constant engine speed. Of the systems considered, a combination of the air-inlet throttle and the variable-area exhaust-nozzle control system gives the best thrust control at all altitudes; with this control the engine can be operated at a constant engine speed of 10,000 rpm for airplane speeds ranging from approximately 200 to 500 miles per hour at all altitudes or at an engine speed of 11,500 rpm at a sacrifice in range of airplane speeds.

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INTRODUCTION

Two factors that are important in the determination of the control and safety of airplanes in flight are the rate at which thrust can be changed and the range of thrust available. During maneuvers in which maximum control of the airplane is desired, rapid variations in thrust may be required. Conventional operation of the direct-coupled turbojet engine, in which thrust is controlled by changing the rate of fuel flow, permits little change in thrust without a substantial change in engine speed (reference 1). The time required for a large change in engine speed is high because of the small variation in turbine-inlet temperature permitted by the maximum allowable value of this temperature. Thrust control by the conventional method is therefore poor. Any method of improving thrust control must provide for a substantial change in thrust without a corresponding change in engine speed. Ideal thrust control would be obtained if the required range of thrust could be obtained at constant engine speed.

Various methods for improving thrust control of direct-coupled turbojet engines are being studied. As part of this general program, the use of an air-inlet throttle, a variable-area exhaust nozzle, and a combination of the two has been investigated. This report presents the derivation of control-parameter relations for use in thrust-control methods of these types. Use of a variable-area exhaust nozzle or an air-inlet throttle changes the operating characteristics of the engine by changing the operating conditions and efficiencies of the turbine, the compressor, and the burner. For this reason, engine operating characteristics with either of these methods of control cannot be predicted directly from operating data obtained with a conventional engine. By use of an analysis developed herein, operating data of the component parts of a typical direct-coupled turbojet engine with a centrifugal-flow compressor are used to predict the operating characteristics of such an engine equipped with a variable-area exhaust nozzle or with an air-inlet throttle. Because of the important effects of changes in ram-pressure ratio and in altitude on engine operation, the analysis was made for the engine installed in a typical high-speed fighter airplane and the engine variables were determined as functions of altitude from sea level to 35,200 feet and of airplane speeds from 200 to 500 miles per hour. No consideration was given to landing conditions.

The addition of a variable-area exhaust nozzle or an air-inlet throttle to the engine permits the use of another independent control parameter in addition to the primary control parameter, fuel flow, or engine speed. Design curves for the control system that relate the independent control variables can be so chosen as to obtain the best thrust control for the engine.

METHOD OF ANALYSIS

The analysis was based on operation of the typical direct-coupled turbojet engine shown schematically in figure 1. The following data were used in the analysis, which was developed to determine the effects of changes in the control variables on engine operation: (1) Performance of the turbine when operating in the engine (figs. 2 to 4) was obtained from NACA wind-tunnel data; (2) compressor performance (fig. 5) was also obtained from NACA wind-tunnel data; these data were obtained over a range of altitude and ram-pressure-ratio conditions; (3) burner performance (figs. 6 and 7) was obtained from reference 2.

The extrapolation of the data of figures 2 and 3 is discussed in appendix A; definitions of the symbols used in the report are also given in this appendix. A single turbine-efficiency curve was used in figure 4 because the engine analysis discussed in appendix A indicated that, in general, only one turbine-operating curve and one efficiency curve could be obtained. Because the data of figure 5 were obtained over only a small range of ram-pressure ratios and at only one exhaust-nozzle area (1.87 sq ft), the compressor-characteristic curves were known for only a small range at each speed. The use of a variable-area exhaust nozzle or an air-inlet throttle will give a wide range of operating conditions at each speed. It was therefore necessary to extend the compressor-characteristic curves in figure 5. Data obtained with this engine in another investigation over a wider range of air flows at each engine speed justified the extension of the compressor-characteristic curves. Compressor surge was not encountered in the aforementioned investigation and it was assumed in figure 5 that the limiting turbine-inlet temperature would be reached at each speed before compressor surge was reached and a surge line was not required. The data in figure 6 were extrapolated to include all points of engine operation used.

Figures 2 to 7 and the airplane-drag curves of figure 8, taken from Lockheed Aircraft Corporation data, were used to calculate the performance of the engine under various operating conditions. The use of an air-inlet throttle and a variable-area exhaust nozzle introduces two additional independent variables that can be imposed on the engine. There are then four independent engine variables that can be directly controlled by the pilot: (1) altitude, (2) fuel flow, (3) exhaust-nozzle area, and (4) throttle pressure ratio. In calculating values for any set of operating conditions, any four variables can be chosen as independent. In this report, altitude,

airplane velocity, exhaust-nozzle area, and turbine-inlet temperature were chosen and corresponding engine speed, fuel flow, and throttle pressure ratio were found. A detailed discussion of the engine analysis and the calculations used are presented in appendix A. The derivations of the principal equations used are presented in appendix B.

RESULTS OF ANALYSIS AND DISCUSSION OF RESULTS

General Results

Before control-parameter relations can be determined, it is first necessary to know the performance characteristics of the engine at various operating conditions.

Performance with air-inlet throttle. - The effects of use of an air-inlet throttle on engine performance at various engine speeds, airplane velocities, turbine-inlet temperatures, and exhaust-nozzle areas are shown in figures 9 and 10. In figure 9 engine speed is plotted against throttle pressure ratio for altitudes from sea level to 35,200 feet at exhaust-nozzle areas from 2.4 to 1.3 square feet. The fuel flows required for these conditions of operation are presented in figure 10. Lines of constant airplane velocity and constant turbine-inlet temperature are shown on the curves. Limitations of the engine operating conditions represented are the wide-open throttle point, the maximum turbine-inlet temperature of 2000° R and the maximum engine speed of 11,500 rpm. All operating conditions represented by these curves are within the burner blow-out limit of figure 7.

For any fixed exhaust-nozzle area and altitude, throttling the inlet-air supply at constant engine speed results in a decrease in airplane speed and, in general, an increase in turbine-inlet temperature, as shown in figure 9. As altitude increases, a greater range of airplane velocities can be obtained at constant engine speed by throttling the engine. The curves of figure 10 show that throttling of the engine increases the fuel consumption at any airplane velocity and that the maximum fuel economy is always obtained at wide-open throttle.

Performance with variable-area exhaust nozzle. - In order to obtain the effect of change in exhaust-nozzle area on the operation of an engine equipped with a variable-area exhaust nozzle, the data of figures 9 and 10 representing operation at wide-open throttle were

cross-plotted and the results are shown in figures 11 and 12. In figure 11, engine speed is plotted against exhaust-nozzle area for altitudes from sea level to 35,200 feet. Lines representing constant airplane velocity and constant turbine-inlet temperature are shown, along with the limiting line of maximum turbine-inlet temperature of 2000° R and maximum allowable engine speed of 11,500 rpm. The fuel flows required for these conditions of operation are presented in figure 12. In this figure, fuel flow is plotted against exhaust-nozzle area at various constant airplane velocities.

The curves of figure 11 show that increasing the exhaust-nozzle area at constant altitude and engine speed results in a decrease in airplane speed and a decrease in turbine-inlet temperature. In general, reduction in exhaust-nozzle area is limited by maximum turbine-inlet temperature and increase in the area is limited by the largest exhaust-nozzle area that will give efficient diffusion from the turbine-outlet area.

The limiting condition of maximum turbine-inlet temperature is the same for all altitudes. Maximum power is reached at the intersection of the maximum engine speed of 11,500 rpm and the maximum turbine-inlet temperature of 2000° R at an exhaust-nozzle area of approximately 1.63 square feet.

The curves of figure 12 show that best fuel economies are obtained for areas between 1.6 and 1.87 square feet at an airplane velocity of 500 miles per hour and for all areas less than an area of 1.87 square feet at airplane velocities between 200 and 400 miles per hour. The effect of change in area is generally the same at all altitudes.

Performance with air-inlet throttle and with variable-area exhaust nozzle. - Consideration was given to engine operation at constant engine speed with both the air-inlet throttle and the variable-area exhaust nozzle, as a means of approaching ideal thrust control. It can be seen from figure 9 that at sea level use of the air-inlet throttle permitted only a small range of airplane speeds for any constant engine speed. Figure 11 shows that at sea level a limited range of airplane speeds is permitted at any constant engine speed when only a variable-area exhaust nozzle is used to control thrust. In order to increase the range of airplane speeds permitted at constant engine speed, the use of an air-inlet throttle and a variable-area exhaust nozzle in combination was considered.

It was found, from figures 9 and 11, that for constant engine speed, with the use of both the air-inlet throttle and the variable-area exhaust nozzle, the widest range of airplane speeds at sea

level was obtained for an engine speed of 10,000 rpm. Figure 13(a), cross-plotted from figures 9 and 11, represents operating conditions at an engine speed of 10,000 rpm, for altitudes from sea level to 35,200 feet. Lines of constant airplane velocity and turbine-inlet temperature are shown in the figure along with the maximum turbine-inlet temperature of 2000° R, and the limiting condition of wide-open throttle. All the operating conditions indicated on figure 13(a) are within safe operating limits with regard to burner blow-out.

At the constant engine speed of 10,000 rpm, power was limited to the maximum power available at that speed. Consideration was therefore given to engine operation at the maximum engine speed of 11,500 rpm with both the air-inlet throttle and the variable-area exhaust nozzle as a means of approaching ideal thrust control without limiting power.

Figure 13(b) was cross-plotted from figures 9 and 11 at an engine speed of 11,500 rpm for altitudes from sea level to 35,200 feet. Curves of constant airplane velocity and the maximum turbine-inlet temperature of 2000° R are shown along with the limiting condition of wide-open throttle. All the operating conditions in figure 13(b) are within the safe limits of burner blow-out.

In general, the curves of figure 13(b) are similar to those of figure 13(a). They differ from the curves in figure 13(a) in that at 11,500 rpm, maximum power can be attained with some sacrifice of the control range available at 10,000 rpm. From sea level to an altitude of 14,900 feet, the low airplane speeds cannot be obtained without exceeding maximum turbine-inlet temperature. Above an altitude of 14,900 feet, a range of airplane speeds from 200 to maximum airplane speed can be obtained.

Air-Inlet-Throttle Control Parameters

In the curves of figure 9, engine operation can be further restricted by designating an operating line that establishes a relation between engine speed and throttle pressure ratio. For a fixed exhaust-nozzle area there would be, at any altitude, only one independent variable (either engine speed or throttle pressure ratio) determining engine operation. This operating line must be so chosen as to obtain the complete range of airplane speeds desired at each altitude and to obtain this range in airplane speeds with the least change in engine speed. For operation at a fixed exhaust-nozzle area, it is noted that if maximum

engine speed is limited to 11,500 rpm the fixed exhaust-nozzle areas of 1.6 and 1.87 square feet allow maximum airplane velocity at sea level. Because the reference engine has an effective exhaust-nozzle area of approximately 1.87 square feet, characteristics of the air-inlet throttle control at that fixed area were investigated.

Operating curves A-A. - Operating curves, which represent the relations between the control parameters that can be produced by an air-inlet-throttle control system, are presented in figure 9(c). These curves give the engine speed that should be automatically set for each throttle pressure ratio. The best operating curve is the one that intersects the lowest airplane speed desired at the maximum turbine-inlet temperature of 2000° R and also intersects the wide-open throttle point at the maximum engine speed of 11,500 rpm. Operating curve A-A in figure 9(c) was obtained by drawing the best operating curve at sea level and repeating this curve at all other altitudes. Straight-line relations between engine speed and throttle pressure ratio were used for the sake of simplicity although any relation could be chosen. The variation of engine speed and throttle pressure ratio is shown in figure 14(a). If the engine speeds follow this curve, the fuel flows required will be those shown in figure 14(b).

Figure 14 can be used to design an air-inlet-throttle control system. The pilot's control would call for the throttle pressure ratio and the corresponding engine speed of figure 14(a). The air-inlet throttle would be controlled to position itself to obtain this throttle pressure ratio, and a governor would be used to regulate the fuel flow to obtain the required engine speed. The fuel flows required for each engine speed at various altitudes, as shown in figure 14(b), show a consistent variation with engine speed. This control system, which regulates fuel flow by change in engine speed, will operate and be stable at all points and should not show excessive hunting.

It is seen from figure 9(c) that operation along line A-A permits the full range of airplane speeds investigated at all altitudes. The approximate change in thrust available at each operating point along line A-A can be obtained from figures 8 and 9(c). The variation of engine speed with throttle pressure ratio for line A-A is for steady-state operating conditions. Rapid thrust changes would be obtained at constant engine speed. Thus, for example, from figure 9(c), at sea level and an airplane velocity of 200 miles per hour, if the throttle pressure ratio were 0.78 and the throttle were suddenly opened, a thrust equivalent to an airplane velocity of approximately 280 miles per hour would be obtained without a change

in engine speed. The change in thrust is 39 percent, from figure 8, considering that drag is equal to thrust. Figure 9(c) shows that for line A-A a greater degree of thrust control is available at altitude than at sea level.

Figure 10(c) shows that fuel economy at any airplane velocity is best at wide-open throttle, and that for all airplane velocities and altitudes additional fuel is required if the engine is throttled. Thus when the engine is operating along line A-A (fig. 9(c)), fuel economy is sacrificed for acceleration at low airplane velocities. In figure 9(c) if an operating line is drawn to obtain greater thrust control, fuel economy will be correspondingly worse.

Operating curves for maximum thrust control. - Another possible operating curve, B-B, was drawn on figure 9(c) to obtain the maximum available thrust control at all altitudes. The variations of engine speed with throttle pressure ratio for altitudes from sea level to 35,200 feet are shown in figure 15(a). If the engine speeds are made to follow this curve, the fuel flows will be as shown in figure 15(b).

Figure 15 can be used to design an air-inlet-throttle control system in the same manner as figure 14 was used. Because of the sharp variation of fuel flow with engine speed at low airplane velocities and high altitudes (fig. 15(b)), the regulation of fuel flow by change in engine speed, as is accomplished in this control system, may require a governor with better response than that required for operating line A-A.

Operating line B-B allows the complete range of airplane velocities at each altitude, and gives a greater degree of available thrust control at altitude than did operating line A-A (fig. 9(c)). In fact, at an altitude of 35,200 feet the engine can be operated at constant speed over its complete range of required thrusts.

Fuel economy. - The fuel economies for operating lines A-A and B-B are shown in figure 16, in which fuel economy (in miles per pound of fuel) is plotted against airplane speed for altitudes from sea level to 35,200 feet. The use of operating line A-A gives better fuel economy at all airplane velocities with the improvement greater at the lower velocities, and at all altitudes except sea level than would be obtained by the use of operating line B-B; at sea level the economies for the two lines are equal.

Variable-Area Exhaust-Nozzle Control Parameters

The engine operating conditions shown in figure 11 can be restricted by choosing a relation between exhaust-nozzle area and engine speed. There will be, at any altitude, only one independent variable (either engine speed or exhaust-nozzle area) that determines engine operation. The operating line chosen here, as in the air-inlet-throttle control system previously described, must be so chosen as to obtain the complete range of airplane velocities desired at each altitude and this range of airplane speeds must be obtained with a minimum change in engine speed. If engine speed is limited to 11,500 rpm, maximum power is obtained at the point at which the line representing the maximum turbine-inlet temperature of 2000° R intersects the line representing an engine speed of 11,500 rpm.

Operating curves. - The operating curves in figure 11 represent the relations between the control parameters that can be produced by a variable-area exhaust-nozzle control system. From these curves the engine speed that should be set for each nozzle area can be obtained. The best operating curve is the one that includes the maximum-power point (where the line for an engine speed of 11,500 rpm intersects the 2000° R temperature line) and the point where the lowest airspeed desired (200 mph) intersects the highest practical exhaust-nozzle area of 2.4 square feet. Operating curve C-C of figure 11 was obtained by drawing the best operating curve at sea level and repeating this curve for all altitudes. A straight-line relation between engine speed and exhaust-nozzle area was again used for the sake of simplicity, although any relation could be chosen. The variation of engine speed with change in exhaust-nozzle area is shown in figure 17(a). If engine speed is made to follow this curve, the fuel flows will be as shown in figure 17(b). Figure 17 can be used to design a variable-area exhaust-nozzle control system. The pilot's control lever would set an exhaust-nozzle area and call for a corresponding engine speed, as indicated in figure 17. A governor would be used to regulate the fuel flow to obtain the required engine speed. The fuel flows required for each engine speed at various altitudes as shown in figure 17(b) show a consistent variation with engine speed. This control system, which regulates fuel flow by change in engine speed, will therefore operate, will be stable at all points, and should not show excessive hunting.

Figure 11 can be used to approximate the change in thrust available when steady-state engine operation is made to follow operating line C-C. Rapid thrust changes would be obtained at constant engine speed. For example, if at an airplane velocity

of 200 miles per hour at sea level, the exhaust-nozzle area is suddenly reduced from 2.4 square feet to its minimum value of 1.63 square feet, a thrust equivalent to an airplane velocity of approximately 320 miles per hour is obtained without a change in engine speed. The increase in thrust is approximately 71 percent, as found from figure 8. The control could also be designed to obtain still greater thrust control by allowing the maximum area reduction, which would give the maximum turbine-inlet temperature of 2000° R at any engine speed. In the preceding example, if the area were further reduced from 1.63 to approximately 1.25 square feet, a thrust equivalent to approximately 420 miles per hour would be obtained without a change in engine speed, which represents a thrust increase of approximately 176 percent. Figure 11 shows that when line C-C is used a greater degree of thrust control is available at altitude than at sea level.

Fuel economy, at any airplane speed, is, in general, affected appreciably by change in exhaust-nozzle area at the smallest and at the largest areas (fig. 12). Operation along line C-C therefore sacrifices fuel economy only at the low airplane speeds as can be seen by comparing figures 11 and 12.

Operating curves for maximum thrust control. - Another possible operating curve D-D was drawn in figure 11 that would give the maximum available thrust control at all altitudes. The variation of engine speed and exhaust-nozzle area for altitudes from sea level to 35,200 feet and for several airplane speeds is shown in figure 18(a). For the engine speeds shown on these curves, the fuel flow required is shown in figure 18(b).

Figure 18 can be used to design a variable-area exhaust-nozzle control system in the same manner as figure 17 was used. The fuel flows required for each engine speed at various altitudes (fig. 18(b)) show a consistent variation with engine speed. Thus a system that regulates fuel flow by change in engine speed, as is done in this control system, will operate, be stable at all points, and should not show excessive hunting.

Both operating lines C-C and D-D allow operation over the complete range of airplane speeds at each altitude. Operating line D-D will give a greater degree of available thrust control at altitude, but with a loss in fuel economy at low airplane speeds. For example, if at an altitude of 35,200 feet, an airplane speed of 200 miles per hour, and an exhaust-nozzle area of 2.4 square feet the area is suddenly reduced to 1.63 square feet, a

thrust equivalent to that of an airplane speed of approximately 480 miles per hour is immediately obtained without a change in engine speed.

The control could also be designed to obtain still greater thrust control by allowing the maximum area reduction, which gives the maximum turbine-inlet temperature of 2000° R at any engine speed. In the preceding example, if the area were further reduced from 1.63 to 1.37 square feet, a thrust equivalent to over 500 miles per hour would be obtained without a change in engine speed.

Fuel economy. - The fuel economies that can be expected with operating lines C-C and D-D are shown in figure 19 where fuel economy is plotted against airplane speed for altitudes from sea level to 35,200 feet. In general, the use of curve C-C gives somewhat better fuel economy at altitudes above 14,900 feet and airplane speeds below 500 miles per hour than the use of curve D-D.

Constant-Engine-Speed Control Parameters

The operating conditions of the engine, shown in figure 13, can be further restricted by choosing a relation between the exhaust-nozzle area and the throttle pressure ratio. There would be at any altitude only one independent variable, either exhaust-nozzle area or throttle pressure ratio, determining engine operation. This operating line should be so chosen as to obtain the largest range of airplane speeds at each altitude. Any operating line should give approximately the same available thrust control, because the control system would be set at constant engine speed.

Operating line. - In figure 13(a) a possible operating line was drawn representing conditions at which a constant-engine-speed control system could operate. This curve gives the exhaust-nozzle area that should be automatically set for each throttle pressure ratio. The operating line includes the maximum-power point, which is the condition where the maximum turbine-inlet temperature curve of 2000° R intersects the wide-open throttle line. Operating curve E-E was drawn in figure 13(a) as a straight line through the maximum-power point and includes the complete range of airplane speeds investigated at sea level. This operating curve was repeated at altitude so that the relation between exhaust-nozzle area and throttle pressure ratio would be unaffected by changes in altitude. In figure 13(b) an operating line could be chosen, in a manner similar to that used in choosing operating line E-E, which would give maximum airplane acceleration because maximum power would be available at any operating condition shown in figure 13(b).

A constant-engine-speed control system could be designed using operating curve E-E of figure 13(a). The pilot would set the exhaust-nozzle area, which would call for the corresponding throttle pressure ratio of figure 13(a). The air-inlet throttle would be automatically controlled to position itself to obtain the required throttle pressure ratios and the governor would be used to regulate the fuel flow to keep the engine speed constant.

Fuel economy. - The fuel economy obtained when using operating line E-E of figure 13(a) is shown in figure 20, in which fuel economy is plotted against airplane speed for altitudes from sea level to 35,200 feet.

Evaluation of Various Control Systems

Thrust-control characteristics. - The thrust-control characteristics of the turbojet engine can be considered in two parts; first, the change in thrust available without change in engine speed, and second, that available with acceleration of the engine. Before any change in engine speed occurs, increased thrust is obtained by increasing the turbine-inlet temperature, by opening the air-inlet throttle, or by reducing the area of the exhaust nozzle. Engine acceleration is obtained by increasing the turbine-inlet temperature or by opening the exhaust nozzle. The criterions of a thrust-control system are the maximum increase of thrust available without change of engine speed and the maximum acceleration of engine speed obtainable.

Both the increase in thrust and the acceleration of the conventional turbojet engine are dependent on an increase in turbine-inlet temperature and a corresponding increase in fuel flow. The engine is thus controlled, in the conventional manner, by this single parameter (fuel flow). As the steady-state operating values of turbine-inlet temperature vary between approximately 1400° and 1900° R, the maximum increase in turbine-inlet temperature is too small to cause any immediate substantial increase in thrust. Increase in thrust of the engine controlled by this method is therefore dependent on increase in engine speed. Because of the limited increase in turbine-inlet temperature and the resultant limitation of turbine power output at constant engine speed, and because of the high inertias of the rotating parts, engine-speed acceleration is relatively low. The thrust control obtained by use of the conventional method is therefore unsatisfactory.

It was shown previously that the use of the air-inlet-throttle control system gives, during acceleration, an increase in thrust without change in engine speed. For instance, the accelerating condition at 200 miles per hour with the air-inlet throttle set at a throttle pressure ratio of 0.78 at sea level can be compared with the accelerating condition at 280 miles per hour with the throttle wide open. If the two control systems give the same maximum turbine-inlet temperature during acceleration, the two conditions differ only by the ram-pressure ratios and the inlet-air drags for the two airplane velocities. The thrust immediately obtained on opening the throttle at an airplane speed of 200 miles per hour is therefore approximately equal to that required for 280 miles per hour. Engine-speed acceleration with the air-inlet-throttle control system is approximately the same as acceleration with the conventional system. At an altitude of 35,200 feet, where the air-inlet-throttle control system can be operated at constant engine speed, maximum thrust can be obtained at any airplane velocity by opening the throttle.

It was previously shown that use of the variable-area exhaust-nozzle control system also gives, during acceleration, a substantial increase in thrust without change in engine speed. For instance, the accelerating condition at 200 miles per hour at sea level with the variable-area exhaust-nozzle control can be compared with the accelerating condition at 320 miles per hour at an exhaust-nozzle area of 1.63 square feet. If the control systems give the same maximum turbine-inlet temperature during acceleration, the two conditions differ only by the ram-pressure ratios and the inlet-air drags for the two airplane velocities. An increase in thrust of approximately 71 percent is therefore obtained immediately when the exhaust-nozzle area is reduced at an airplane speed of 200 miles per hour and is approximately that required for 320 miles per hour. Engine-speed acceleration at the exhaust-nozzle area of 1.63 square feet is somewhat less than at the fixed exhaust-nozzle area of approximately 1.87 square feet because of the reduced allowable turbine-inlet temperature increase at the smaller exhaust-nozzle area. If in the previous example the area were further reduced to obtain greater thrust, engine-speed acceleration would be sacrificed until, at the minimum area of 1.25 which gives the maximum thrust (equivalent to 420 mph), no increase in engine speed could be obtained without exceeding the maximum turbine-inlet temperature of 2000° R. At an altitude of 35,200 feet, the thrust required for an airplane speed of 480 miles per hour can be obtained at 200 miles per hour by reducing the exhaust-nozzle area without change in engine speed. The variable-area exhaust-nozzle control system has better thrust-control characteristics at sea level but slightly inferior thrust-control characteristics at an altitude of 35,200 feet than the air-inlet-throttle control system. (See figs. 9(c) and 11.)

It was previously shown that the engine can be operated at a constant speed of 10,000 rpm by use of a combination of the variable-area exhaust nozzle and the air-inlet throttle (fig. 13(a)). The thrust equivalent to approximately 500 miles per hour can be immediately obtained at 200 miles per hour at sea level by opening the throttle and closing the exhaust nozzle. The constant-speed-control system therefore gives ideal thrust-control characteristics for the engine. In order to obtain the highest and lowest values of thrust required at sea level, a small change in engine speed may be required and this additional requirement could be incorporated in the control system.

It was previously shown that the engine can be operated at a constant engine speed of 11,500 rpm by use of a combination of the variable-area exhaust nozzle and the air-inlet throttle. A thrust equivalent to maximum power can be obtained at an airplane speed of approximately 300 miles per hour at sea level and at approximately 200 miles per hour at altitudes above 14,900 feet by opening the air-inlet throttle and closing the exhaust nozzle.

Fuel economy. - The fuel economies obtained by the use of the various control systems are shown in figure 21 in which the fuel economy is plotted against airplane speed for altitudes from sea level to 35,200 feet. The fuel economy obtained with the conventional engine control is compared with that obtained using the operating lines chosen for maximum available thrust control for the air-inlet-throttle, variable-area exhaust-nozzle, and constant-engine-speed control systems. In general, the various control systems can be rated on the basis of fuel economy as follows: The conventional control, the variable-area exhaust-nozzle control, and the air-inlet-throttle control systems. Fuel economies for the constant-engine-speed control system improve with altitude and at an altitude of 35,200 feet compare favorably with those obtained with the conventional control.

SUMMARY OF RESULTS

The rate at which thrust can be changed on a typical direct-coupled turbojet engine with a centrifugal-flow compressor can be increased over that obtained by controlling only fuel flow by the addition to the standard configuration of an air-inlet throttle or a variable-area exhaust nozzle. By means of an analysis developed in this report on this engine installed in a fighter airplane, characteristics of engine operation with an air-inlet throttle,

with a variable-area exhaust nozzle, or with a combination of the two are predicted and control-parameter curves chosen from which such control systems can be designed.

1. This turbojet engine controlled by use of an air-inlet-throttle system can, at sea level and an airplane velocity of 200 miles per hour, deliver an increase in thrust of approximately 39 percent without a change in engine speed. At an altitude of 35,200 feet such an engine can be operated over the complete range of thrust investigated at constant engine speed with an air-inlet-throttle control.

2. This turbojet engine controlled by use of a variable-area exhaust-nozzle control system can, at sea level and an airplane velocity of 200 miles per hour deliver an increase in thrust of approximately 176 percent without a change in engine speed. At an altitude of 35,200 feet such an engine can be operated over the complete range of thrust investigated at constant engine speed.

3. This turbojet engine controlled by a combination of the air-inlet throttle and the variable-area exhaust nozzle has the best thrust control of the systems considered at all altitudes and flight speeds. With such a control system, the engine can be operated at a constant speed of 10,000 rpm for all airplane speeds between 200 and 500 miles per hour at all altitudes. With the same control system, the engine can be operated at a constant engine speed of 11,500 rpm for all airplane speeds between 300 miles per hour and maximum power at all altitudes below 14,900 feet and between 200 miles per hour and maximum power at altitudes above 14,900 feet.

4. In general, the fuel economies obtained with the control systems investigated and the conventional fuel-flow control system can be rated as follows in order of decreasing fuel economy: the conventional control, the variable-area exhaust-nozzle control, and the air-inlet-throttle control. Fuel economies for the 10,000 rpm constant-engine-speed control improve with altitude and at an altitude of 35,200 feet compare favorably with those obtained with the conventional fuel-flow control.

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APPENDIX A

DISCUSSION OF ANALYSIS

Symbols

The following symbols are used:

A	effective area of exhaust nozzle, sq ft
C	compressor slip factor
c_p	specific heat at constant pressure, Btu/(lb)($^{\circ}$ R)
D	airplane drag, lb
d	compressor impeller diameter, 30 in.
F_j	jet thrust, lb
g	acceleration of gravity, 32.2 ft/sec ²
H_f	heat of combustion of fuel, 18,400 Btu/lb
h_3	total enthalpy of air at burner inlet, Btu/lb
h_4	total enthalpy of gas at burner outlet, Btu/lb
(hp) _c	compressor horsepower required
(hp) _t	turbine horsepower output
J	mechanical equivalent of heat, 778 ft-lb/Btu
K_1, K_2	constants
N	engine speed, rpm
P	total pressure, lb/sq in. absolute
p	static pressure, lb/sq in. absolute
R	gas constant for air, ft-lb/(lb)($^{\circ}$ R)
T	total temperature, $^{\circ}$ R
t	static temperature, $^{\circ}$ R

V_0	airplane velocity, ft/sec
V_5	gas velocity at exhaust-nozzle throat, ft/sec
W_a	air flow, lb/sec
W_f	fuel flow, lb/hr
W_g	gas flow, lb/sec
γ	ratio of specific heats
δ	total pressure divided by NACA standard sea-level pressure (14.7 lb/sq in. absolute)
η_b	combustion efficiency of burner
θ	total temperature divided by NACA standard sea-level temperature (518° R)
σ	relative air density

Subscripts:

0	ambient air
1	air-inlet throttle
2	compressor inlet
3	compressor outlet or burner inlet
4	turbine inlet or burner outlet
5	turbine outlet or exhaust nozzle

Discussion

The performance of the engine when operating with a variable-area exhaust nozzle or an air-inlet throttle was obtained from the following engine analysis. The data presented in figures 2 to 4 show the performance of the turbine when operating in the engine and were obtained over a range of altitude and ram-pressure-ratio conditions. In order to simplify the calculations, an average value of γ of 1.35 was assumed for the combustion gases in the

turbine as well as in the exhaust nozzle. In general, turbine characteristics can be described by a single relation among the following quantities: pressure ratio P_4/P_5 , corrected power $(hp)_t/W_g \theta_4$, and corrected speed $N/\sqrt{\theta_4}$. For the centrifugal compressor assumed in the engine, the power required can be expressed as follows (reference 3):

$$\frac{(hp)_c}{W_a} = K_1 N^2 \quad (A1)$$

If it is assumed that all the power of the turbine is absorbed by the compressor and that the ratio of compressor air flow to turbine gas flow is constant, equation (A1) then becomes:

$$\frac{(hp)_t}{W_g \theta_4} = K_2 \left(\frac{N}{\sqrt{\theta_4}} \right)^2 \quad (A2)$$

A single relation therefore exists between turbine corrected speed and corrected power. Because these quantities determine turbine pressure ratio and consequently corrected air flow and efficiency, there is a single relation between any two of the turbine quantities. The curves of figures 2 to 4 will therefore remain unchanged under all conditions of engine operation.

Values of gas flow corrected to conditions in the exhaust nozzle were found from the following equation:

$$\frac{W_g \sqrt{\theta_5}}{\delta_5} = \frac{W_g \sqrt{\theta_4}}{\delta_4} \frac{P_4}{P_5} \sqrt{\frac{T_5}{T_4}} \quad (A3)$$

For each value of P_4/P_5 there is a corresponding value of $W_g \sqrt{\theta_4}/\delta_4$ from figure 2 and a corresponding value of T_5/T_4 obtained from turbine efficiency of figure 4 and therefore a corresponding value of $W_g \sqrt{\theta_5}/\delta_5$ from equation (A3). This relation is plotted in figure 22.

In figure 23 the general thermodynamic relation between corrected gas flow and pressure ratio is shown for the exhaust nozzle. This relation can be expressed as follows:

$$\frac{W_g \sqrt{\theta_5}}{A \delta_5} = 144 \times 14.7 \sqrt{\frac{2\gamma}{\gamma-1} \frac{g}{519R}} \frac{\left[\left(\frac{P_5}{P_5} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{\frac{1}{2}}}{\left(\frac{P_5}{P_5} \right)^{\frac{\gamma+1}{2\gamma}}} \quad (A4)$$

When sonic flow exists in the exhaust nozzle, $W_g \sqrt{\theta_5}/A \delta_5$ reaches a maximum value. For any given exhaust-nozzle area there is a maximum value of $W_g \sqrt{\theta_5}/\delta_5$ and thus a maximum value of turbine pressure ratio (fig. 22), and consequently a maximum value of turbine corrected gas flow and engine speed (figs. 2 and 3). The smaller the exhaust-nozzle area, the lower will be the maximum value of P_4/P_5 .

Tests have shown that a choking condition is reached in the turbine rotor or at the turbine discharge, which limits corrected turbine power at each corrected speed. At the point where the turbine operating line as determined by equation (A2) reaches this choking limit, corrected speed reaches a maximum value. It was found that this choking limit is reached at approximately the point where sonic velocity is reached in the exhaust nozzle when the standard exhaust-nozzle area is used. This point is at a turbine-pressure ratio of 2.55. Figures 2 and 3 were thus extrapolated vertically from the turbine-rotor choking point. Corrected gas flow of figure 2 reaches a maximum value when sonic velocity exists in the throat of the turbine nozzle at a pressure ratio of approximately 1.8.

For exhaust-nozzle areas less than 1.87 square feet, the exhaust nozzle will choke at turbine-pressure ratios less than 2.55 and the turbine-rotor choking limit will not be reached. For areas larger than 1.87 square feet, turbine-rotor choking will be reached before the exhaust nozzle chokes. For these areas it is assumed that beyond the turbine-rotor choking limit there will not be supersonic flow in the tail pipe and that increasing P_5/P_5 and $W_g \sqrt{\theta_5}/\delta_5$ in the exhaust nozzle and thus P_4/P_5 (fig. 22) will require total-pressure shock losses at the turbine exit. In this region a distinction must be made between the total pressure at the turbine exit and in the exhaust nozzle. The pressure ratio P_4/P_5 will thus increase beyond 2.55 until choking occurs in the exhaust nozzle. This discussion of the effect of turbine-rotor choking is substantiated in reference 4. Turbine efficiency was defined to include

the effect of losses after the turbine by measuring the total pressure after the turbine in the exhaust nozzle. This efficiency will decrease beyond the turbine-rotor choking condition.

By the use of figures 2, 3, 22, and 23, curves were drawn relating F_j/δ_0 , $W_a\sqrt{\theta_4}/\delta_0$, $N/\sqrt{\theta_4}$, and P_4/P_0 at fixed exhaust-nozzle areas. These curves are shown in figures 24, 25, and 26, respectively, and were obtained in the following manner: At each value of P_4/P_5 , $W_g\sqrt{\theta_5}/\delta_5$ was obtained from figure 22. Dividing by the exhaust-nozzle areas gave $W_g\sqrt{\theta_5}/A\delta_5$. The corresponding value of P_5/P_5 was found from figure 23. For subsonic flow in the exhaust nozzle, corrected jet thrust was found from the following equation:

$$\frac{F_j}{\delta_0} = 144 \times 14.7A \frac{2\gamma}{\gamma-1} \left[\left(\frac{P_5}{P_5} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (A5)$$

Expansion pressure ratio P_4/P_0 was found from the product of P_4/P_5 and P_5/P_5 , where $P_5 = P_0$, and $N/\sqrt{\theta_4}$ was obtained from figure 3. Corrected air flow was found from the following equation:

$$\frac{W_a\sqrt{\theta_4}}{\delta_0} = \frac{W_g\sqrt{\theta_4}}{\delta_4} \frac{P_4}{P_0} \frac{1}{W_g/W_a} \quad (A6)$$

$W_g\sqrt{\theta_4}/\delta_4$ was found from figure 2 and W_g/W_a was assumed constant at 1.015.

When the abscissa of figure 3 reaches a maximum value, sonic flow exists in the exhaust nozzle and P_4/P_5 and $W_g\sqrt{\theta_4}/\delta_4$ reach a maximum value. The equation for corrected jet thrust can be written as follows:

$$\frac{F_j}{\delta_0} = 2672A \frac{P_4/P_0}{(P_4/P_5)_{\max}} - 2116.8 A \quad (A7)$$

or

$$\frac{F_j}{\delta_0} = \frac{2672 A \frac{W_a \sqrt{\theta_4}}{\delta_0} \left(\frac{W_g}{W_a} \right)}{\left(\frac{P_4}{P_5} \right)_{\max} \left(\frac{W_g \sqrt{\theta_4}}{\delta_4} \right)_{\max}} - 2116.8 A \quad (A8)$$

For sonic flow in the exhaust nozzle, $N/\sqrt{\theta_4}$ reaches a limiting value if its value has not already been limited by turbine-rotor choking.

All required engine operating characteristics can be obtained from figures 24, 25, and 26 except the ram-pressure ratio. This quantity is obtained from the compressor plot (fig. 5), which gives the required compressor-inlet pressure for the air flow, engine speed and turbine-inlet pressure of figures 24, 25, and 26. In order to facilitate this calculation, lines of constant $\sqrt{T_4/T_2}$ were drawn in the compressor plot and are shown in figure 27. They were drawn by use of the following equation:

$$\frac{W_a \sqrt{\theta_2}}{\delta_2} = \frac{P_3}{P_2} \left(\frac{W_g \sqrt{\theta_4}}{\delta_4} \right) \frac{1}{\sqrt{\frac{T_4}{T_2}}} \frac{1}{\left(\frac{W_g}{W_a} \right) \left(\frac{P_3}{P_4} \right)} \quad (A9)$$

The quantities W_g/W_a and P_3/P_4 were assumed constant at 1.015 and 1.06, respectively. For sonic flow in the turbine nozzle, $W \sqrt{\theta_4}/\delta_4$ is constant and lines of constant $\sqrt{T_4/T_2}$ are straight lines in the compressor plot. For subsonic flow in the turbine nozzle, figures 2 and 3 give the following functional relation

$$\frac{W_g \sqrt{\theta_4}}{\delta_4} = f \left(\frac{N}{\sqrt{\theta_4}} \right)$$

Equation (A9) can therefore be rewritten as follows

$$\frac{W_a \sqrt{\theta_2}}{\delta_2} = \frac{P_3}{P_2} f \left(\frac{N}{\sqrt{\theta_2}} \sqrt{\frac{T_2}{T_4}} \right) \frac{1}{\sqrt{\frac{T_4}{T_2}}} \frac{1}{\left(\frac{W_g}{W_a} \right) \left(\frac{P_3}{P_4} \right)} \quad (A10)$$

The compressor characteristics (fig. 5) can be expressed as follows

$$\frac{W_a \sqrt{\theta_2}}{\delta_2} = f \left(\frac{P_3}{P_2} \frac{N}{\sqrt{\theta_2}} \right) \quad (A11)$$

Equations (A10) and (A11) were solved graphically to extend lines of constant $\sqrt{T_4/T_2}$ below the point of sonic flow in the turbine nozzles.

The method of calculating engine operating conditions at any altitude, airplane velocity, exhaust-nozzle area, and turbine-inlet temperature is as follows: At the velocity and altitude chosen, the airplane drag was found from figure 8. The values of airplane velocity, altitude pressure, drag, and turbine-inlet temperature that were chosen were inserted in the following equation

$$\frac{F_j}{\delta_0} = \frac{D}{\delta_0} + \left(\frac{W_a \sqrt{\theta_4}}{\delta_0} \right) \frac{v_0}{g \sqrt{\theta_4}} \quad (A12)$$

This relation was drawn in figure 24 and the intersection of this line and the curve for the exhaust-nozzle area chosen gave the values of F_j/δ_0 and $W_a \sqrt{\theta_4}/\delta_0$. Corresponding values of $N/\sqrt{\theta_4}$ and P_4/p_0 were found from figures 25 and 26, respectively. Jet thrust, air flow, engine speed, and turbine-inlet pressure were thus obtained. Values of compressor-inlet temperature were obtained from the altitude and airplane speed chosen. Values of $N/\sqrt{\theta_2}$ and $\sqrt{T_4/T_2}$ were found and used in figure 27 to find P_3/P_2 . The throttle pressure ratio was then found from the following equation

$$\frac{P_2}{P_1} = \frac{\frac{P_4}{P_0} \frac{P_3}{P_4}}{\frac{P_1}{P_0} \frac{P_3}{P_2}} \quad (A13)$$

In this equation, P_3/P_4 was assumed constant at 1.06 and P_1/P_0 was found from the velocity and altitude assuming 100-percent ram efficiency.

The temperature of the air leaving the compressor was found from the following equation

$$\frac{T_3}{T_2} = 1 + 0.5079 \times 10^{-8} \left(\frac{N}{\sqrt{\theta_2}} \right)^2 \quad (\text{A14})$$

Burner efficiency was found from figure 6 from values of T_3 , T_4 , and P_3 . Fuel flow required was then calculated from the heat-balance equation

$$W_f = \frac{W_a (h_4 - h_3)}{\eta_b H_f} \left(\frac{W_g}{W_a} \right) 3600 \quad (\text{A15})$$

The enthalpies were obtained from reference 5, W_g/W_a was assumed constant at 1.015 in this equation, and the heat of combustion of the fuel was assumed to be 18,400 Btu per pound.

APPENDIX B

DEVELOPMENT OF EQUATIONS

Jet thrust is defined by the following equation:

$$F_j = \frac{W}{g} \frac{V_5}{g} + 144 A (p_5 - p_0) \quad (B1)$$

Gas flow can be written

$$W = A_5 V_5 \frac{144 p_5}{R t_5} \quad (B2)$$

When this expression is inserted in equation (B1), the following equation is obtained:

$$F_j = 144 A_5 p_5 \left(\frac{V_5^2}{g R t_5} \right) + 144 A (p_5 - p_0) \quad (B3)$$

The relation between velocity and pressures in the exhaust nozzle can be expressed as follows:

$$\frac{V_5^2}{g R t_5} = \frac{2\gamma}{\gamma-1} \left[\left(\frac{p_5}{p_0} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (B4)$$

Inserting this expression in equation (B3) and rearranging the resulting expression gives the following:

$$F_j = 144 \times 14.7 A \frac{p_5}{p_0} \frac{2\gamma}{\gamma-1} \left[\left(\frac{p_5}{p_0} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] + 144 \times 14.7 A \left(\frac{p_5}{p_0} - 1 \right) \quad (B5)$$

For subsonic flow in the exhaust nozzle, p_5 is equal to p_0 and equation (B5) becomes

$$\frac{F_j}{\delta_0} = 144 \times 14.7 A \frac{2\gamma}{\gamma-1} \left[\left(\frac{P_5}{P_0} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (B6)$$

This equation is presented as equation (A5) in appendix A.

For sonic flow in the exhaust nozzle, P_4/P_5 becomes constant and equation (B5) can be rewritten as follows:

$$\frac{F_j}{\delta_0} = 144 \times 14.7 A \frac{P_5}{P_0} \left[\frac{2\gamma}{\gamma-1} \left(\frac{P_5}{P_0} \right)^{\frac{\gamma-1}{\gamma}} - \frac{2\gamma}{\gamma-1} + 1 \right] - 144 \times 14.7 A$$

or

$$\frac{F_j}{\delta_0} = 144 \times 14.7 A \frac{P_5}{P_0} \left[\frac{\frac{2\gamma}{\gamma-1} \left(\frac{P_5}{P_0} \right)^{\frac{\gamma-1}{\gamma}} - \frac{2\gamma}{\gamma-1} + 1}{\frac{P_5}{P_0}} \right] - 144 \times 14.7 A \quad (B7)$$

The bracketed term is constant and equation (B7) becomes

$$\frac{F_j}{\delta_0} = 2672 A \frac{P_5}{P_0} - 2116.8 A \quad (B8)$$

Because P_4/P_5 reaches a maximum value for sonic flow in the exhaust nozzle, equation (B8) can be rearranged as follows

$$\frac{F_j}{\delta_0} = 2672 A \frac{P_4/P_0}{\left(\frac{P_4}{P_5} \right)_{\max}} - 2116.8 A \quad (B9)$$

This equation is presented as equation (A7) in appendix A.

Because $W_g \sqrt{\theta_4} / \delta_4$ is also at a maximum value for sonic flow in the exhaust nozzle, equation (B8) can be rearranged as follows

$$\frac{F_j}{\delta_0} = \frac{2672A \frac{W_a \sqrt{\theta_4}}{\delta_0} \left(\frac{W_g}{W_a} \right)}{\left(\frac{P_4}{P_5} \right)_{\max} \left(\frac{W_g \sqrt{\theta_4}}{\delta_4} \right)_{\max}} 2116.8 A \quad (\text{B10})$$

In this expression, W_g/W_a is assumed constant at 1.015; equation (B10) is presented as equation (A8) in appendix A.

The relation among jet thrust, airplane drag, air flow and airplane velocity is well known and may be expressed by the following equation:

$$F_j = D + \frac{W_a V_0}{g} \quad (\text{B11})$$

Rearranging this equation to include the turbine-inlet temperature gives the following equation:

$$\frac{F_j}{\delta_0} = \frac{D}{\delta_0} + \left(\frac{W_a \sqrt{\theta_4}}{\delta_0} \right) \frac{V_0}{g \sqrt{\theta_4}} \quad (\text{B12})$$

This equation is presented as equation (A12) in appendix A.

The power required by the compressor can be expressed as follows (reference 3):

$$(\text{hp})_c = C \frac{W_a \pi^2 d^2 N^2}{g 3600 \times 550} \quad (\text{B13})$$

Because all the energy into the compressor is absorbed by the air, the following also holds:

$$(\text{hp})_c = \frac{c_p W_a J (T_3 - T_2)}{550} \quad (\text{B14})$$

Equating equations (B13) and (B14) and rearranging gives the following equation:

$$\frac{T_3}{T_2} = 1 + \left(\frac{C \pi^2 d^2}{519 g 3600 c_p J} \right) \left(\frac{N}{\sqrt{\theta_2}} \right)^2 \quad (B15)$$

For a compressor-rotor diameter of 2.5 feet and an assumed slip factor C of 0.925, equation (B15) becomes

$$\frac{T_3}{T_2} = 1 + 0.5079 \times 10^{-8} \left(\frac{N}{\sqrt{\theta_2}} \right)^2 \quad (B16)$$

This equation is presented as equation (A14) in appendix A.

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4. Moyes, S. J.: An Analysis of the Equilibrium Running Condition of Jet-Propulsion Units. Rep. No. E.3960, Nov. 1942, R.A.E.
5. Pinkel, Benjamin, and Turner, L. Richard: Thermodynamic Data for the Computation of the Performance of Exhaust-Gas Turbines. NACA ARR No. 4B25, 1944.

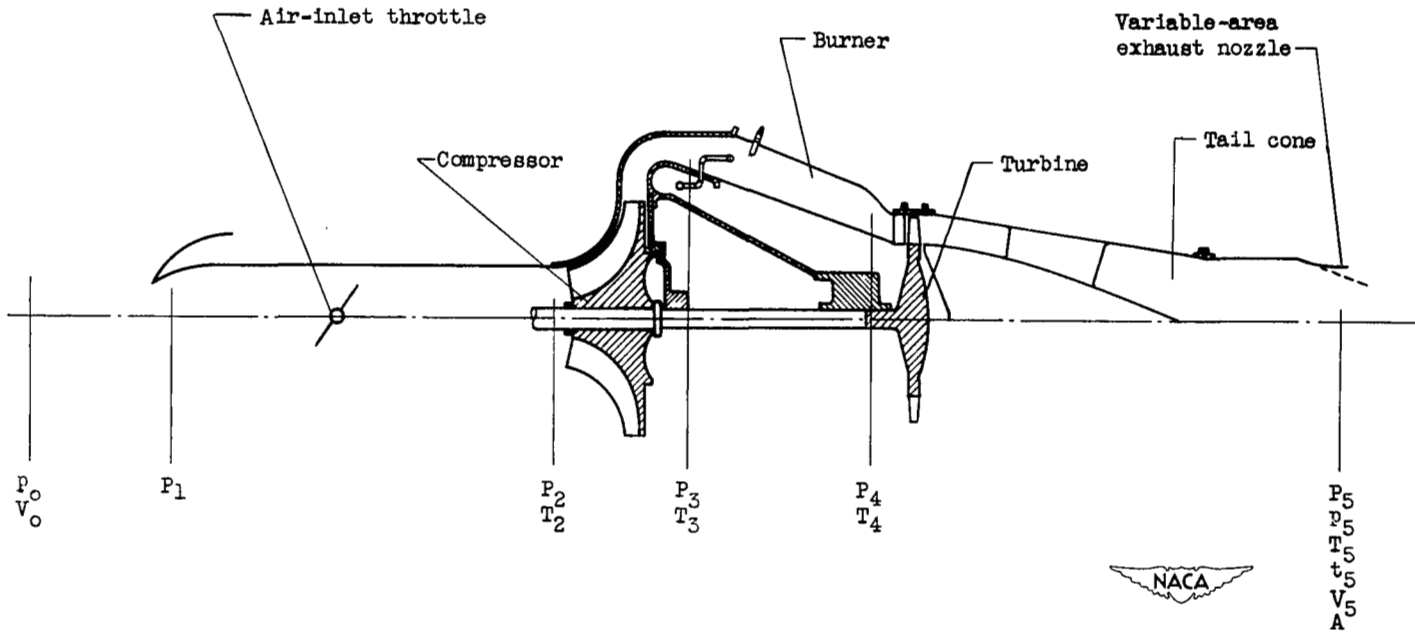


Figure 1. - Typical configuration of a direct-coupled turbojet engine.

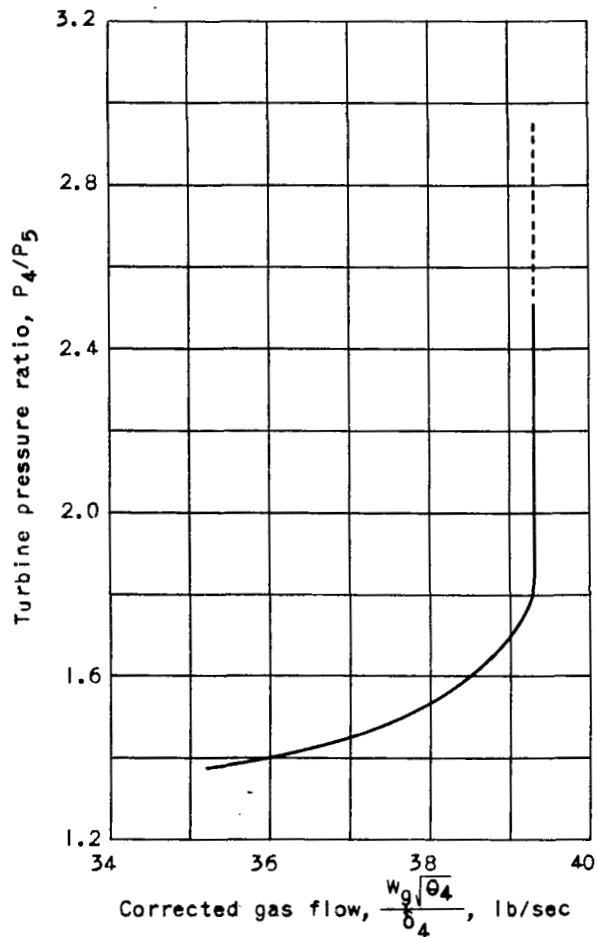


Figure 2.- Variation of turbine pressure ratio with gas flow corrected to turbine-inlet pressure and temperature relative to NACA standard atmospheric conditions at sea level. (Data obtained from NACA wind-tunnel investigation and extrapolated.)

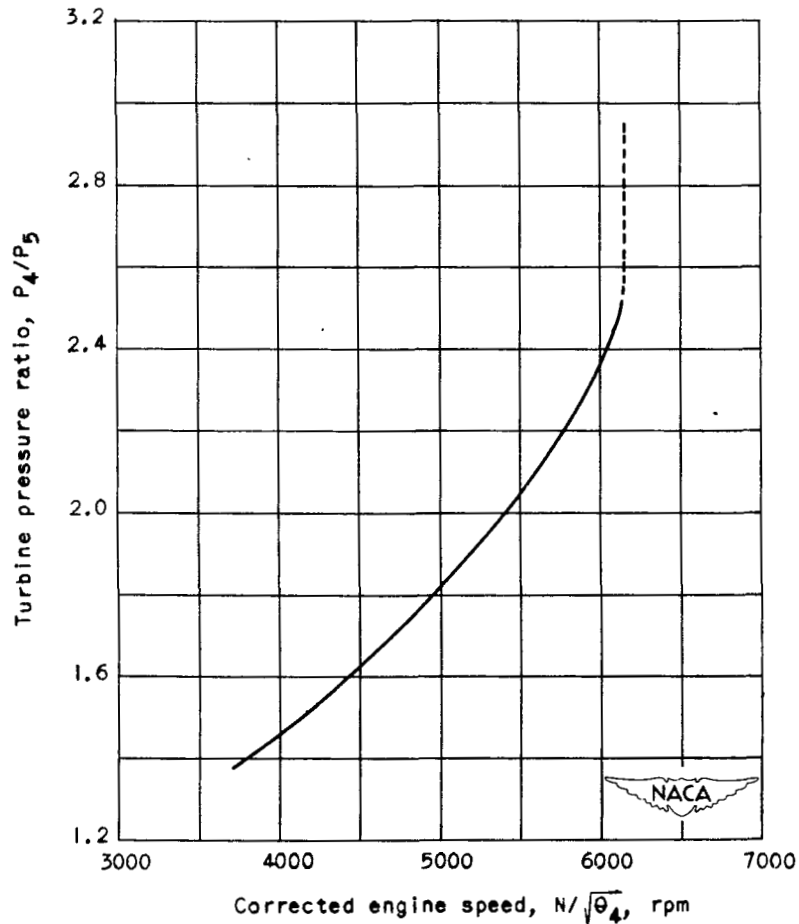


Figure 3. - Variation of turbine pressure ratio with engine speed corrected to turbine-inlet pressure and temperature relative to NACA standard atmospheric conditions at sea level. (Data obtained from NACA wind-tunnel investigation and extrapolated.)

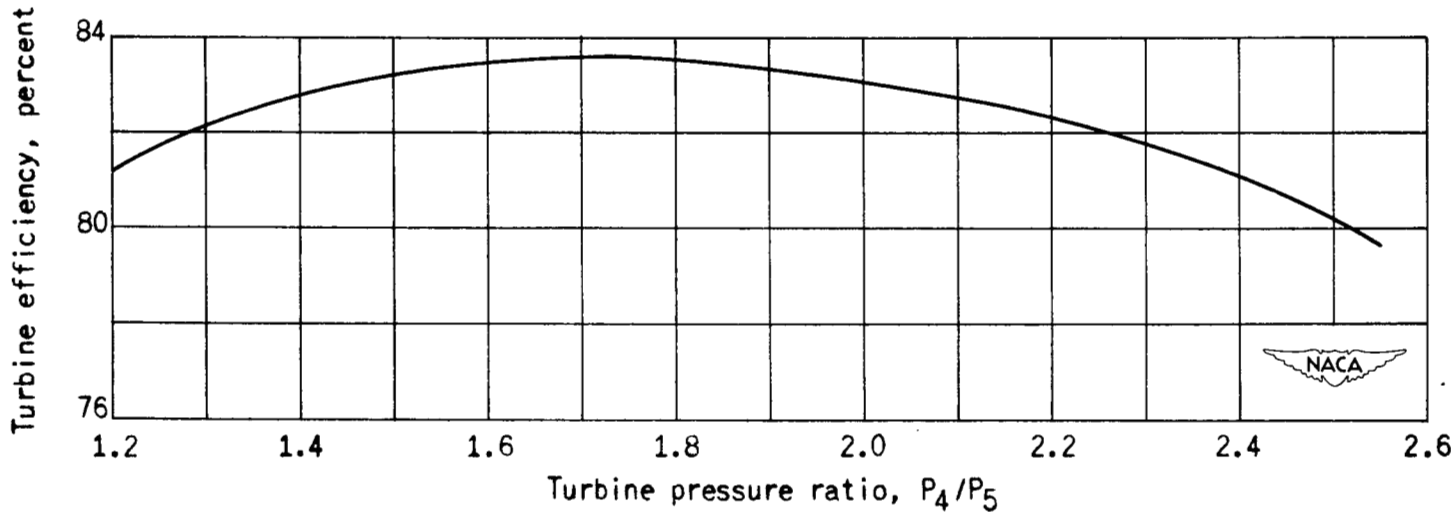


Figure 4. - Turbine efficiency as a function of turbine pressure ratio. (Data obtained from NACA wind-tunnel investigation.)

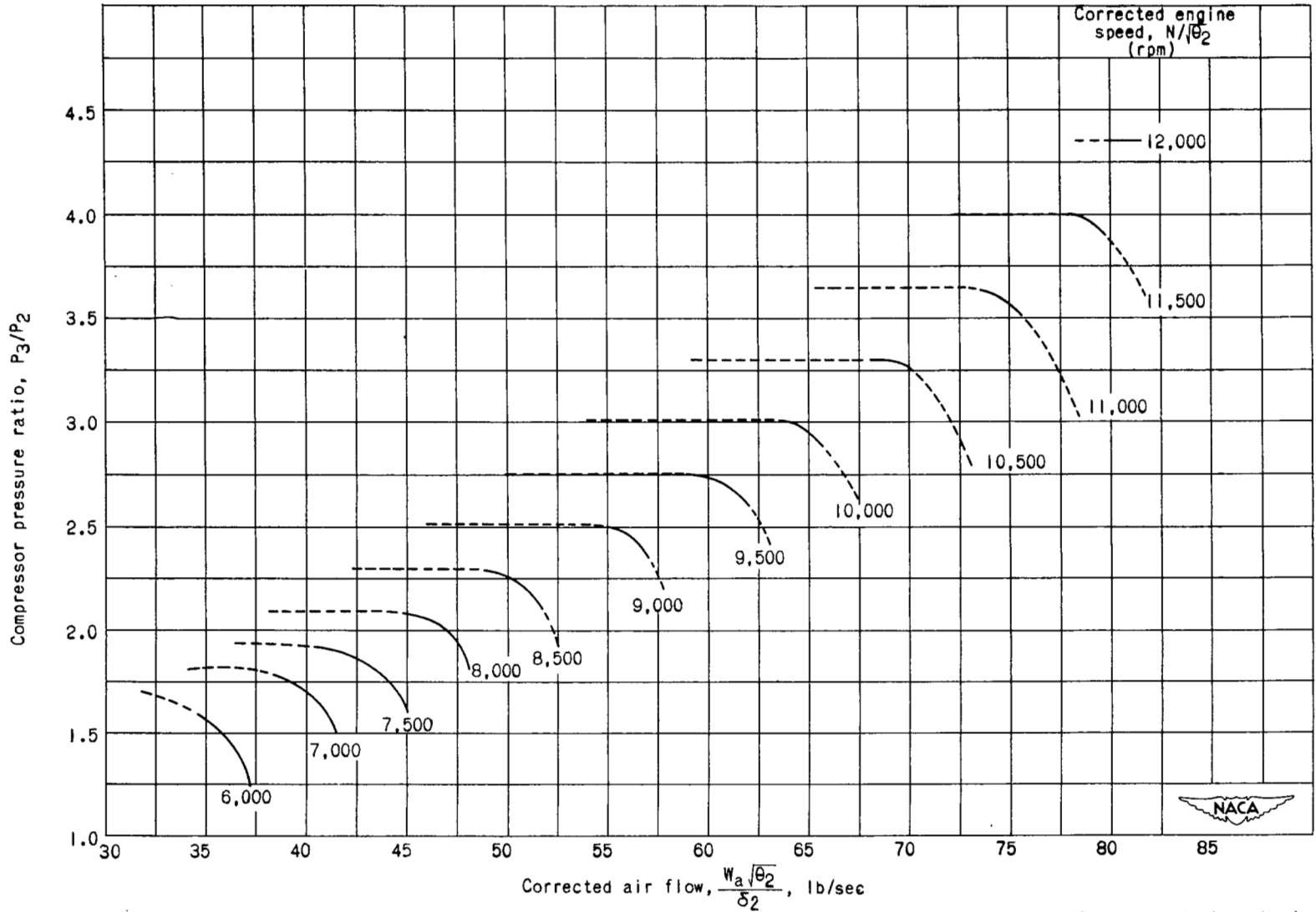


Figure 5. - Compressor characteristics corrected to compressor-inlet temperature and pressure relative to NACA standard atmospheric conditions at sea level. (Data obtained from NACA wind-tunnel investigation, cross-plotted and extrapolated.)

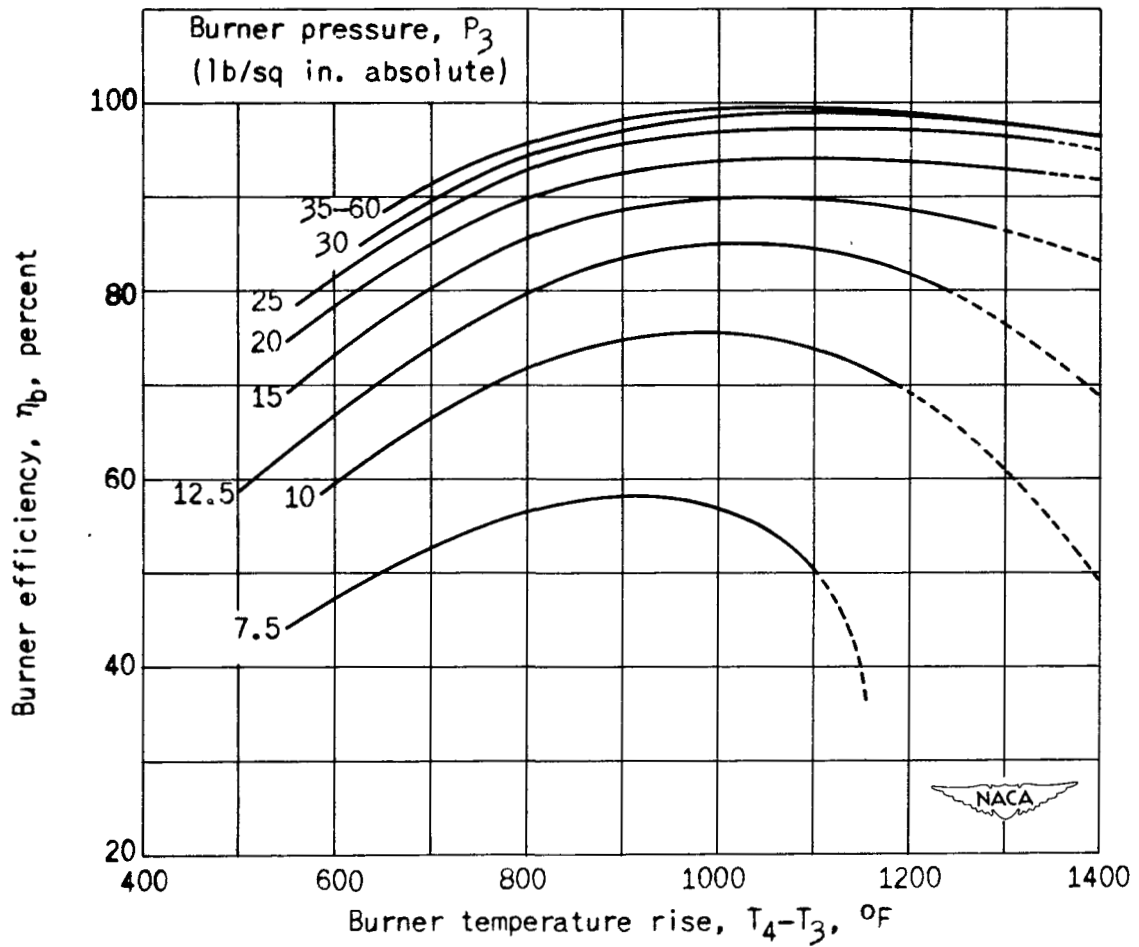


Figure 6. - Burner efficiency as a function of burner temperature rise and pressure. (Curve reproduced from reference 2.)

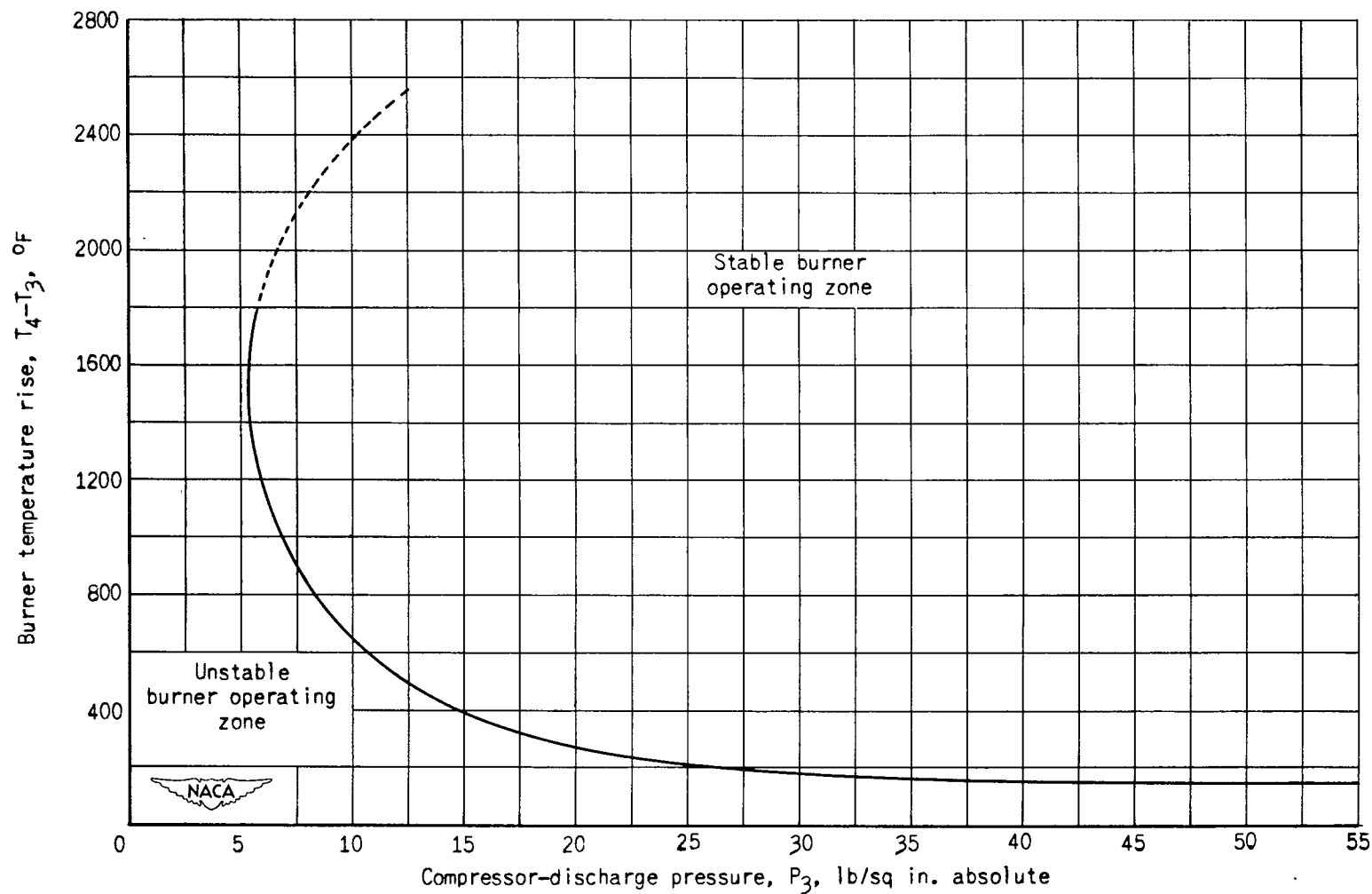


Figure 7. - Burner operation as a function of burner temperature rise and compressor-discharge pressure, showing burner operating zone. (Curve reproduced from reference 2.)

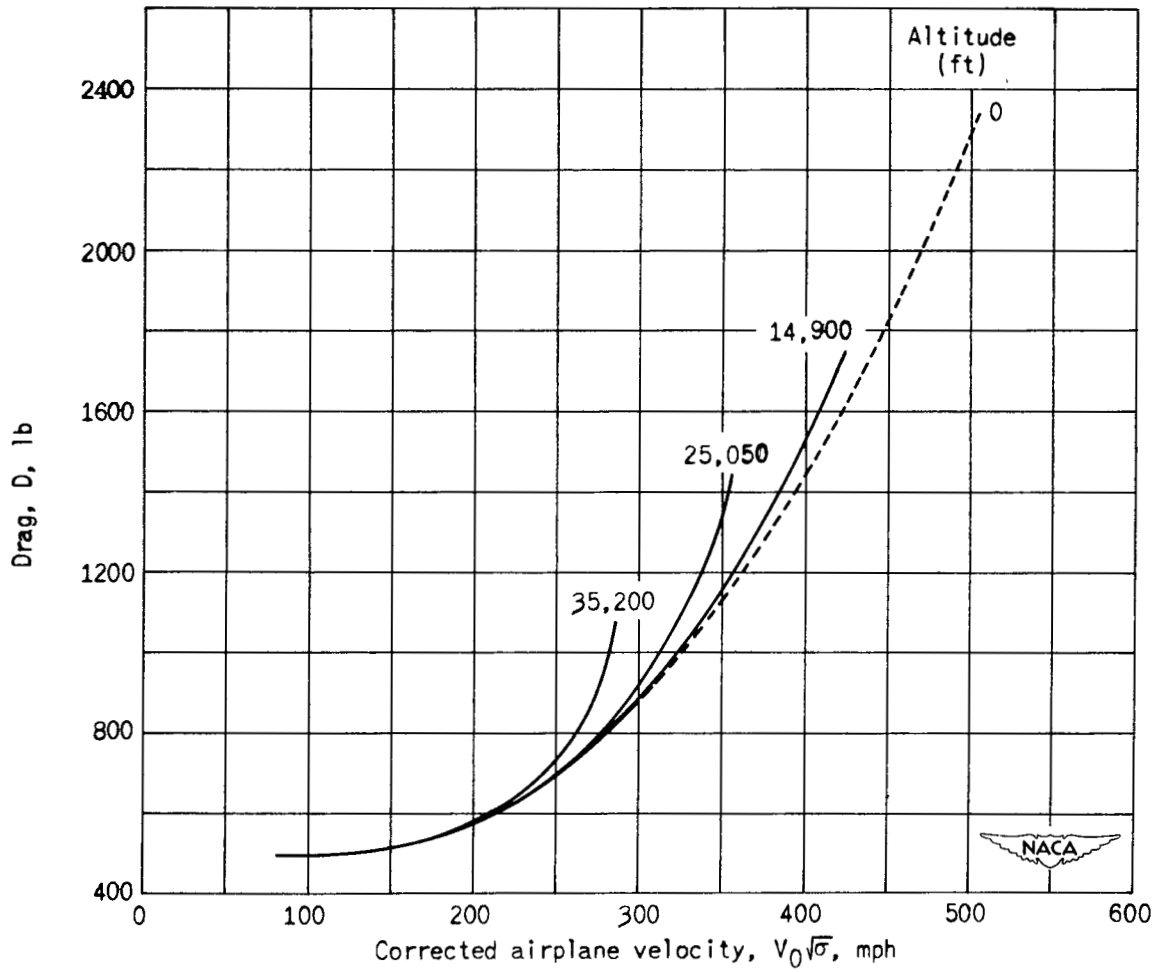
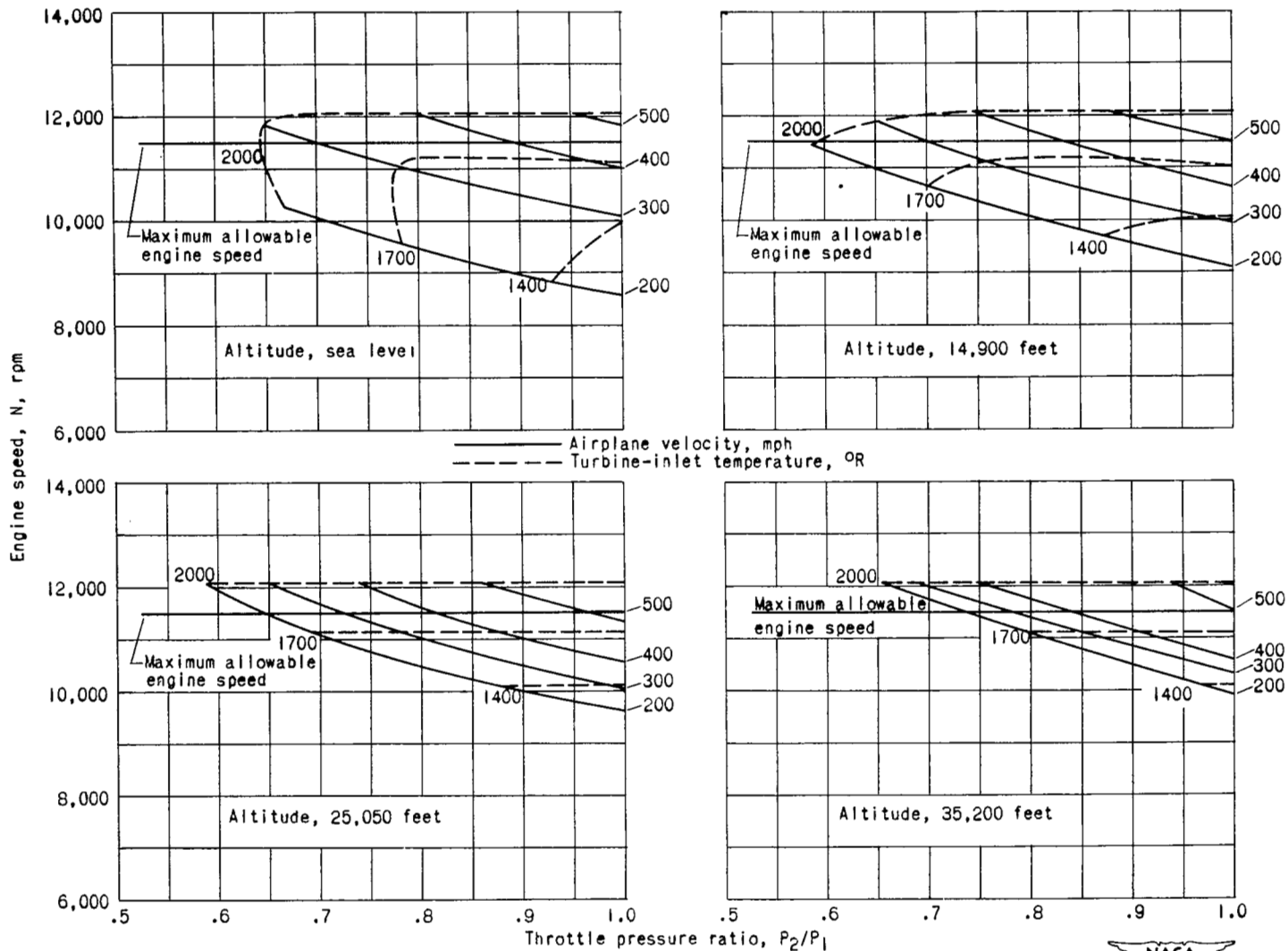


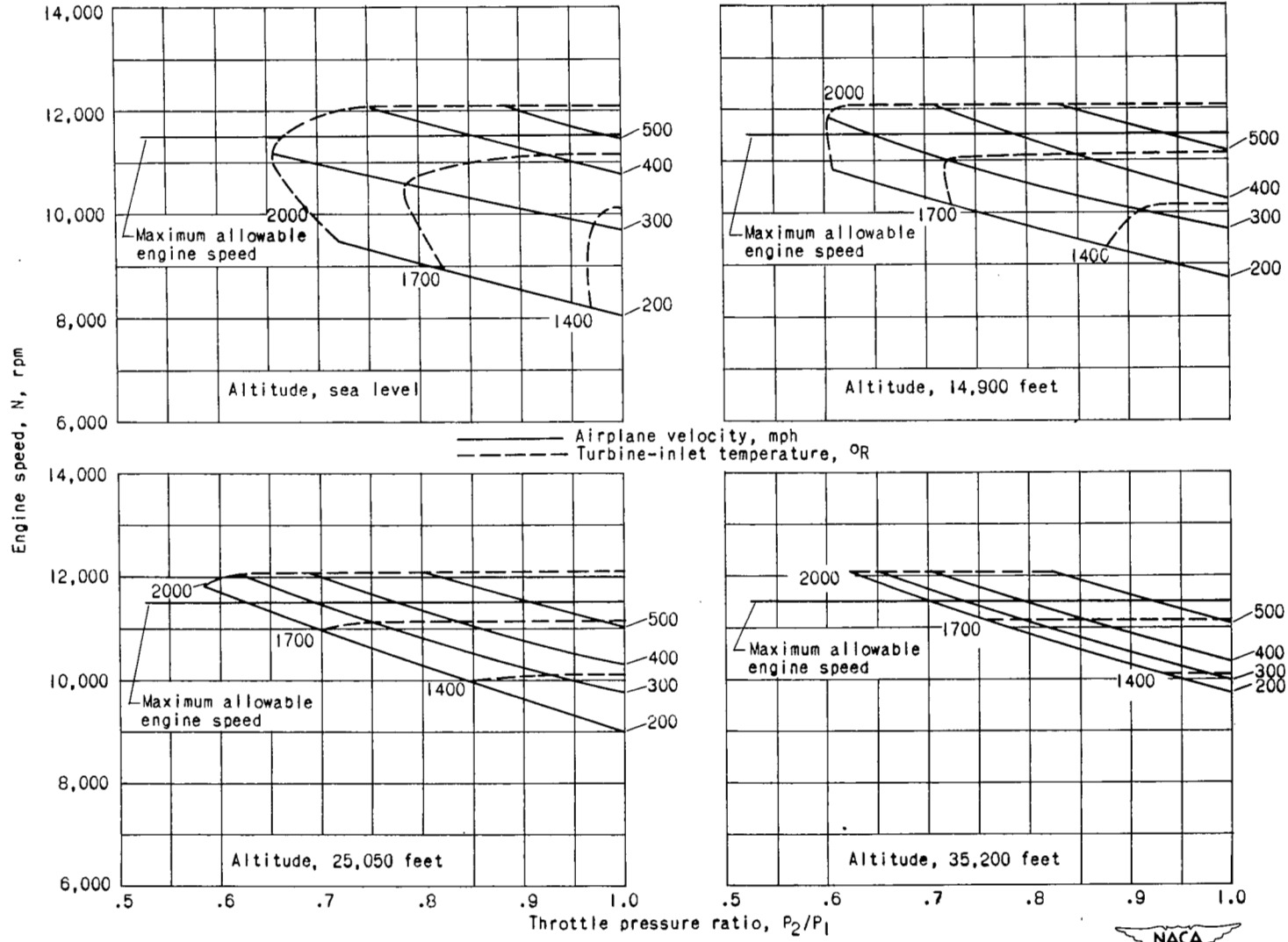
Figure 8. - Drag as a function of airplane velocity and altitude. (Curve reproduced from Lockheed Aircraft Corporation data.)



(a) Exhaust-nozzle area, 2.4 square feet.

Figure 9. - Effect of change in throttle pressure ratio on engine speed for several airplane velocities. The variation of turbine-inlet temperature is also shown.

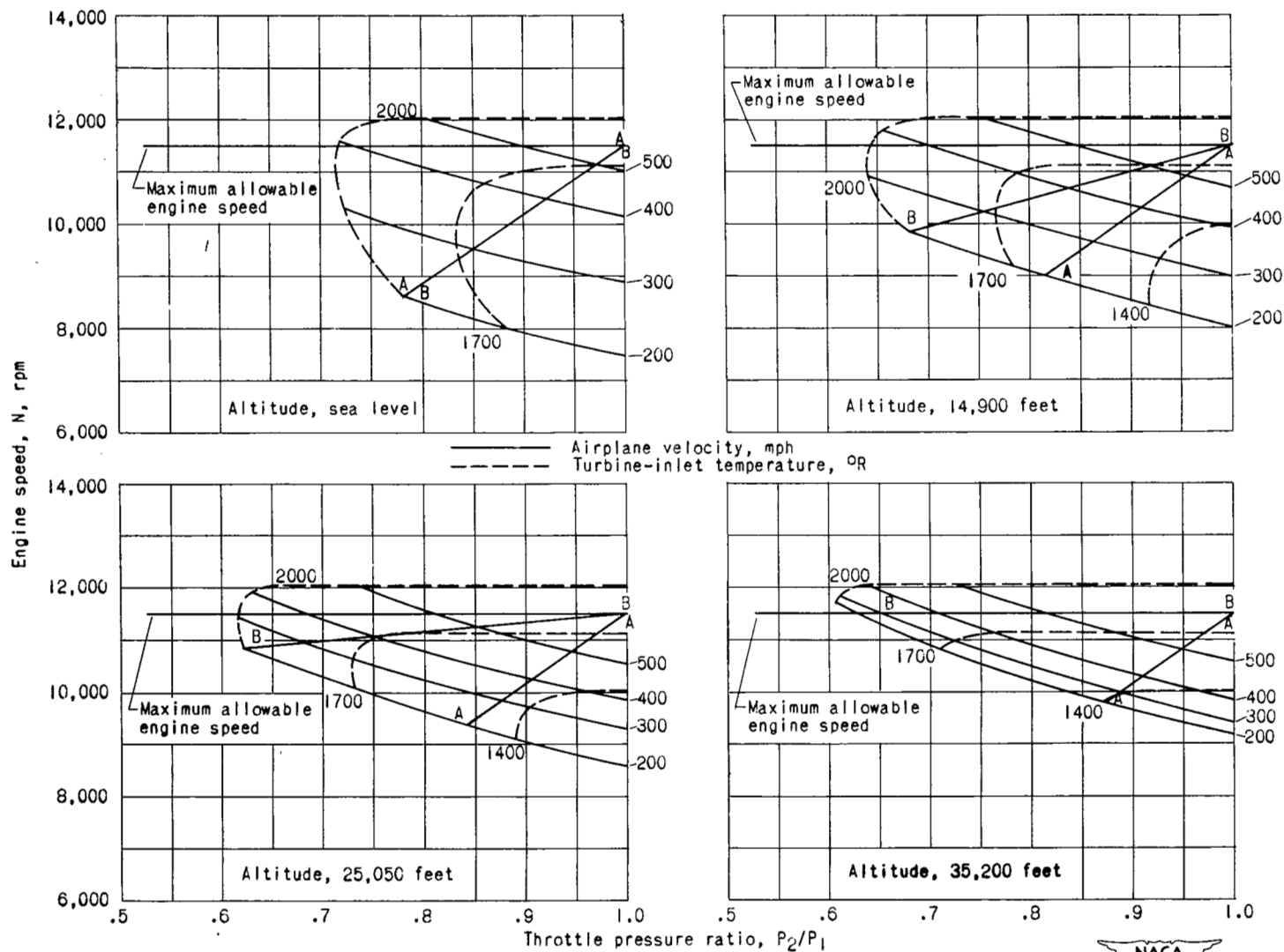




(b) Exhaust-nozzle area, 2.2 square feet.

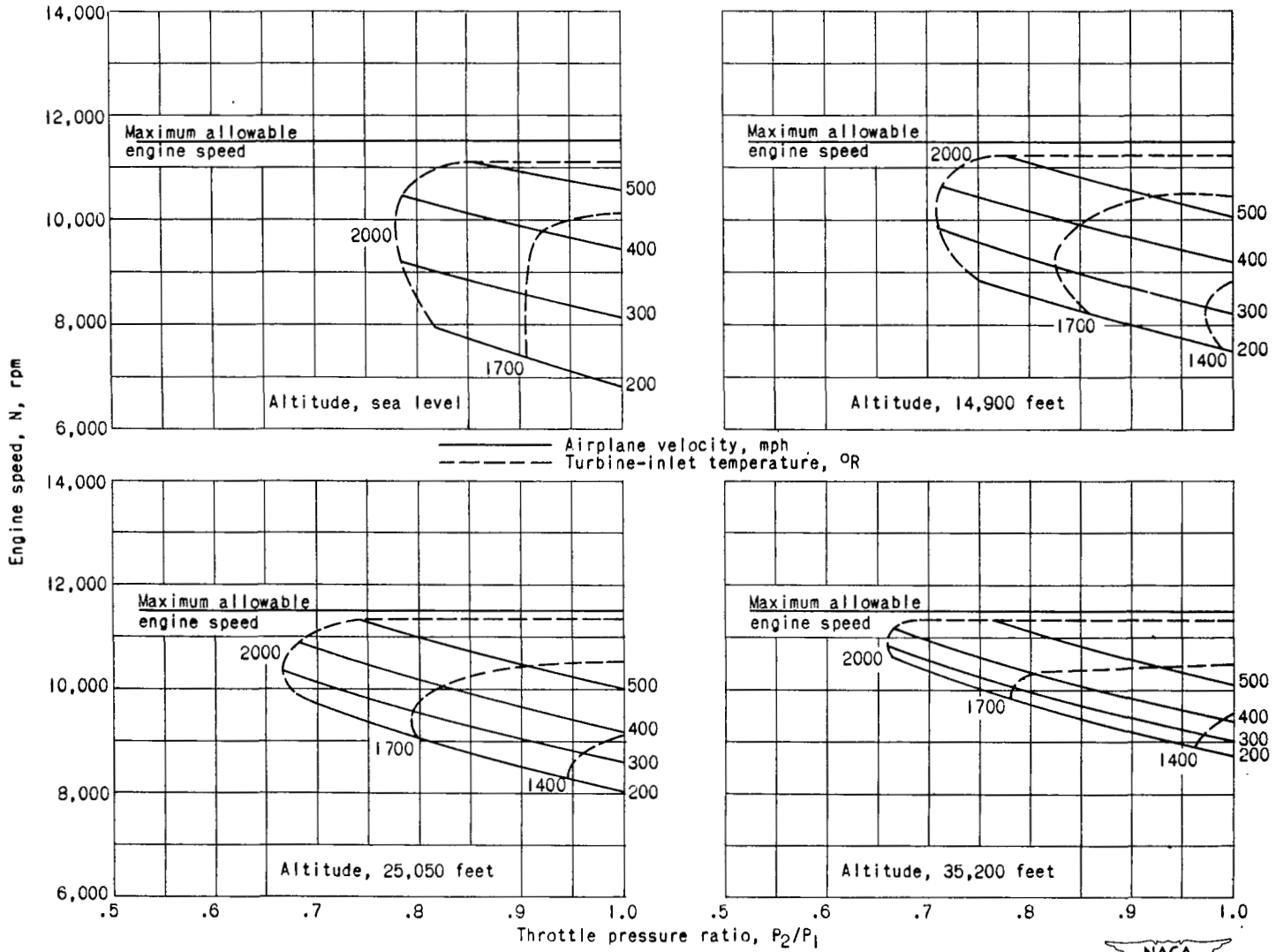
Figure 9. - Continued. Effect of change in throttle pressure ratio on engine speed for several airplane velocities. The variation of turbine-inlet temperature is also shown.





(c) Exhaust-nozzle area, 1.87 square feet; operating lines A-A and B-B.
 Figure 9. - Continued. Effect of change in throttle pressure ratio on engine speed for several airplane velocities. The variation of turbine-inlet temperature is also shown.

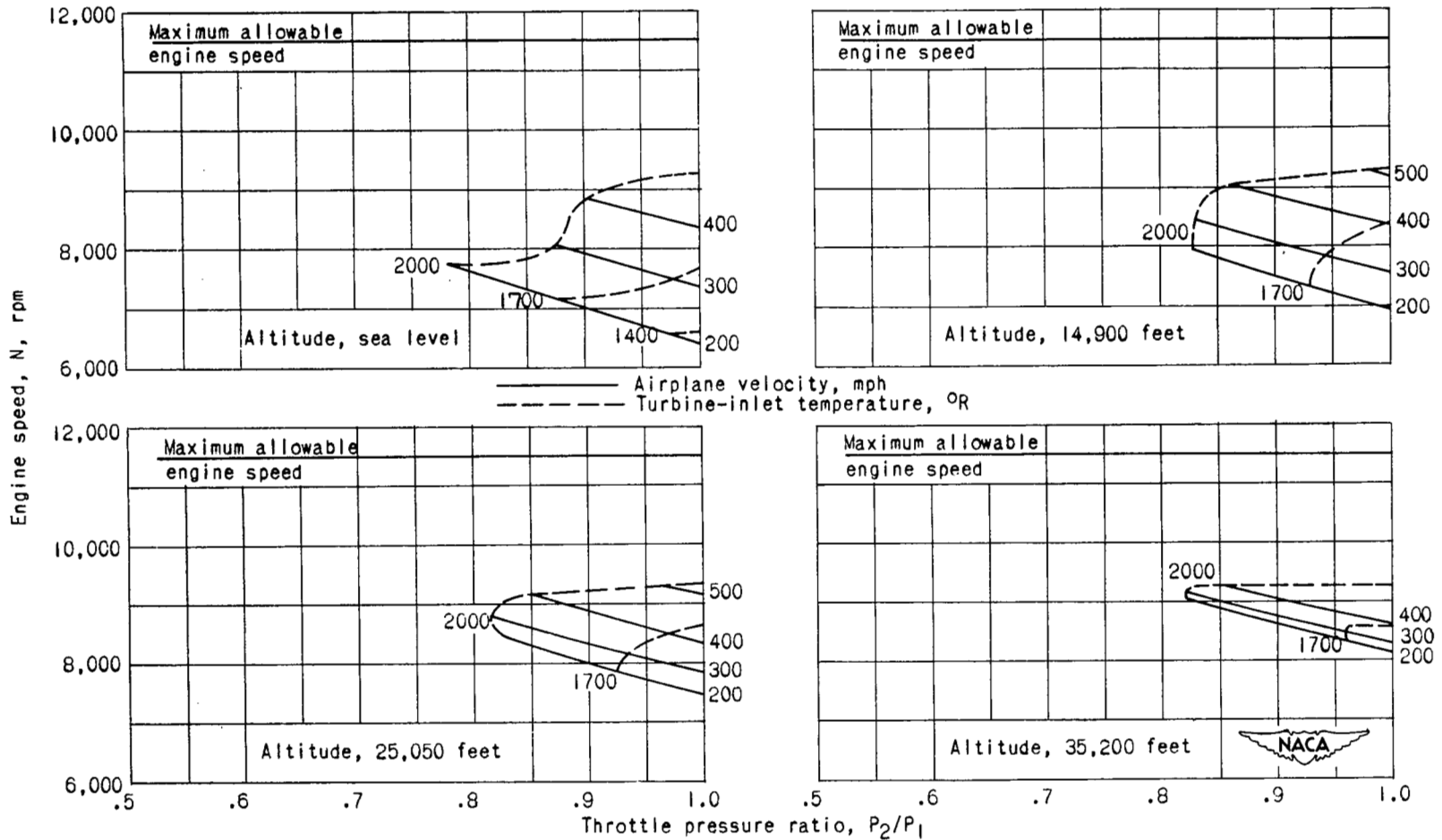




(d) Exhaust-nozzle area, 1.6 square feet.

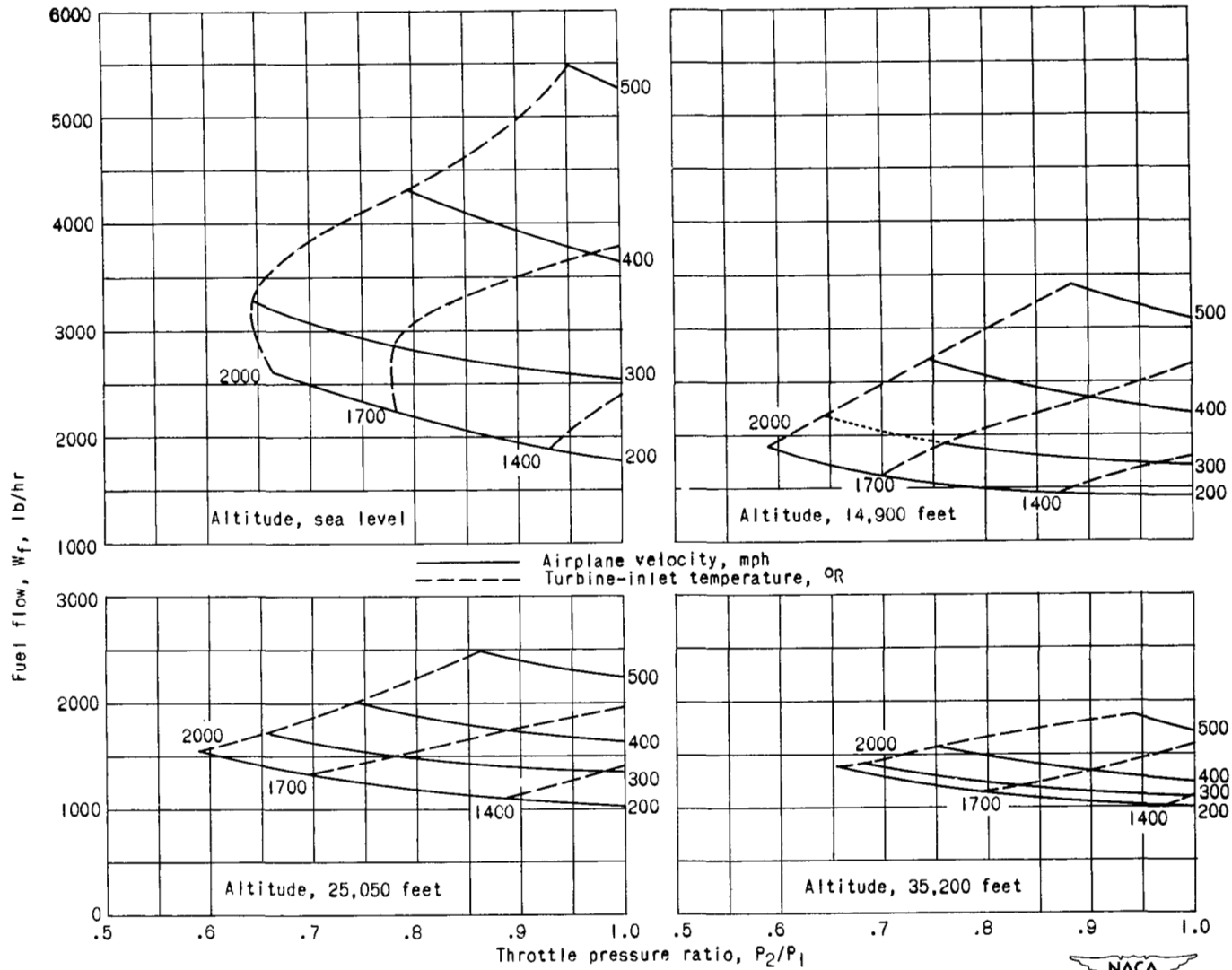
Figure 9. - Continued. Effect of change in throttle pressure ratio on engine speed for several airplane velocities. The variation of turbine-inlet temperature is also shown.





(e) Exhaust-nozzle area, 1.3 square feet.

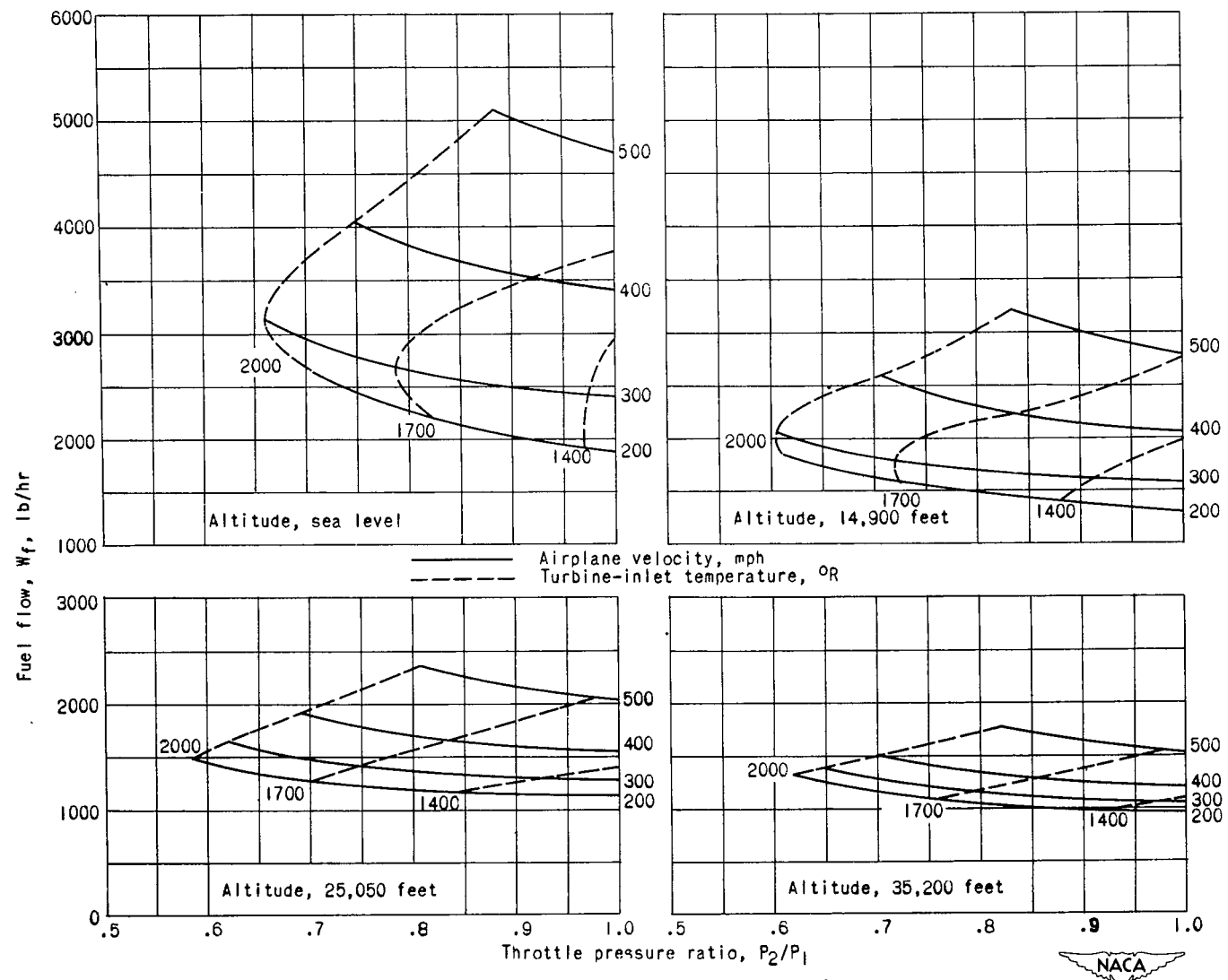
Figure 9. - Concluded. Effect of change in throttle pressure ratio on engine speed for several airplane velocities. The variation of turbine-inlet temperature is also shown.



(a) Exhaust-nozzle area, 2.4 square feet.

Figure 10. - Effect of change in throttle pressure ratio on fuel flow for several airplane velocities. The variation of turbine-inlet temperature is also shown.

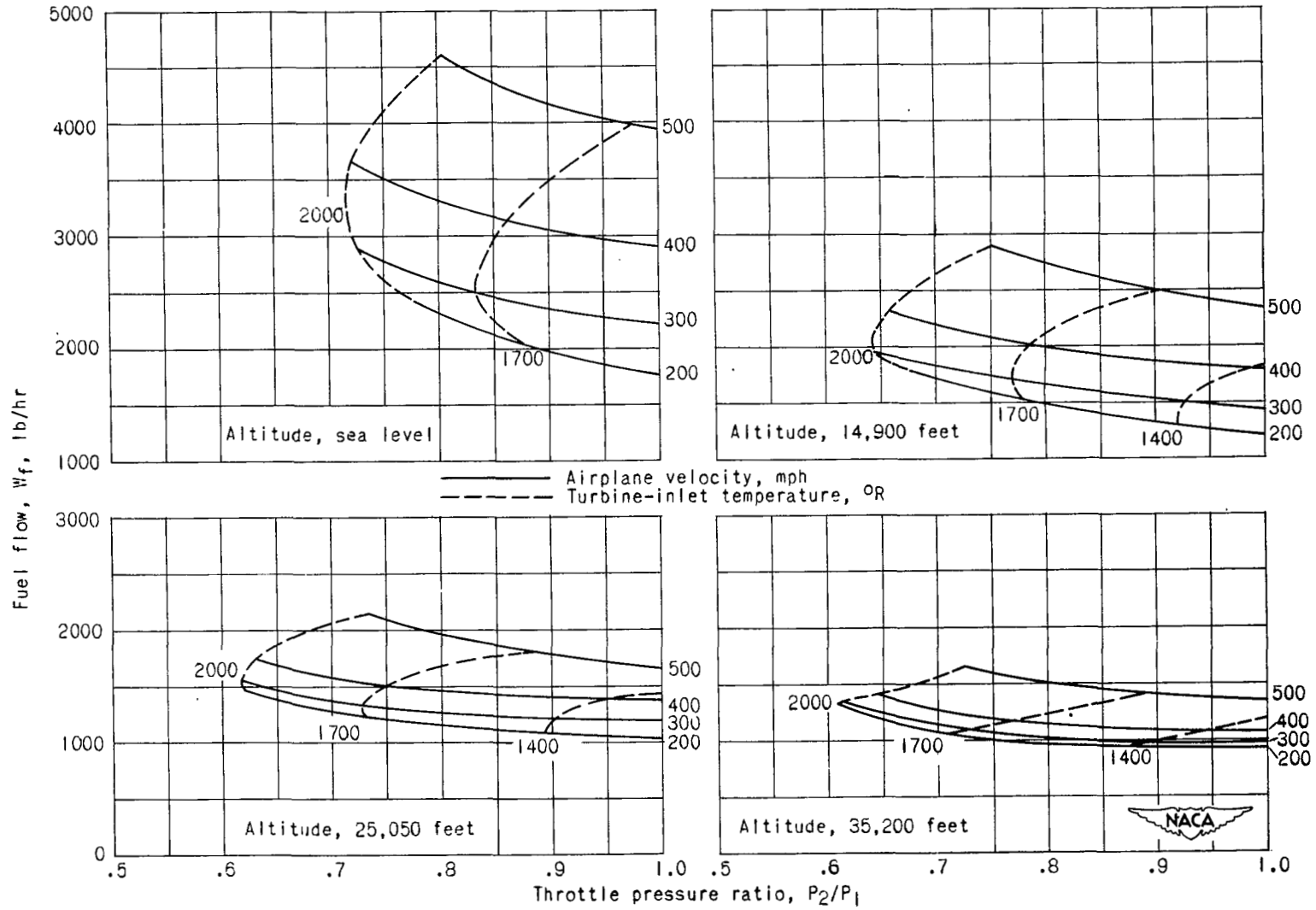




(b) Exhaust-nozzle area, 2.2 square feet.

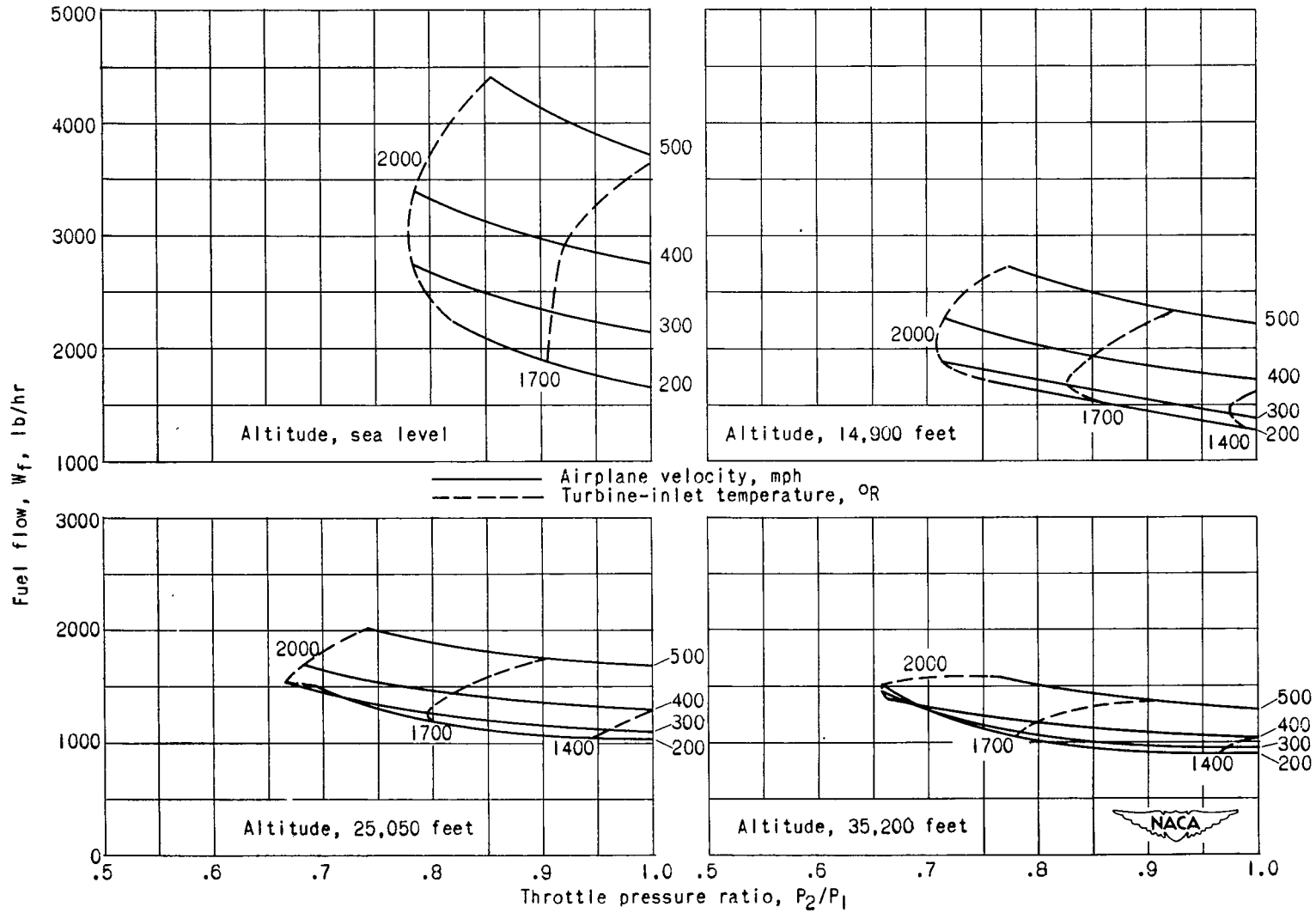
Figure 10. - Continued. Effect of change in throttle pressure ratio on fuel flow for several airplane velocities. The variation of turbine-inlet temperature is also shown.





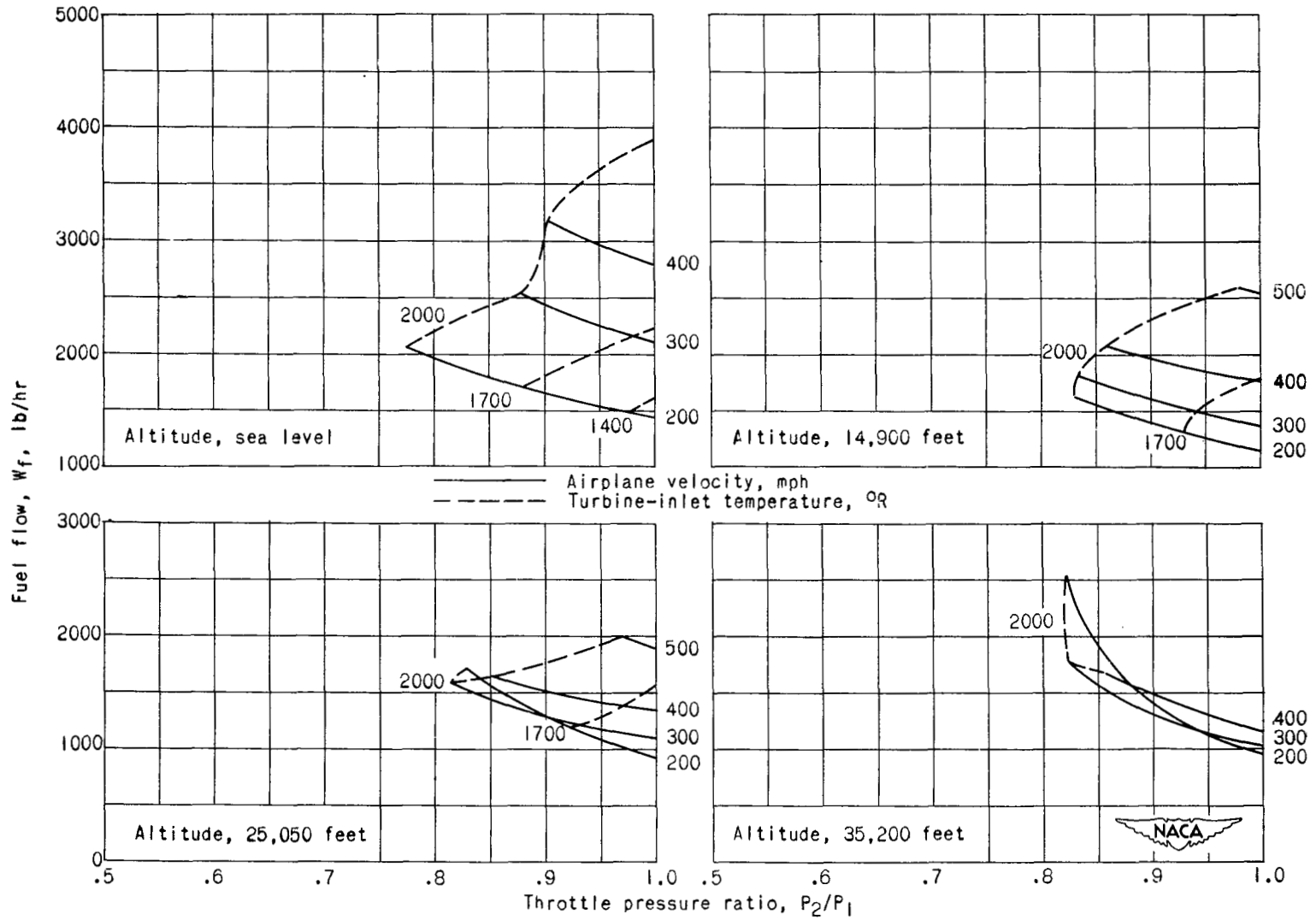
(c) Exhaust-nozzle area, 1.87 square feet.

Figure 10. - Continued. Effect of change in throttle pressure ratio on fuel flow for several airplane velocities. The variation of turbine-inlet temperature is also shown.



(d) Exhaust-nozzle area, 1.6 square feet.

Figure 10. - Continued. Effect of change in throttle pressure ratio on fuel flow for several airplane velocities. The variation of turbine-inlet temperature is also shown.



(e) Exhaust-nozzle area, 1.3 square feet.

Figure 10. - Concluded. Effect of change in throttle pressure ratio on fuel flow for several airplane velocities. The variation of turbine-inlet temperature is also shown.

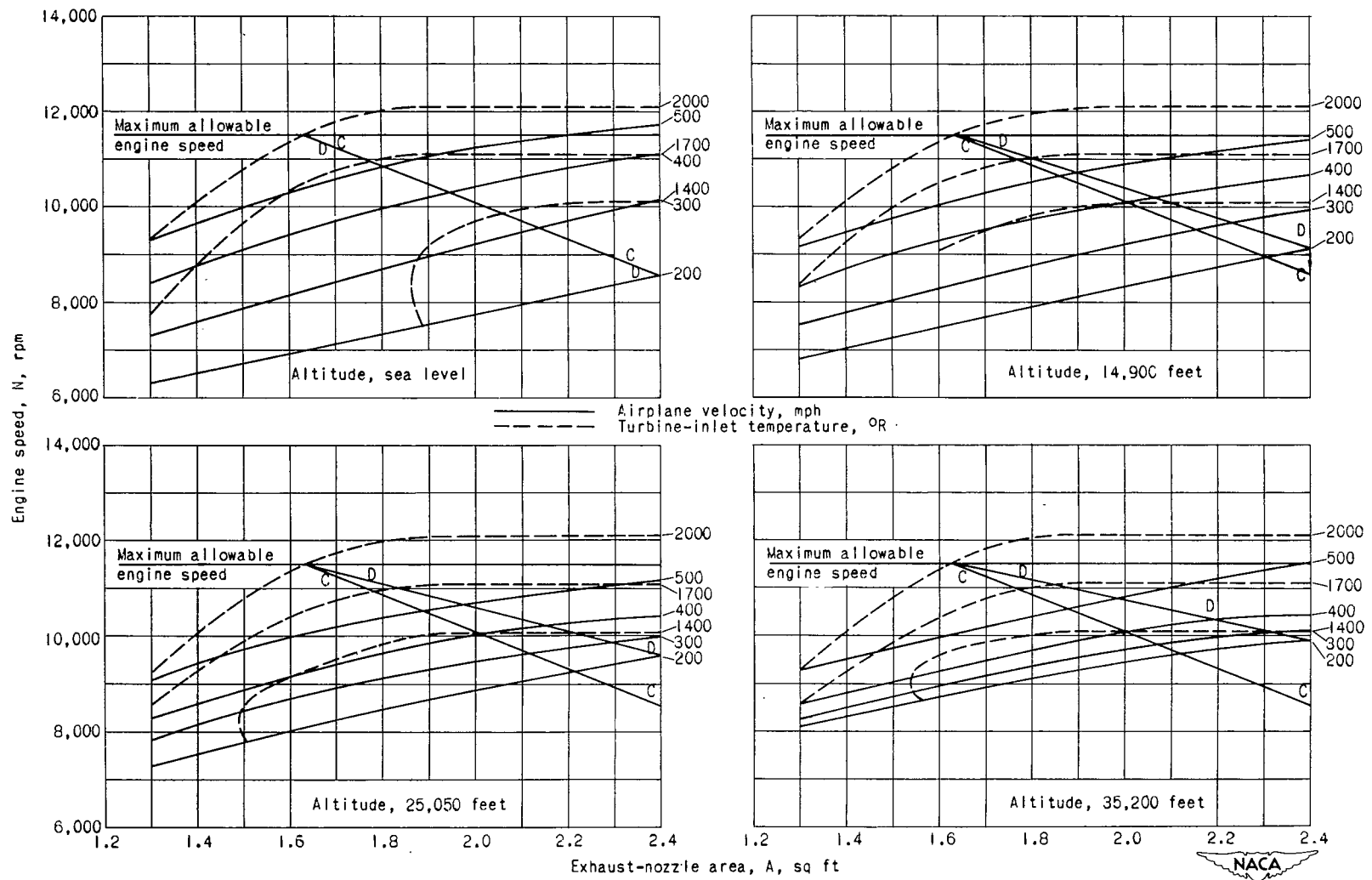


Figure 11. - Effect of change in exhaust-nozzle area on engine operating conditions for several airplane velocities. The variation of turbine-inlet temperature and operating lines C-C and D-D are also shown.



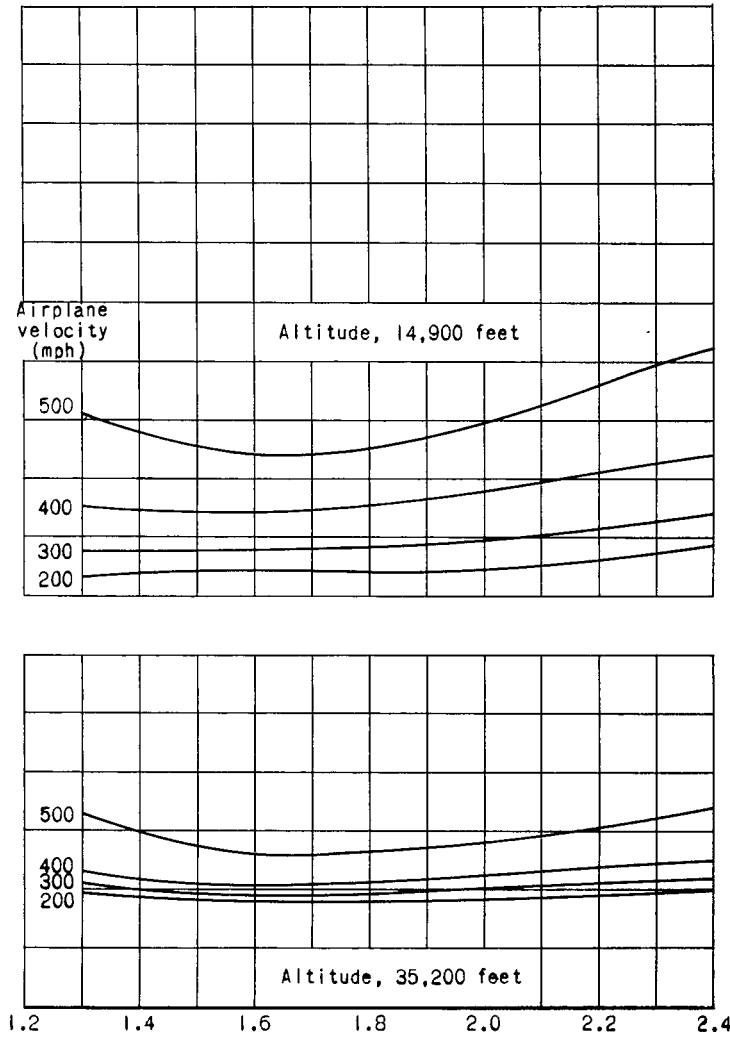
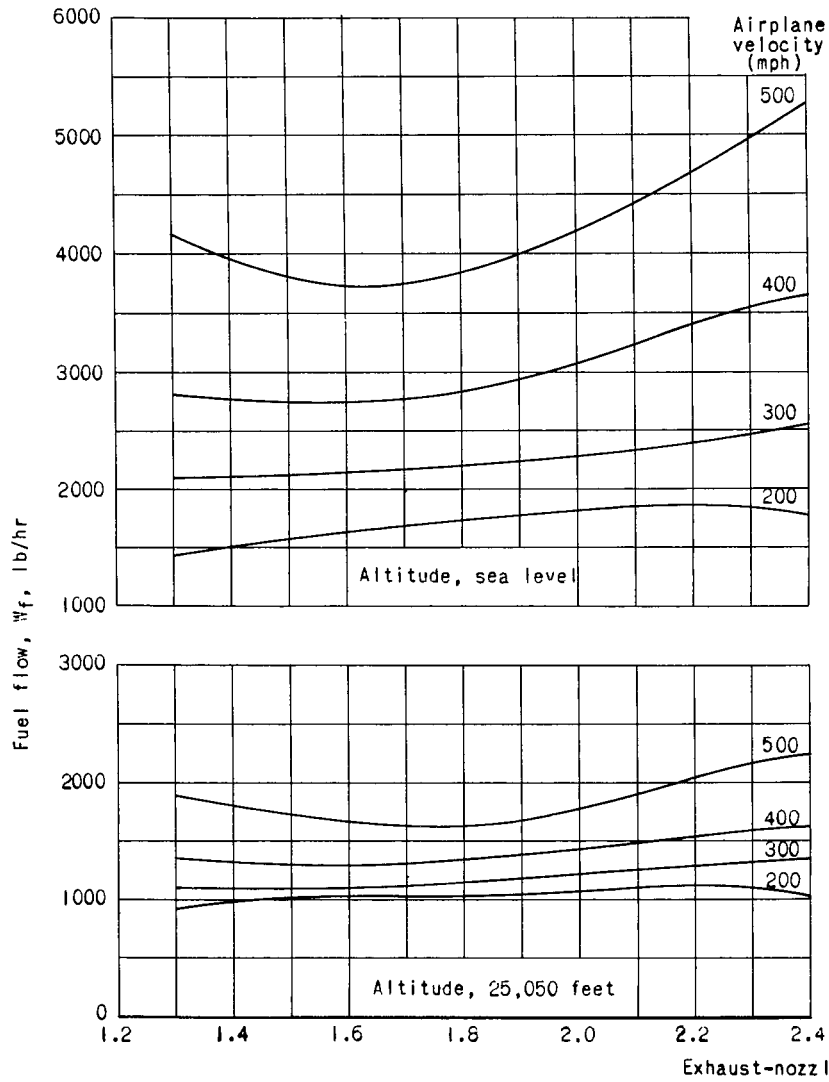
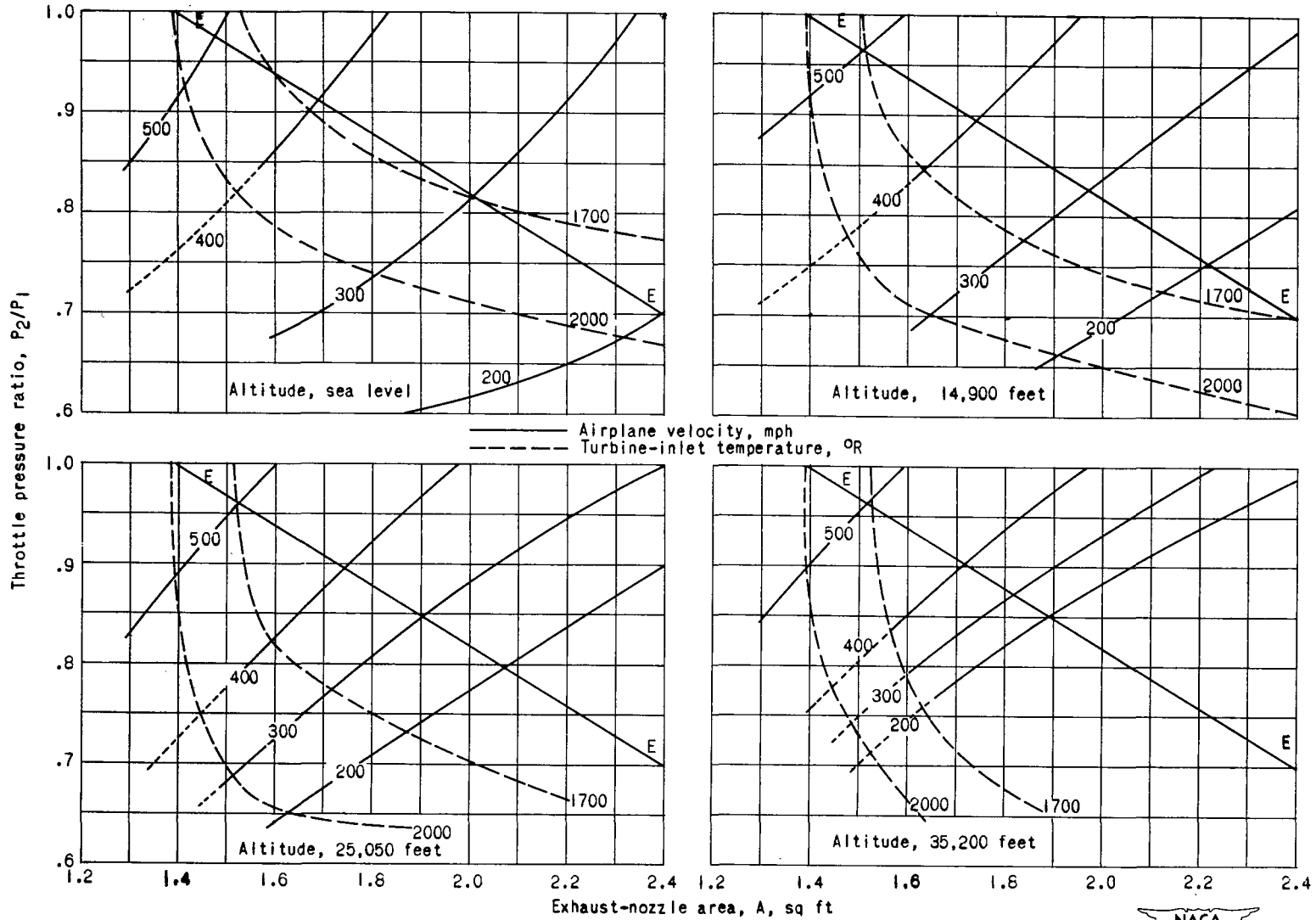


Figure 12. - Effect of change in exhaust-nozzle area on fuel flow required for several airplane velocities.

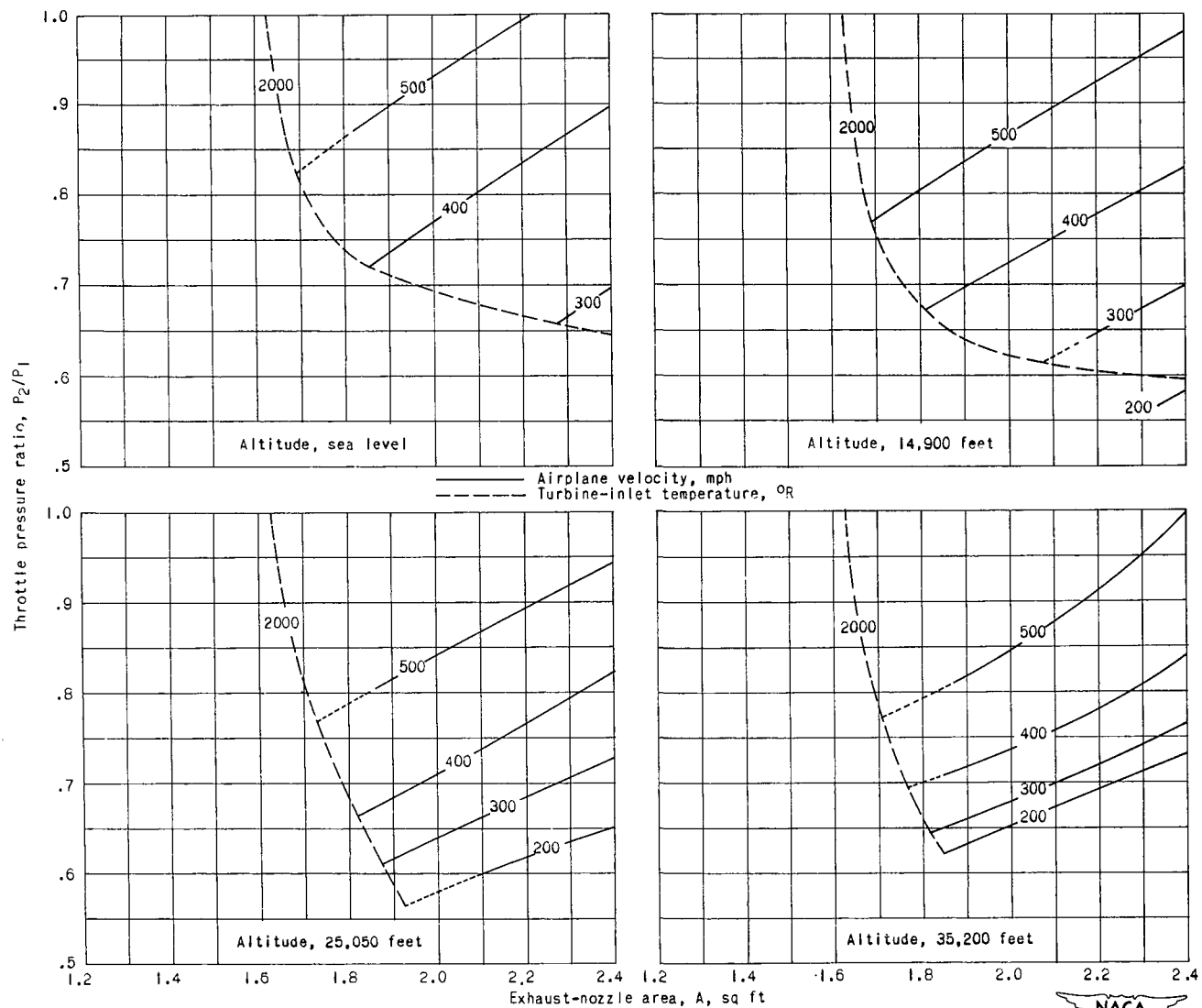




(a) Engine speed, 10,000 rpm; operating line E-E.

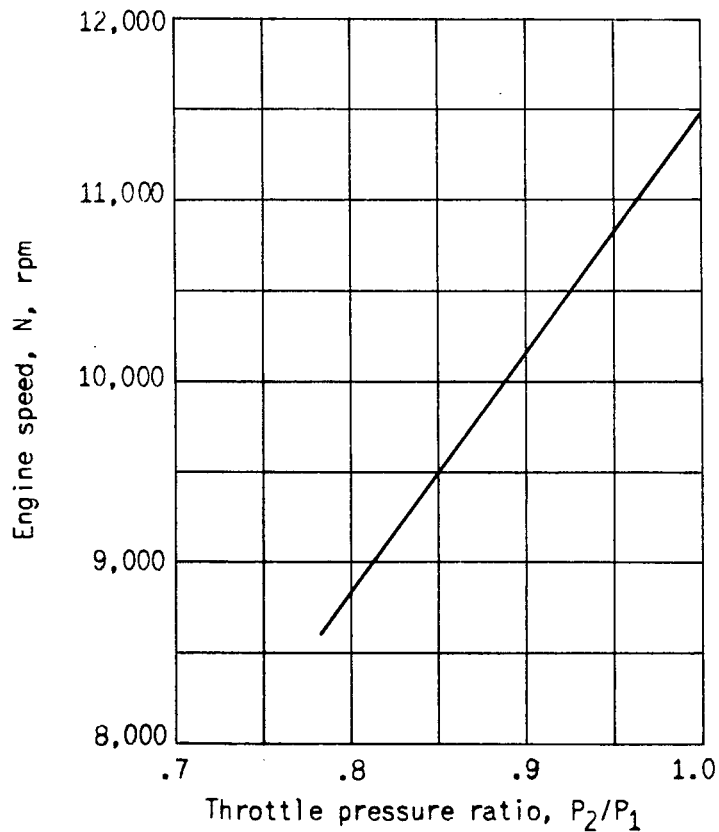


Figure 13. - Variation of throttle pressure ratio with change in exhaust-nozzle area for several airplane velocities. The variation of turbine-inlet temperature is also shown. (Cross plot of figs. 9 and 11.)

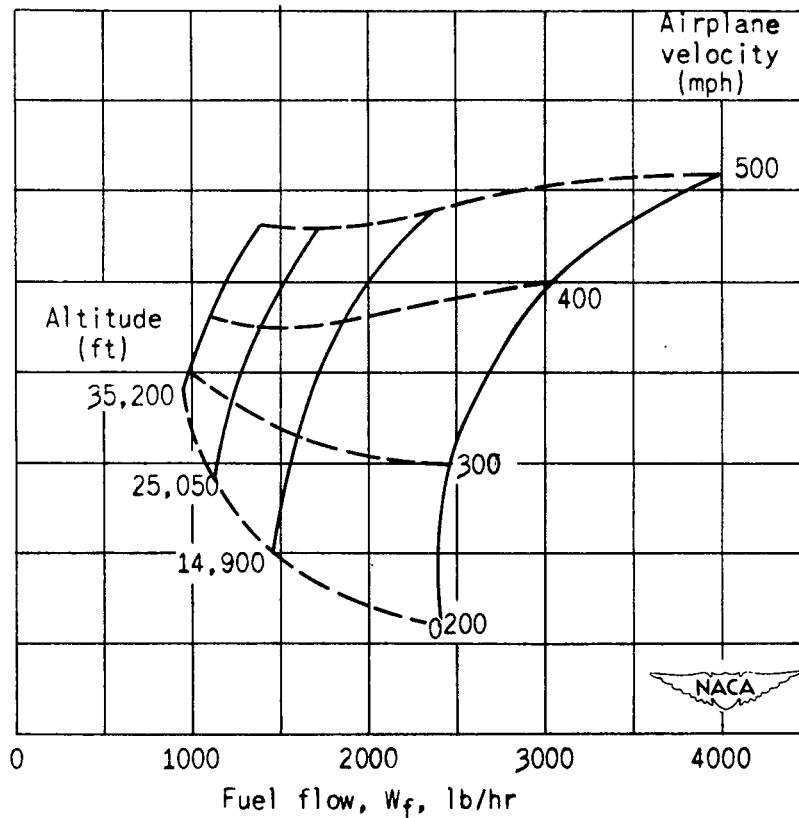


(b) Engine speed, 11,500 rpm.

Figure 13. - Concluded. Variation of throttle pressure ratio with change in exhaust-nozzle area for several airplane velocities. The variation of turbine-inlet temperature is also shown. (Cross plot of figs. 9 and 11.)

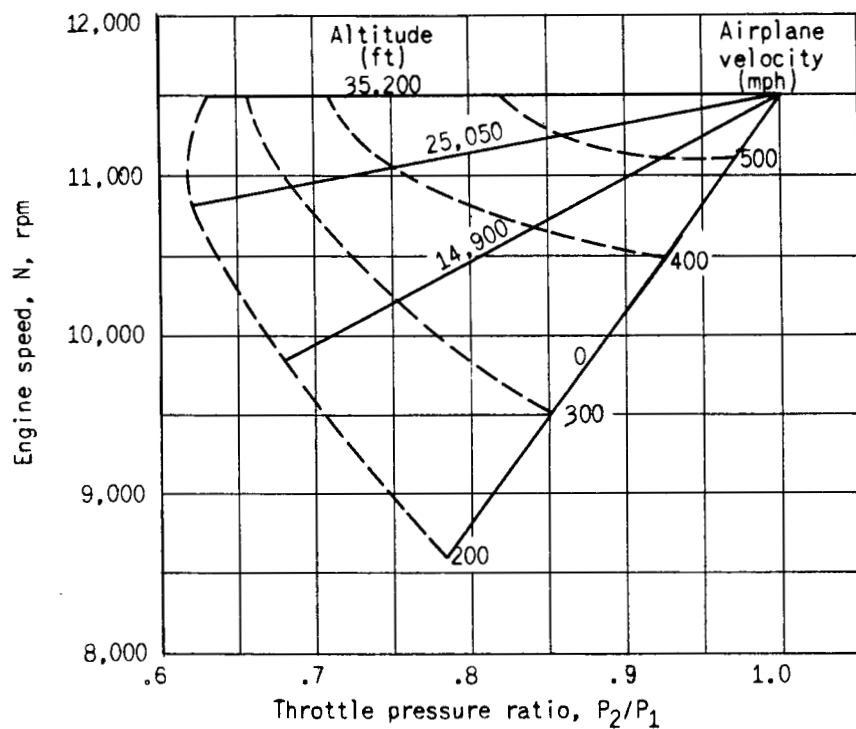


(a) Variation of engine speed with throttle pressure ratio.

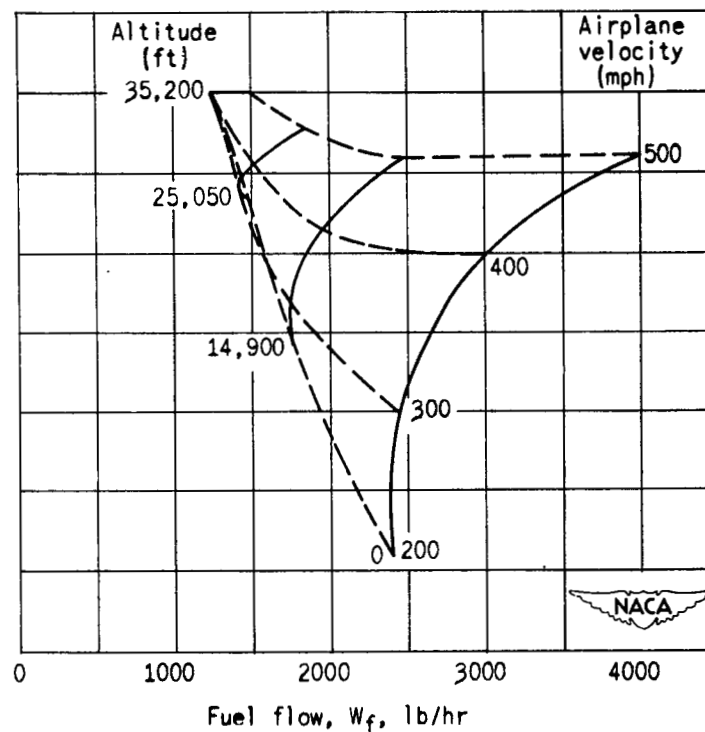


(b) Fuel flow required at various engine speeds.

Figure 14. - Control-parameter relations for throttle-inlet control system using operating line A-A. (Cross plot of figs. 9(c) and 10(c).)

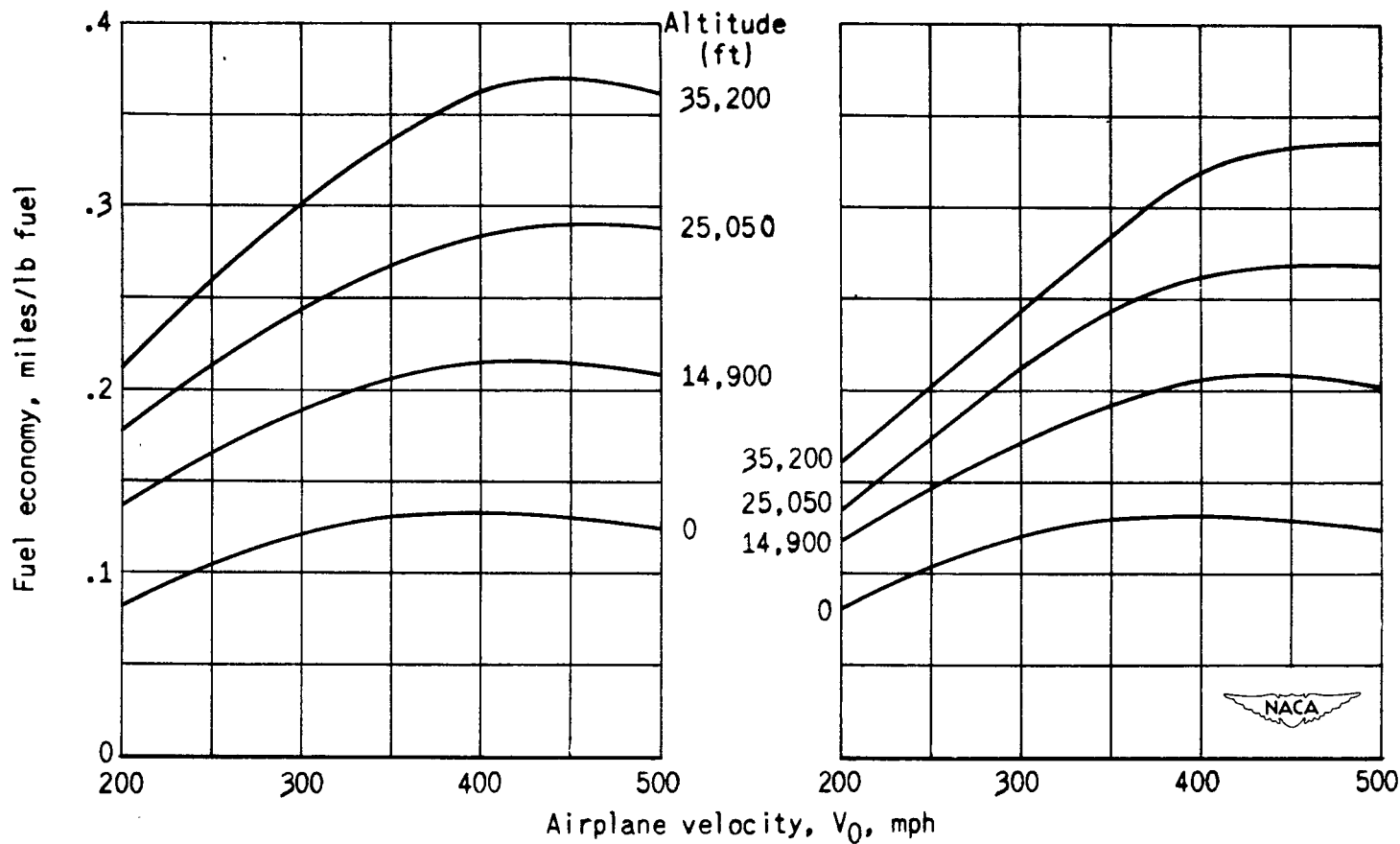


(a) Variation of engine speed with throttle pressure ratio.



(b) Fuel flow required at various engine speeds.

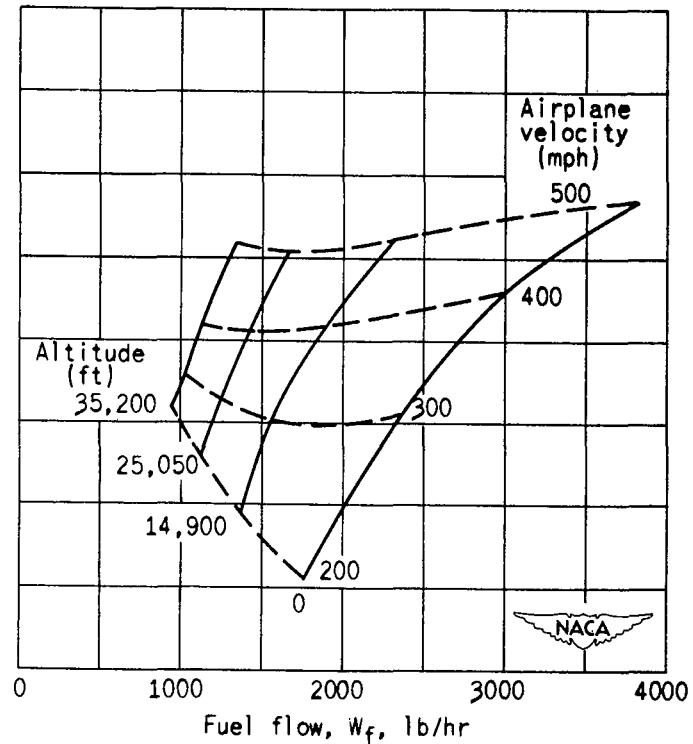
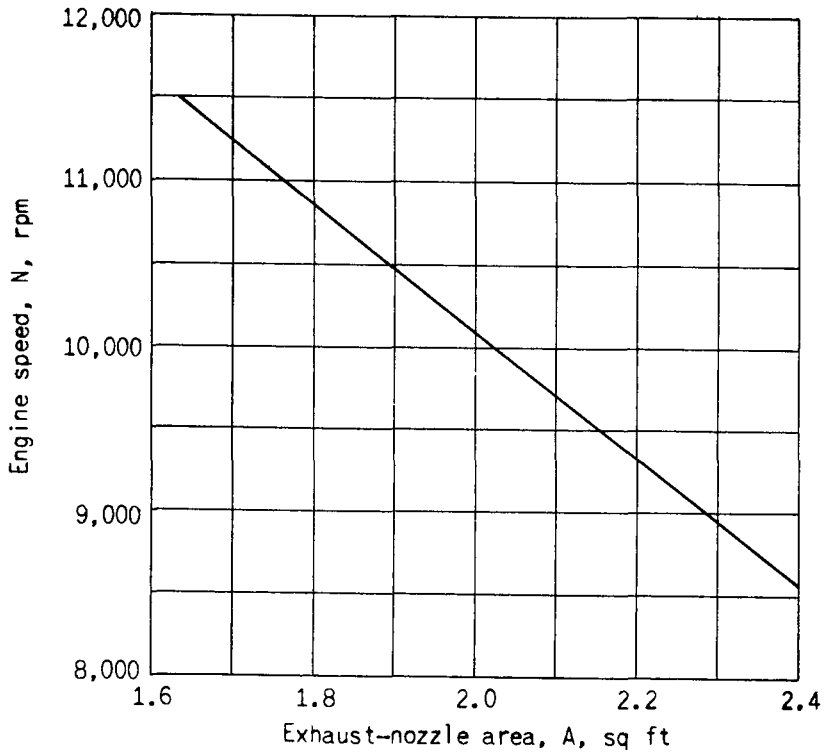
Figure 15. - Control-parameter relations for throttle-inlet control system using operating line B-B. (Cross plot of figs. 9(c) and 10(c).)



(a) Operating line A-A.

(b) Operating line B-B.

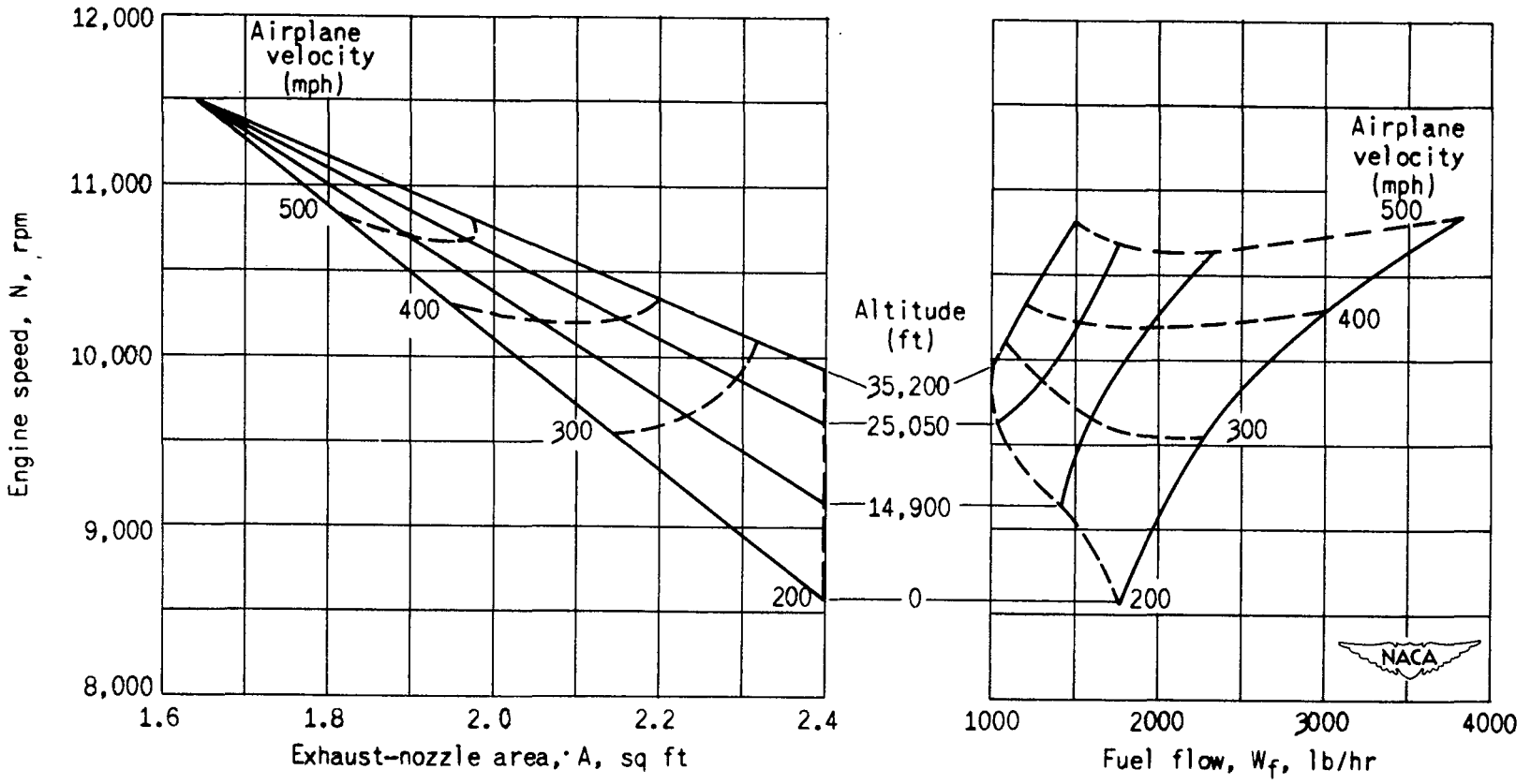
Figure 16. - Variation of fuel economy with airplane velocity for several altitudes for throttle-inlet control systems.



(a) Settings of exhaust-nozzle area and engine speed.

(b) Fuel flow required at various engine speeds.

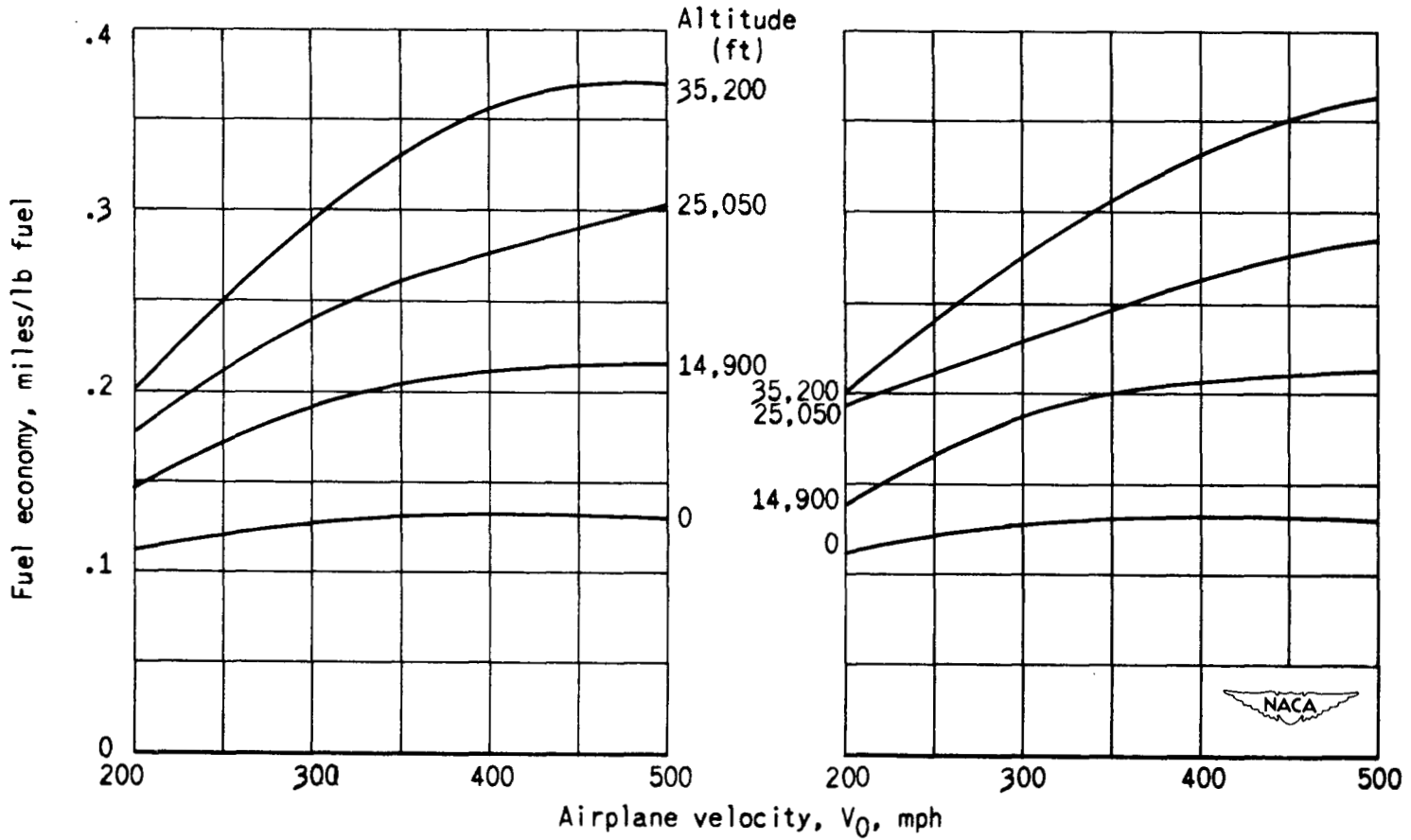
Figure 17. - Control-parameter relations for variable-area exhaust-nozzle control system using operating line C-C. (Cross plot of figs. 11 and 12.)



(a) Settings of exhaust-nozzle area and engine speed.

(b) Fuel flow required at various engine speeds.

Figure 18. - Control-parameter relations for variable-area exhaust-nozzle control system using operating line D-D. (Cross plot of figs. 11 and 12.)



(a) Operating line C-C.

(b) Operating line D-D.

Figure 19. - Variation of fuel economy with airplane velocity for several altitudes for variable-area exhaust-nozzle fuel control system.

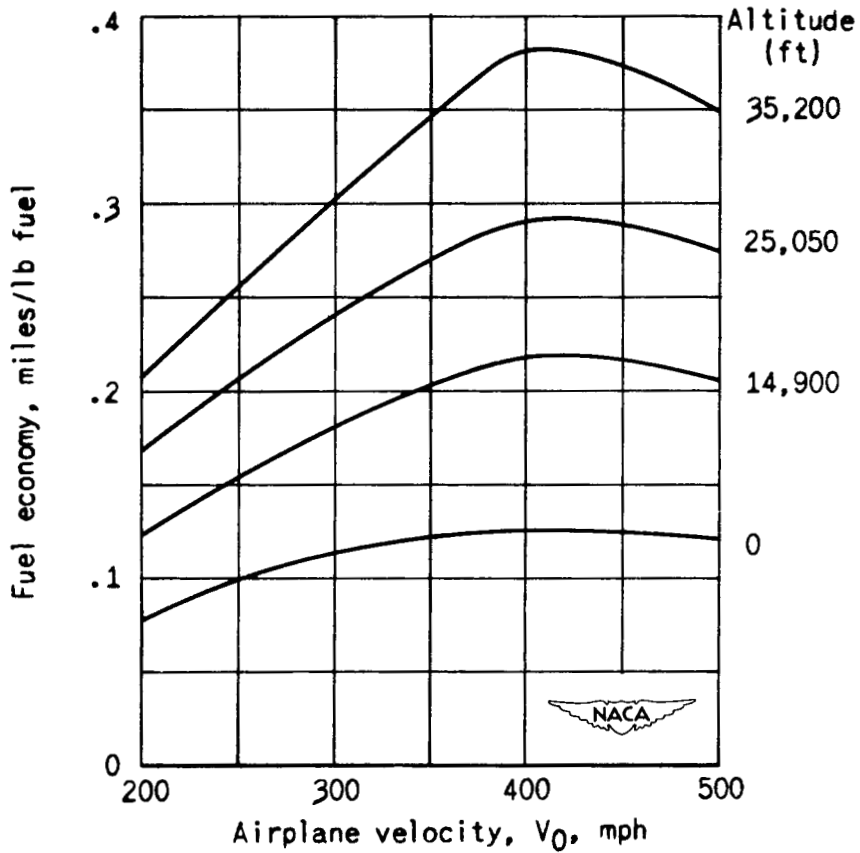


Figure 20. - Variation of fuel economy with airplane velocity for several altitudes for operation at engine speed of 10,000 rpm using operating line E-E.

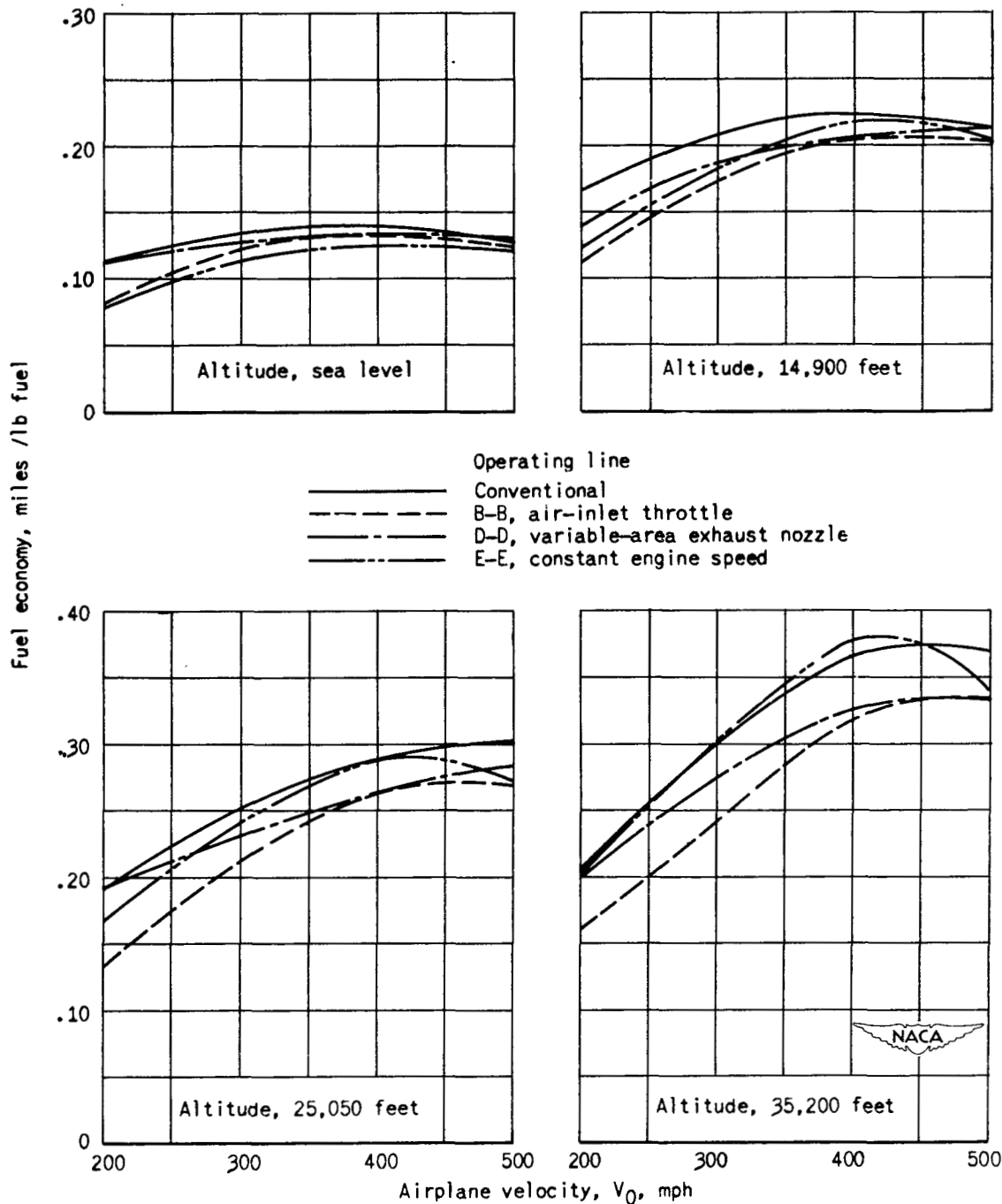


Figure 21. - Comparison of fuel economy obtained by operating with various control systems.

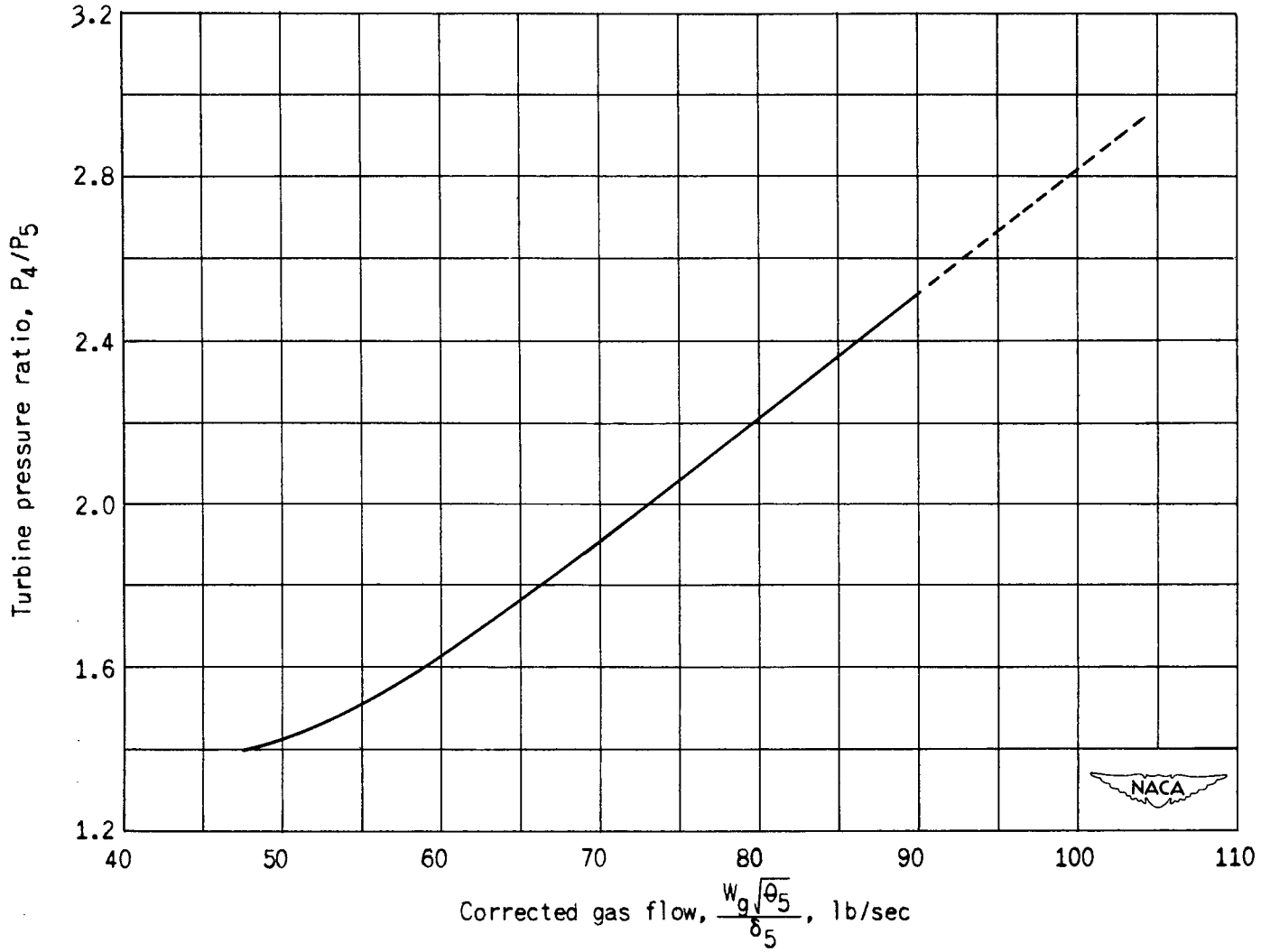


Figure 22. - Variation of turbine pressure ratio with gas flow corrected to total pressure and temperature in the exhaust nozzle relative to NACA standard atmospheric conditions at sea level.

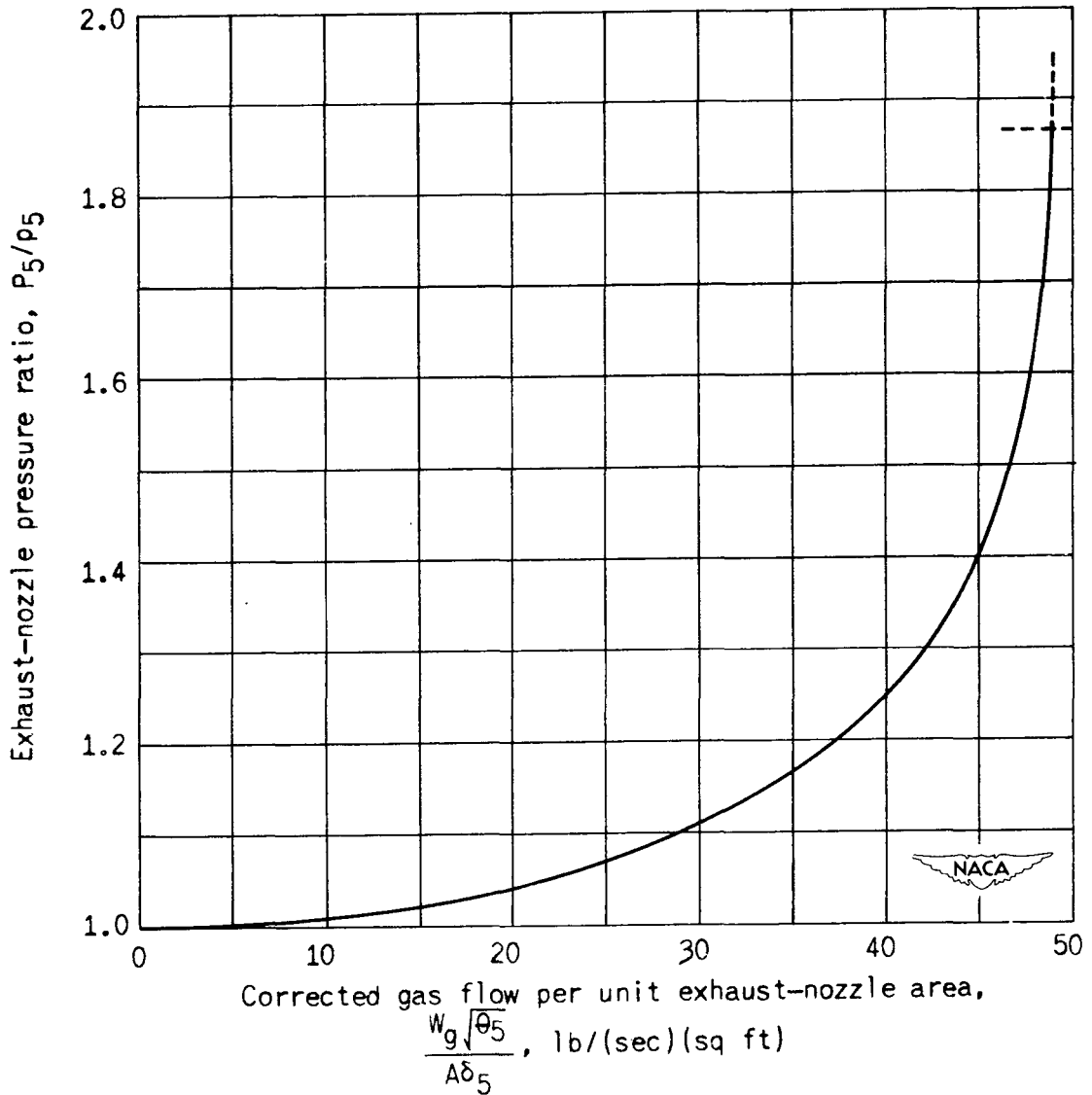


Figure 23. - Variation of exhaust-nozzle pressure ratio with gas flow per unit exhaust-nozzle area corrected to total pressure and temperature in the exhaust nozzle relative to NACA standard atmospheric conditions at sea level.

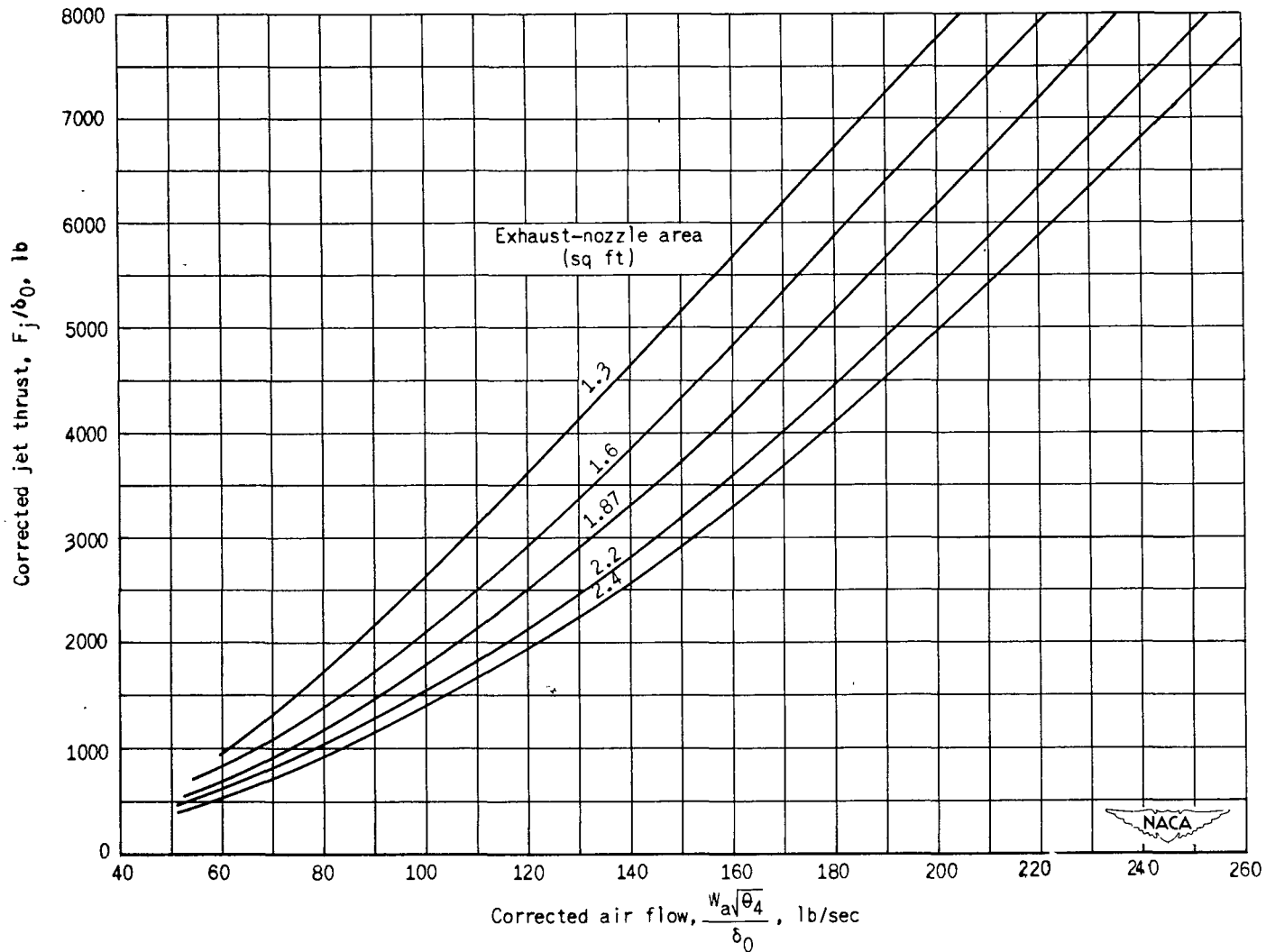


Figure 24. - Variation of corrected jet thrust with air flow corrected to turbine-inlet temperature and ambient air pressure relative to NACA standard atmospheric conditions at sea level for several exhaust-nozzle areas.

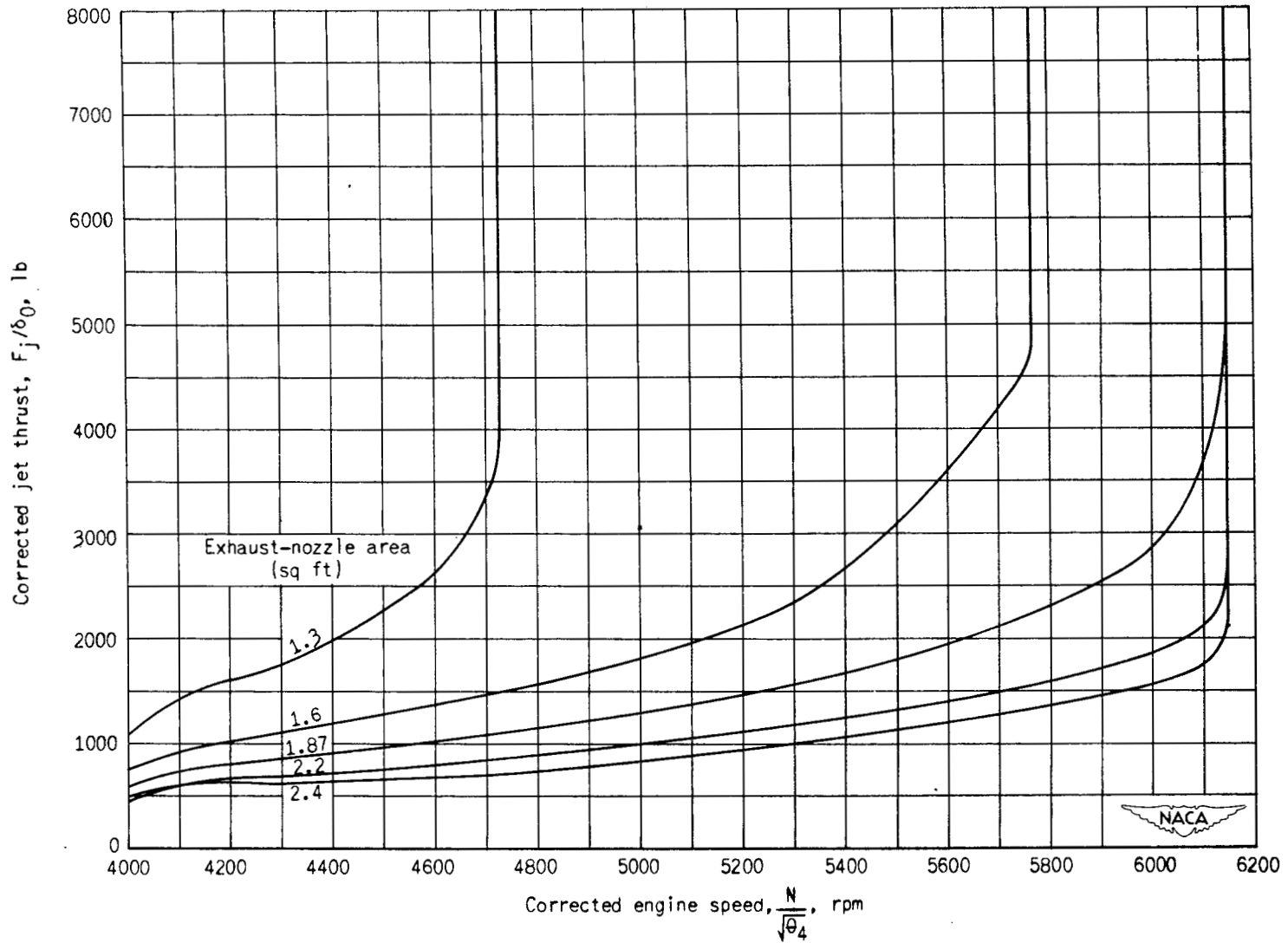


Figure 25. - Variation of corrected jet thrust with engine speed corrected to turbine-inlet temperature relative to NACA standard atmospheric conditions at sea level for several exhaust-nozzle areas.

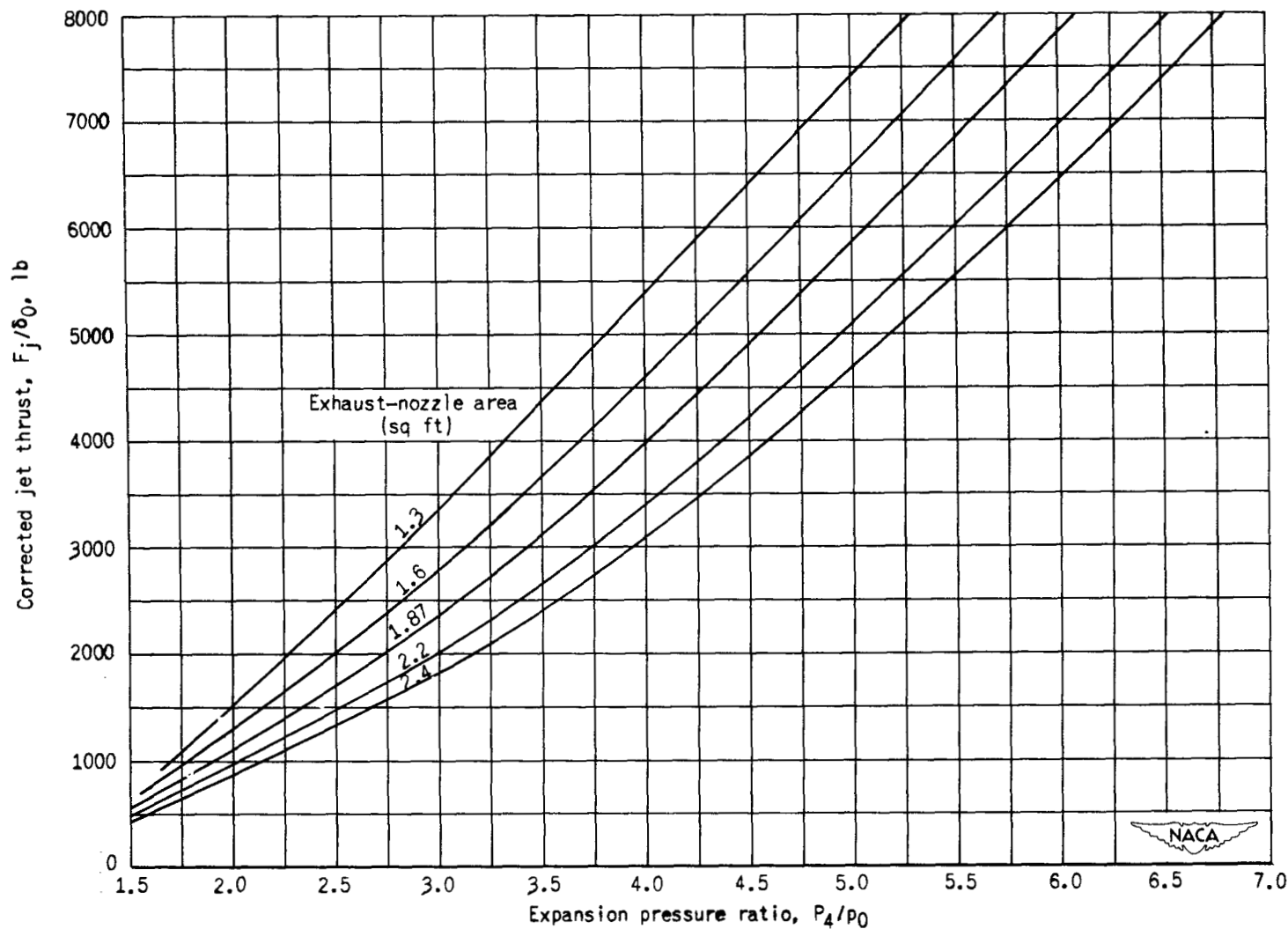


Figure 26. - Variation of corrected jet thrust with the ratio of turbine-inlet total pressure to ambient air pressure for several exhaust-nozzle areas.

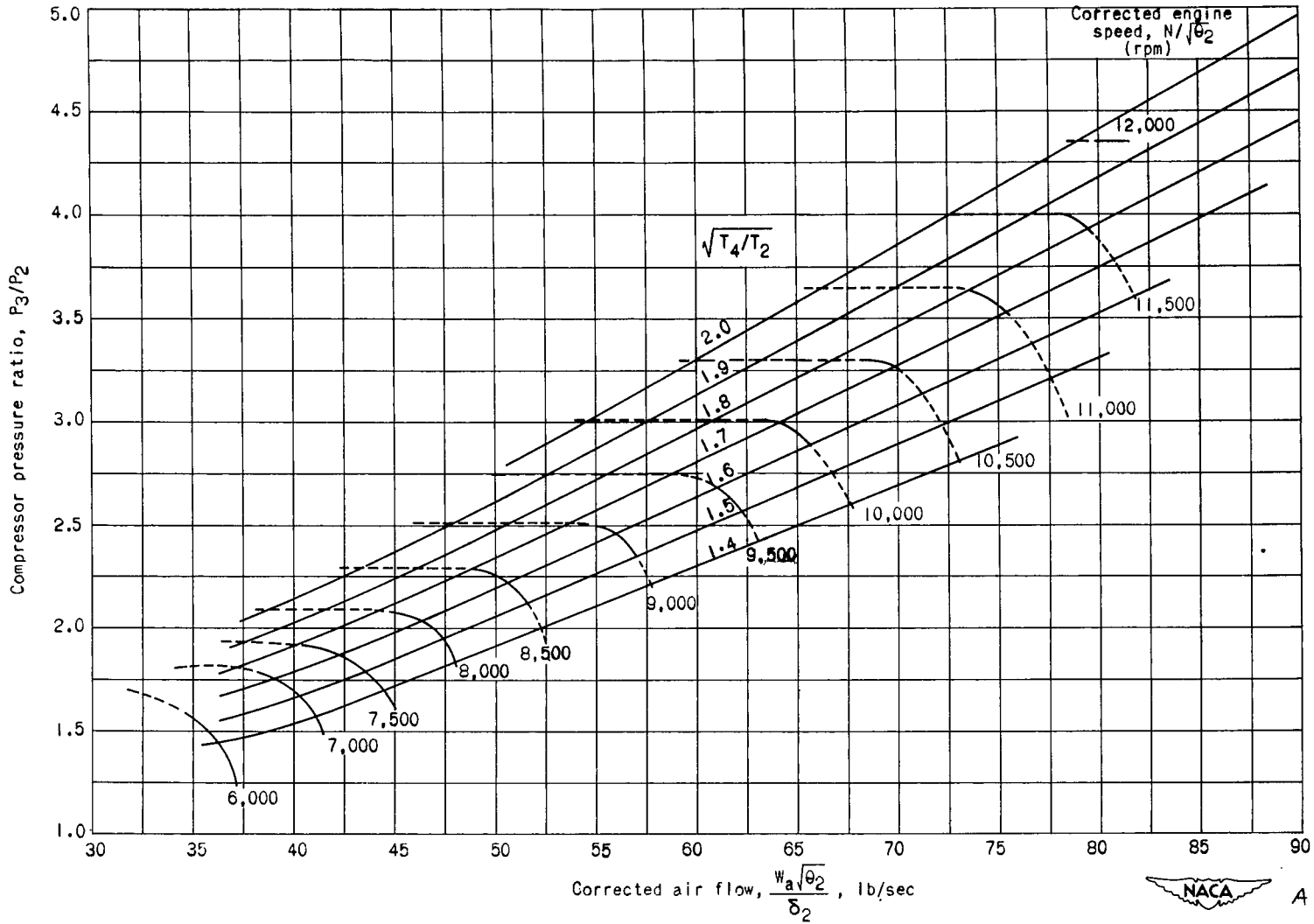


Figure 27. - Compressor characteristics corrected to compressor-inlet temperature and pressure relative to NACA standard atmospheric conditions at sea level. Curves of constant ratio of turbine-inlet temperature to compressor-inlet temperature for the engine are superimposed on the compressor-characteristic curves. (Data obtained from NACA wind-tunnel investigation, cross-plotted and extrapolated.)

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