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RESEARCH MEMORANDUM

GRAPHIC ANALYSIS OF AMERICAN AND BRITISH AXIAL-FLOW TURBOJET ENGINE PERFORMANCE TRENDS

FOR REFERENCE (CURRENT AND FUTURE)

By Richard S. Cesaro and James Lazar

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RESEARCH MEMORANDUM

GRAPHIC ANALYSIS OF AMERICAN AND BRITISH AXIAL-FLOW TURBOJET ENGINE PERFORMANCE TRENDS (CURRENT AND FUTURE)

By Richard S. Cesaro and James Lazar

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SUMMARY

This report presents a compilation of static sea-level data on existing or designed American and British axial-flow turbojet engines in terms of basic engine parameters such as thrust and air flow. In the data presented, changes in the over-all engine performance with time are examined as well as the relation of the various engine parameters to each other. The following conclusions are made:

(1) Thrust: Static sea-level thrust is being increased at the rate of 4000 pounds per year. The afterburner has increased static sea-level thrust between 45 to 55 percent. A considerable number of engines exist in the same thrust class at any one time.

(2) Air flow: The air-flow handling ability of the conventional axial-flow compressor, while steadily improving, is approaching a point of diminishing returns. To progress to higher air-flow handling rates, application of the transonic principle to compressor design is indicated.

(3) Pressure ratio: A general trend of increasing pressure ratio with time is indicated.

(4) Specific fuel consumption: A general trend of decreasing specific fuel consumption at sea-level static conditions is indicated, largely as a result of the trend toward increasing compressor pressure ratio.

(5) Weight and diameter: A general trend of decreased engine weight with time is indicated. Engine diameters remain essentially constant (between 40 to 45 in.) in the time period of 1950-1955. Beyond 1955, engine diameter is expected to increase (because the air-flow handling ability of the compressor is approaching a limit) to a value of approximately 60 inches by 1961 in order to keep up with the thrust-increase trend.

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INTRODUCTION

The development of the gas-turbine engine since its introduction by Commodore Whittle a little more than 10 years ago has progressed at a tremendous rate in comparison with other aircraft power plants. In this relatively short period of growth, an ever increasing amount of engine performance data has been accumulated. These data have not previously been compiled in convenient form for analysis and study from the standpoint of viewing possible performance trends and over-all engine development.

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This report presents a compilation of data on existing or designed American and British axial-flow turbojet engines in terms of basic engine parameters such as thrust per unit of engine frontal area, air flow per unit of engine frontal area, and specific fuel consumption. The data, as presented, provide information that will assist in engine analyses, reveal certain operational requirements for research test facilities, and reveal areas in the engine development program requiring further emphasis. In the data presented, changes in the over-all engine performance with time are examined, as well as the relation of the various engine parameters to each other.

In the figures presented, current and future engines are included. For current engines, the most recent operational data available are used. For future engines, the data are based on the performance specifications of the manufacturer. Since these specifications are changed during the production and design of the engines, discrepancies may exist between the data presented herein and other tabulations of this information. These differences will not be sufficient to affect the general trends presented. A "paper" engine, which represents axial-flow turbojet performance discussed by the Military Services for 1961, is included. The time period covered in this report is from 1948 to 1961. Of this period, data on British engines are not available after 1952.

The data presented herein have been compiled with the cooperation and assistance of the Research and Development Board, the United States Air Force, and the Bureau of Aeronautics, Department of the Navy. Data presented are current as of May 1, 1951.

PRESENTATION OF DATA

In order to illustrate performance trends, figures are presented indicating variations with time and with one another of thrust, air flow, fuel consumption, thrust per unit of engine frontal area, air flow per unit of engine frontal area, and other performance data for sea-level static conditions. By plotting these parameters against time (based on completion of 150-hr qualification test) and against one another,

trends are indicated. In each case, the time used in plotting is the date the engine has passed the 150-hour test or the date the manufacturer estimates the engine will pass the 150-hour test.

The engine performance for a 1961 "paper" engine, included in all principal figures, has been estimated by the Panel on Aircraft Propulsive Systems, Committee on Aerodynamics, Research and Development Board. The data cover engines in the following stages:

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1. Design study engines; data points indicated by a circle (○)

2. Development engines; data points indicated by a square (□)

3. Production engines; data points indicated by a diamond (◇)

For design study engines, data are based on manufacturers' estimated engine performance. For development and production engines, data are based on results achieved in engine test-stand operation. Engines with afterburners are indicated by "pips" on the symbols (○, □, and ◇). The information on a few of the design study engines is incomplete as far as detailed performance data are concerned, since the design has not progressed to a point where the omitted information is available; accordingly, not all of the engines are plotted in all figures presented. Theoretical performance curves determined from engine cycle analysis are plotted on some of the principal plots. Component efficiencies η_b, η_c, and η_t used in the cycle analysis, together with other parameters and symbols used throughout this report, are defined and evaluated in the appendix. American engines are identified by open points. British engines are identified by solid points.

It has been found, for the bulk of engines considered in this report, that the performance data given for an engine in the design stage do not appreciably change in going through the development and production stages. There is a time spacing of approximately $3\frac{1}{2}$ years between the design and the beginning of production of any given engine. During this time period, basic components of the engine can and do change in order that its final performance may be in general agreement with the original design estimate. Moreover, slight changes in engine performance and time of engine completion will not appreciably change the trends of the curves. This fact is brought out in the several figures presented in the report where the trend of the curve is maintained when engine data from the three stages are plotted. This result also permits the plotting of basic engine parameters with time and against one another, providing an insight of engine performance in the future.

The performance data contained herein do not include several important design details and operating limits associated with the individual engines. For example, design of engines for supersonic flight at sea level requires strengthening of engine structure over that

required for subsonic flight. On a weight basis, then, the supersonic engine shows up at a disadvantage when compared to the subsonic engine. Further, results presented are for sea-level static conditions and, as such, may not truly reflect the over-all utility or value of specific engines. Accordingly, although engine data trends can be compared, the reader is cautioned against making specific engine comparisons indicating one engine to be superior to another, particularly when the differences in engine performance are marginal.

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RESULTS AND DISCUSSION

The variation of static sea-level thrust as a function of time is shown in figure 1. An approximate linear relationship is indicated, with sea-level static thrust being increased at the rate of approximately 4000 pounds per year. It is indicated that at any one time period up to approximately 1953, a considerable number of engines exist in the same approximate thrust class.

For present-day engines, the use of an afterburner increases static sea-level thrust approximately 45 to 50 percent as shown in figure 2. More than half of the American engines included in this report are equipped with afterburners. No information is available on afterburners for British engines. In addition to increasing static sea-level thrust, the afterburner at supersonic speeds affords 200 to 300 percent thrust increase over the nonaugmented-thrust engine. For the time period of afterburner operation, this, in effect, reduces engine weight by approximately 60 percent over what would be required to achieve the same thrust without the use of the afterburner. There is a similar reduction in engine frontal area for the same comparison. The afterburner's disadvantages, when not in use, are, largely, increase in basic engine weight, increase in engine frontal area, 2 to 3 percent loss in static sea-level thrust, and 2 to 3 percent increase in specific fuel consumption. The thrust loss and increase in fuel consumption are attributed, largely, to flow losses through the afterburner. When in operation, the only significant disadvantage of the afterburner is the large increase in fuel consumption.

The thrust increases indicated in figure 1 are principally a result of a linear increase in air flow with time, as shown in figure 3. The air flow is increased each year approximately 75 pounds per second as indicated in figure 3.

With the combined information presented in figures 1, 2, and 3, research test-facility requirements for axial-flow turbojet engines, in terms of static sea-level thrust and air flow at any time within the time period covered (1948-1961), can be approximated.

It is of interest now to examine the factors related to the air-flow increases indicated for the turbojet engines presented. An increase in static sea-level engine air flow is due to an increase in air flow per unit of engine frontal area (increase in air flow per unit of compressor frontal area), or an increase in engine frontal area (diameter), or a combination of both. The theoretical relationship between air-handling capacity of the compressor, effective compressor-inlet Mach number, and compressor hub-tip ratio is shown in figure 4. The area in this case is the flow area at the compressor inlet. The bulk of the engines considered have compressor hub-tip ratios in the range from 0.5 to 0.6 with a few advanced engines as low as 0.45. With effective compressor-inlet Mach number in the range from 0.4 to 0.6, air flow handling capacities of the order of 20 to 35 pounds per second per square foot of compressor frontal area are obtained, the higher value being indicated for advanced engines.

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In order to progress to values of mass flow beyond approximately 35 pounds per second per square foot of compressor frontal area to take advantage of the theoretical potential increases available (of the order of 40 percent as indicated in fig. 4) in mass-flow handling capacity, a transition from the conventional subsonic axial-flow compressor to a transonic type compressor is required. In any case, to attain values of hub-tip ratios of 0.3 and effective inlet Mach numbers of 0.7 requires application of the transonic principle. Further increases in effective compressor-inlet Mach numbers beyond 0.7 or decreases below hub-tip ratio of 0.3 will yield small gains in air flow per unit of compressor (engine) frontal area even after the practical problems are solved. (See fig. 4.) None of the American or British engines presented in this report is equipped with a transonic compressor. If air flows of 36 to 40 pounds per second per square foot of compressor frontal area are realized in the future, then air flows of 30 to 35 pounds per second per square foot of engine frontal area will be obtained after engine compressor-casing thickness is taken into consideration.

For the 1961 "paper" engine, the value of air flow per unit of engine frontal area will, of course, depend upon the state of development of the compressor. The values mentioned above, if attained by 1961, will result in an engine diameter of approximately 60 to 65 inches to obtain the 55,000 pounds of thrust estimated for the 1961 engine. For the purposes of plotting the 1961 "paper" engine in all principal performance charts, a value of air flow per unit of engine frontal area of 35 pounds per second per square foot was chosen for this engine, resulting in an engine diameter of approximately 60 inches.

Plots of air flow per unit of engine frontal area and engine diameter as functions of time are presented in figures 5 and 6, respectively. From these curves, it appears that in the period of 1950 to 1955 the major portion of the increase in air flow will be due to the increase in

air flow per unit of engine frontal area; the diameter of most of the engines in this period will remain essentially constant. After this period, however, the rate of increase in air flow per unit of engine frontal area may be expected to diminish or reach a value beyond which further increases will be difficult and impractical, whereupon the major portion of increase in air flow will be accomplished by increasing engine diameter.

The engine thrust per unit of engine frontal area F/A is plotted against time in figure 7. This curve is of the same form as the curve for air flow per unit of engine frontal area plotted against time in figure 5 and will also begin to show a lower rate of increase after 1955 until a final value of F/A is attained. Theoretical values of F/A for various turbine-inlet gas temperatures up to 4000° R have been plotted in this figure to indicate future increases available. Calculations show that with a turbine-inlet gas temperature of 2000° R and burning to 4000° R in the afterburner, F/A is within 30 percent of the maximum possible value obtained when burning to 4000° R before the turbine for static sea-level conditions. Making the same comparison for a Mach number of 1.8 at 50,000 feet, however, indicates no gain in F/W or F/A in going to 4000° R gas temperatures at the turbine inlet. Burning in the afterburner under any condition of operation is less efficient than is burning prior to the turbine. For the conditions just mentioned, the specific fuel consumption is 1.7 pounds per pound thrust per hour without afterburning and with a 4000° R gas temperature at the turbine inlet. With the afterburner operating at 4000° R and turbine-inlet gas temperature at 2000° R, the specific fuel consumption is 2.2 pounds per pound thrust per hour, a 29 percent increase.

A composite plot of figures 5 and 7 is presented in figure 8 where the thrust per unit of engine frontal area is plotted against the air flow per unit of engine frontal area. The slope of this curve (pounds of thrust per pound of air) up to a turbine-inlet gas temperature of 2000° R is approximately equal to 65.0 pounds of thrust per pound of air. As this curve approaches the limiting value of air flow per unit of engine frontal area, further important increases in thrust per pound of air (or F/A of fig. 8) will be accomplished by increases in turbine-inlet gas temperature. Increases in component efficiencies will not effect important increases in pounds of thrust per pound of air as can be determined from reference 1. This is largely because component efficiencies are presently at a fairly high operating level. Theoretical values of maximum pounds of thrust per unit of engine frontal area are plotted in figure 8 for W/A equal to 35 pounds per second per square foot and for various inlet-gas temperatures at optimum pressure ratios up to and including 4000° R.

The weight per pound of engine thrust W_e/F as a function of time is plotted in figure 9. The data show a general downward trend. At any one time there is an appreciable scatter of the engine data. Because the

afterburner adds to the engine weight, the engines are plotted without afterburner weight included (fig. 9(a)) and with afterburner weight included (fig. 9(b)). In addition to figure 9, other plots such as W_e/F against F, F/W_e against specific fuel consumption, W_e/F against compressor pressure ratio, W_e/F against time, and W_e against time were made. These plots indicated no significant trends. Close inspection of the factors affecting engine weight reveals certain points worthy of mention. In comparing the differences between the American 150-hour qualification test and the British counterpart, the most significant difference is in the operating time at maximum power; the American engine is required to operate three times longer ($31\frac{1}{4}$ hr for the American as compared to $10\frac{1}{4}$ hr for the British) at maximum power than is required under the British acceptance test. Because operation at maximum power represents the most severe operating conditions of the test schedule due to the attendant elevated temperatures and high-stress conditions, the longer running time requires added strength. The British compressors are of aluminum construction rather than steel as is the case with American compressors. Further, American engines are equipped, as required by military specifications, with dual engine controls and other duplications of vital accessories, all added, of course, at the expense of engine weight.

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It is of interest to note now the effect of engine development on specific fuel consumption, engine compressor pressure ratio, and thrust per pound of air. The decrease in specific fuel consumption with time shown in figure 10 results mainly from the increase in pressure ratio with time, figure 11, that has accompanied engine development. Specific fuel consumption of the various engines as a function of compressor pressure ratio is presented in figure 12. The variation of thrust per pound of air with compressor pressure ratio is shown in figure 13.

The general trend of figure 11 indicating an increase in compressor pressure ratio with time does not necessarily mean it is advantageous to increase the pressure ratio of the compressor. In selecting compressor pressure ratio, the flight operating conditions must be considered. The effects of ram pressure, for example, resulting from flight speed and altitude operation, can indicate a need for lower compressor pressure ratios with increasing flight speeds. Effects of extended combat loiter times or subsonic flight over prolonged periods can indicate a need for higher pressure ratio compressors. Evaluations of these effects have been covered in many analyses and are beyond the scope of this report. It may be stated that high pressure ratios in a turbojet engine at increasing Mach number are not necessarily desirable and, in general, the higher the flight speed the lower the compressor pressure ratio for both optimum economy and maximum power.

CONCLUDING REMARKS

This report has presented in terms of basic engine parameters a compilation of static sea-level data on existing or designed American axial-flow turbojet engines and on existing British axial-flow turbojet engines. The data presented provide information that will assist in engine analyses, indicate certain operational requirements for research test facilities, and indicate areas in the engine development program requiring further emphasis. In the data presented, changes in the over-all engine performance with time are examined, as well as the relation of the various engine parameters to each other. The following general conclusions can be made: 2478

(1) Thrust: A linear relationship with time is indicated, with thrust being increased at the rate of approximately 4000 pounds per year. The afterburner has increased static sea-level thrust of the order of 45 to 50 percent. No information is available on afterburners for British engines. There is a considerable number of engines in the same thrust class at any one time.

(2) Air flow: The air-flow handling ability of the conventional axial-flow compressor, while steadily improving, is approaching a point of diminishing returns. To progress to higher air flow handling rates, application of the transonic principle to compressor design is indicated.

(3) Pressure ratio: A general trend of increasing pressure ratio with time is indicated. This trend does not necessarily mean that it is of over-all advantage to increase pressure ratio of the compressor.

(4) Specific fuel consumption: The general trend of decreasing static sea-level specific fuel consumption is largely a result of the trend toward increasing compressor pressure ratio.

(5) Weight and diameter: Engine specific weight is indicated to decrease with time. Other plots of weight parameters such as pound thrust per pound engine weight against thrust and specific fuel consumptions, pound engine weight per pound thrust against compressor pressure ratio and time, and engine weight against time indicated no significant trend. Engine diameters are expected to remain essentially constant (between 40 to 45 in.) in the time period of 1950 to 1955. Beyond 1955, engine diameters are expected to increase to a value of approximately 60 inches in 1961 to keep up with the thrust-increase trend.

APPENDIX - SYMBOLS

A engine frontal area, based on maximum engine diameter, sq ft

A_c compressor frontal area, sq ft

D maximum engine diameter, in.

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D_M compressor hub diameter, in.

D_T compressor tip diameter, in.

F engine thrust at sea-level static conditions; military rated value used unless otherwise specified, lb

W_a engine air flow rate, lb/sec; value used at military rated thrust conditions unless otherwise specified

W_e engine dry weight, lb. (In engine with afterburners, a total weight value is used which includes the afterburner weight)

η_b combustion efficiency equal to ideal fuel-air ratio required to obtain temperature rise in combustion chamber divided by actual fuel-air ratio; value used = 96 percent

η_c compressor adiabatic efficiency, that is, ideal power required in adiabatically compressing air from compressor-inlet total temperature and pressure to compressor-outlet total pressure divided by compressor shaft power; value used = 85 percent

η_t turbine total efficiency, that is, turbine-shaft power divided by ideal power of gas jet expanding adiabatically from turbine-inlet total pressure and temperature to turbine-outlet static pressure less kinetic power corresponding to average axial velocity of gas at turbine outlet; value used = 90 percent

M Mach number

SFC specific fuel consumption W_f/F, (lb fuel/hr)/lb thrust

REFERENCE

1. Pinkel, Benjamin, and Karp, Irving M.: A Thermodynamic Study of the Turbojet Engine. NACA TR 891.

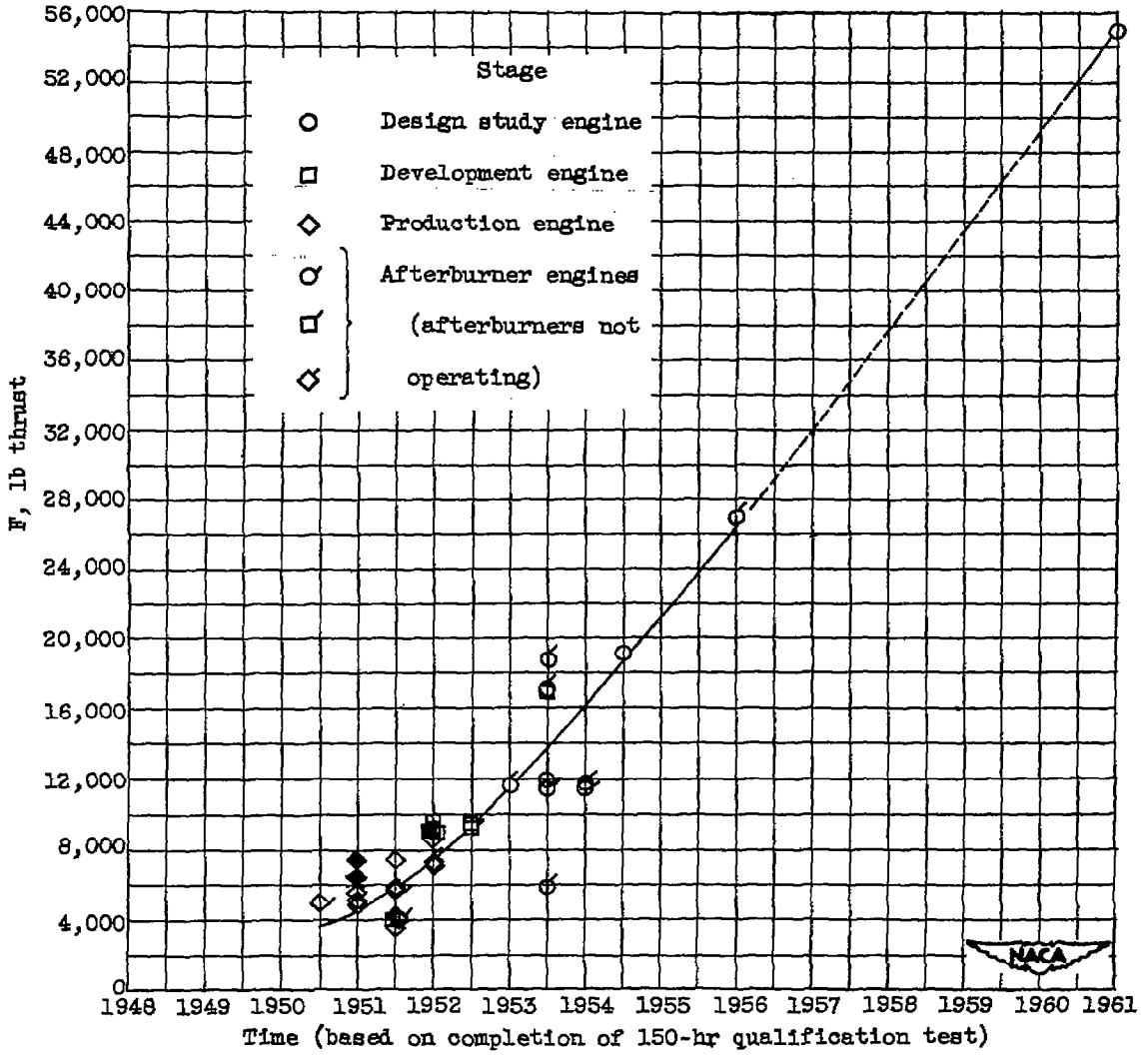

Figure 1. - Variation of engine thrust with time.

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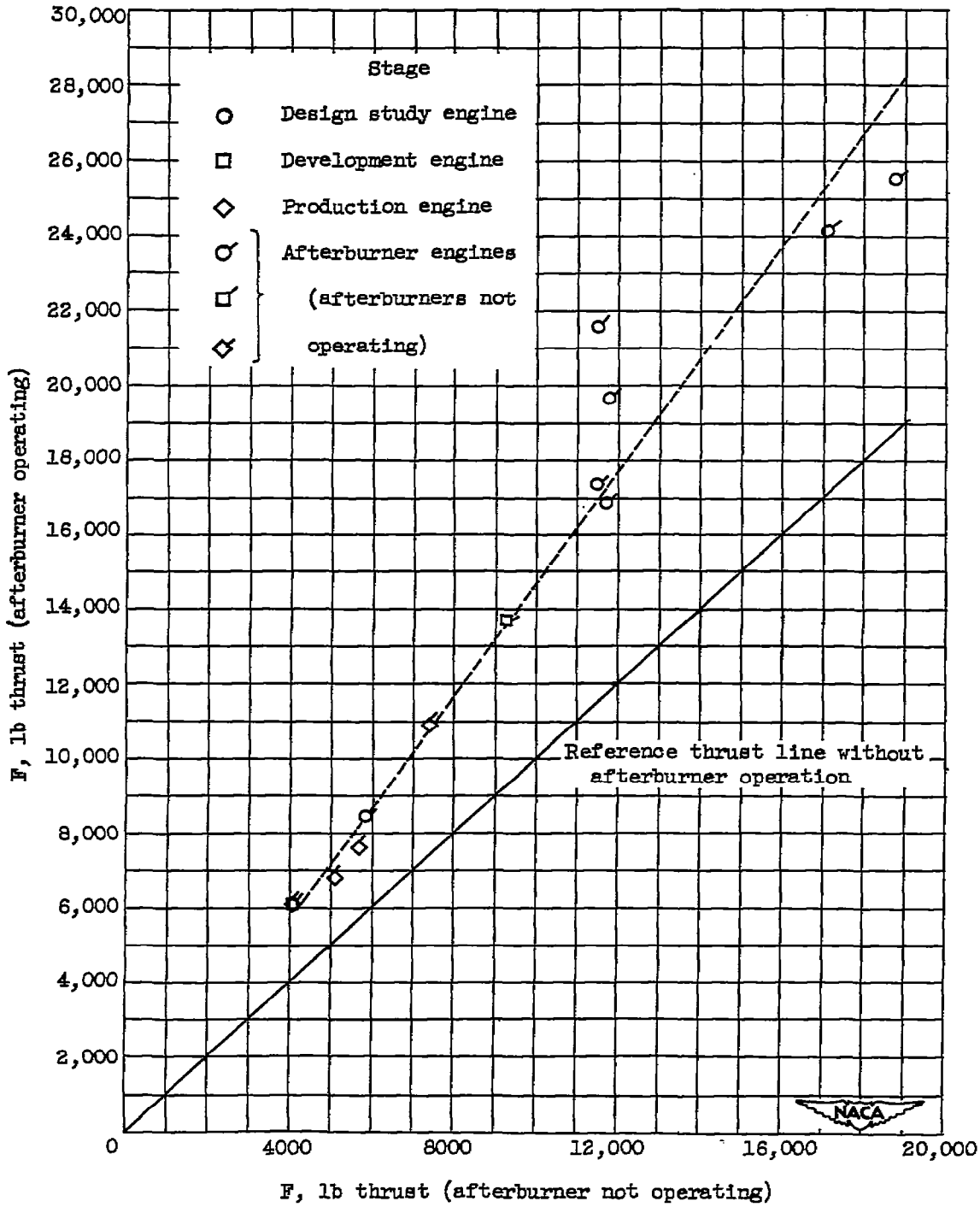

Figure 2. - Increase in static sea-level thrust with afterburner operation.

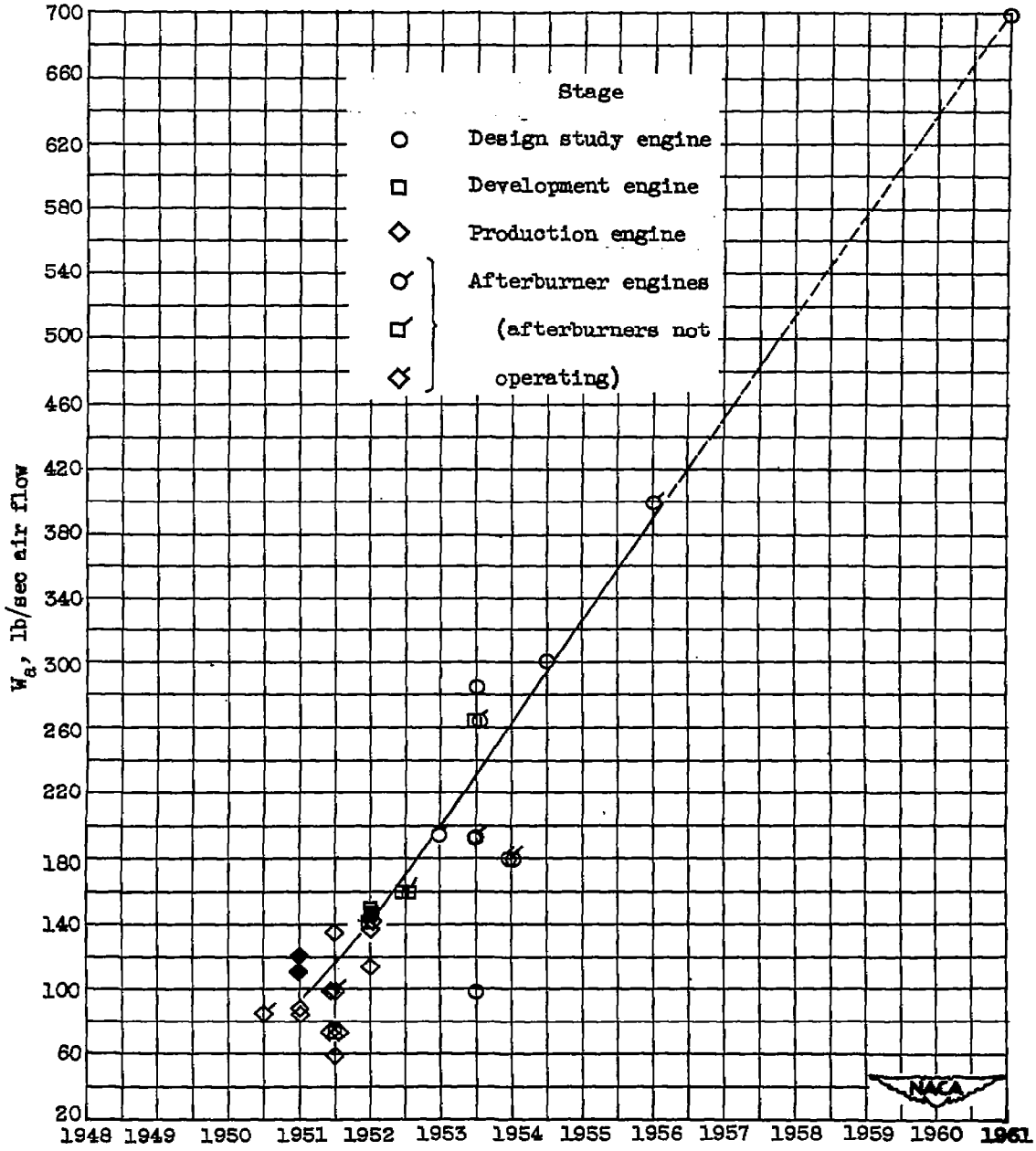

Figure 3. - Variation of engine mass flow with time.

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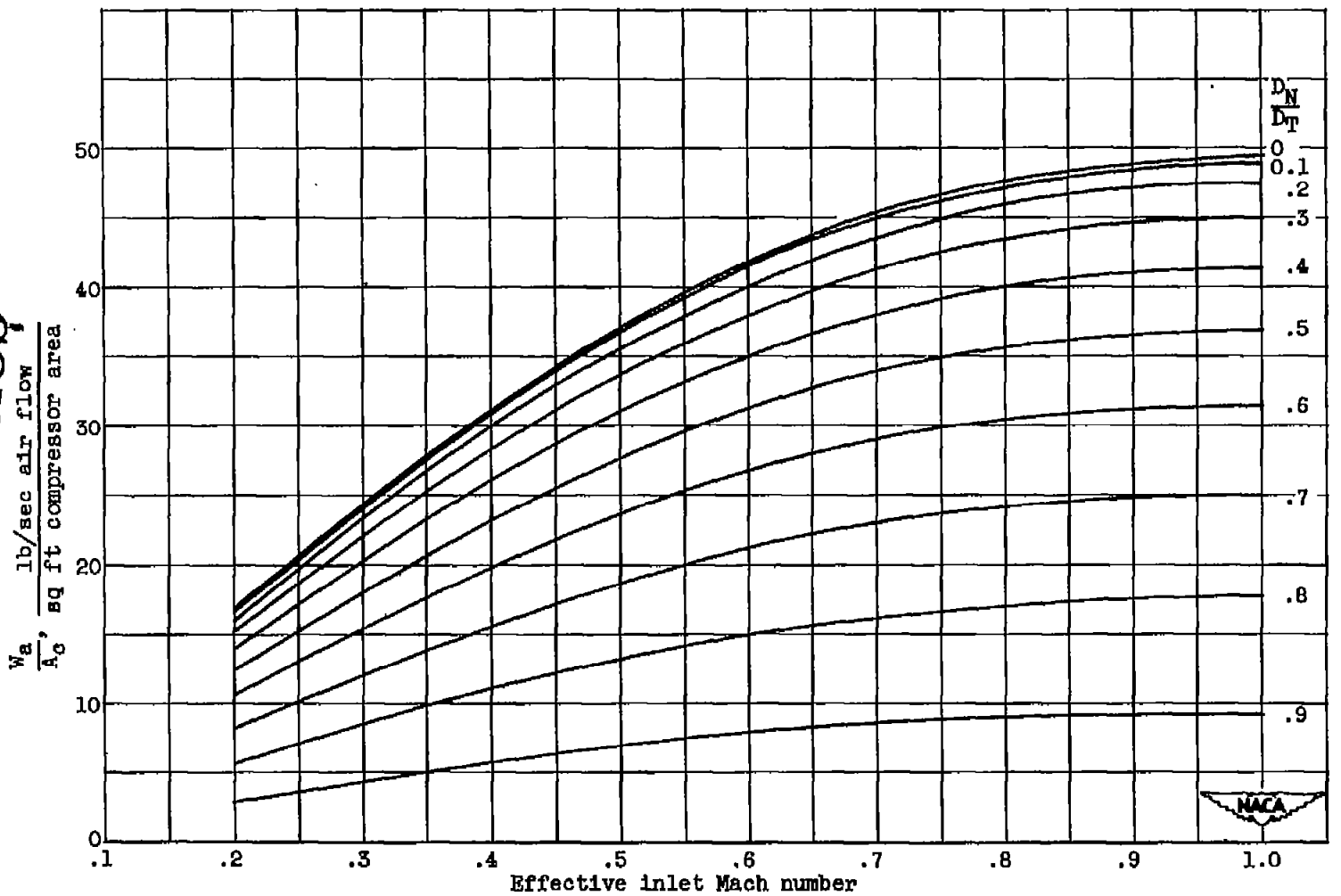

Figure 4. - Variation of air flow per unit compressor frontal area with effective inlet Mach number for constant hub-tip ratios.

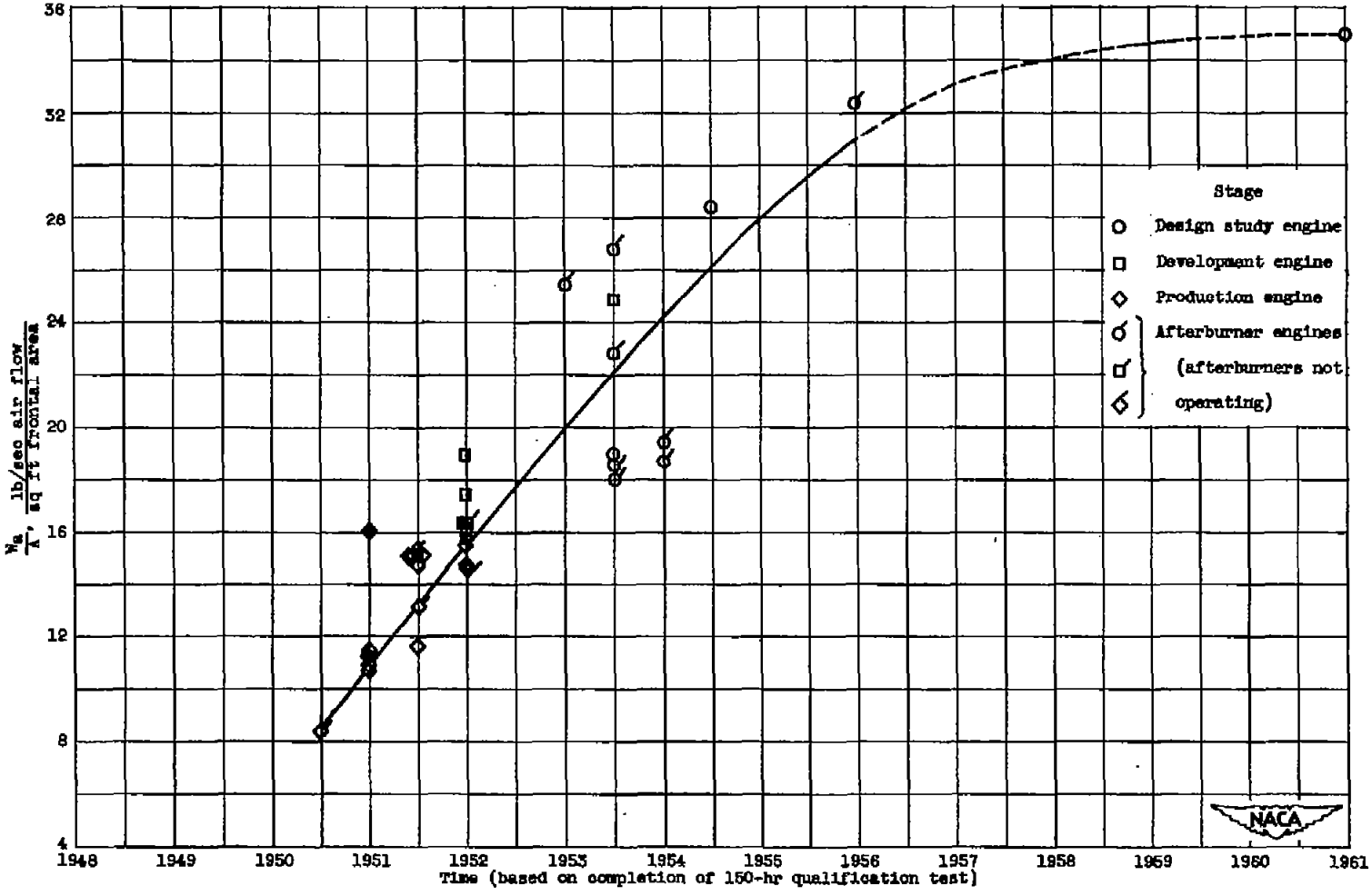

Figure 5. - Variation of engine mass-flow rate per unit engine frontal area with time.

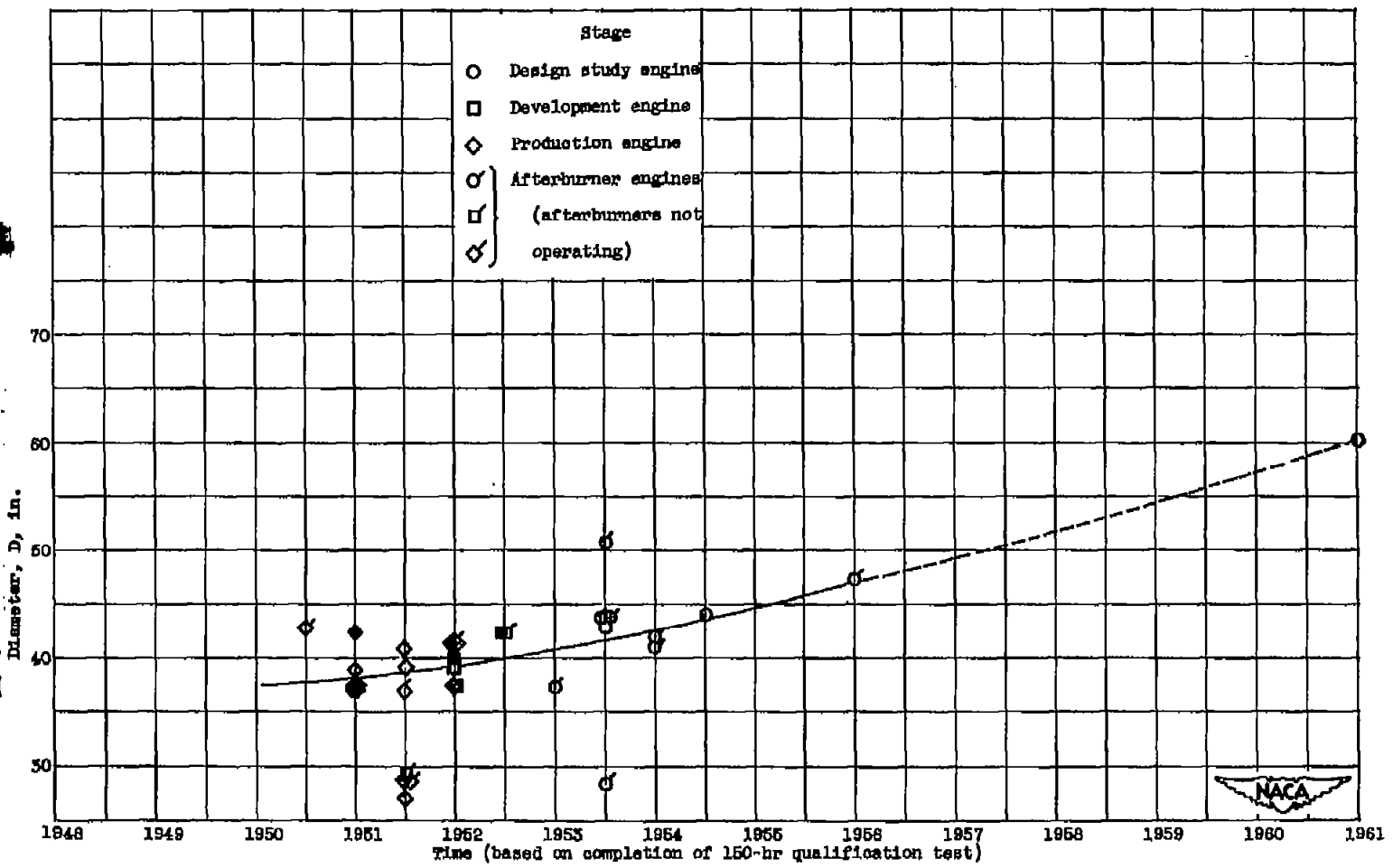

Figure 6. - Variation of engine diameter with time.

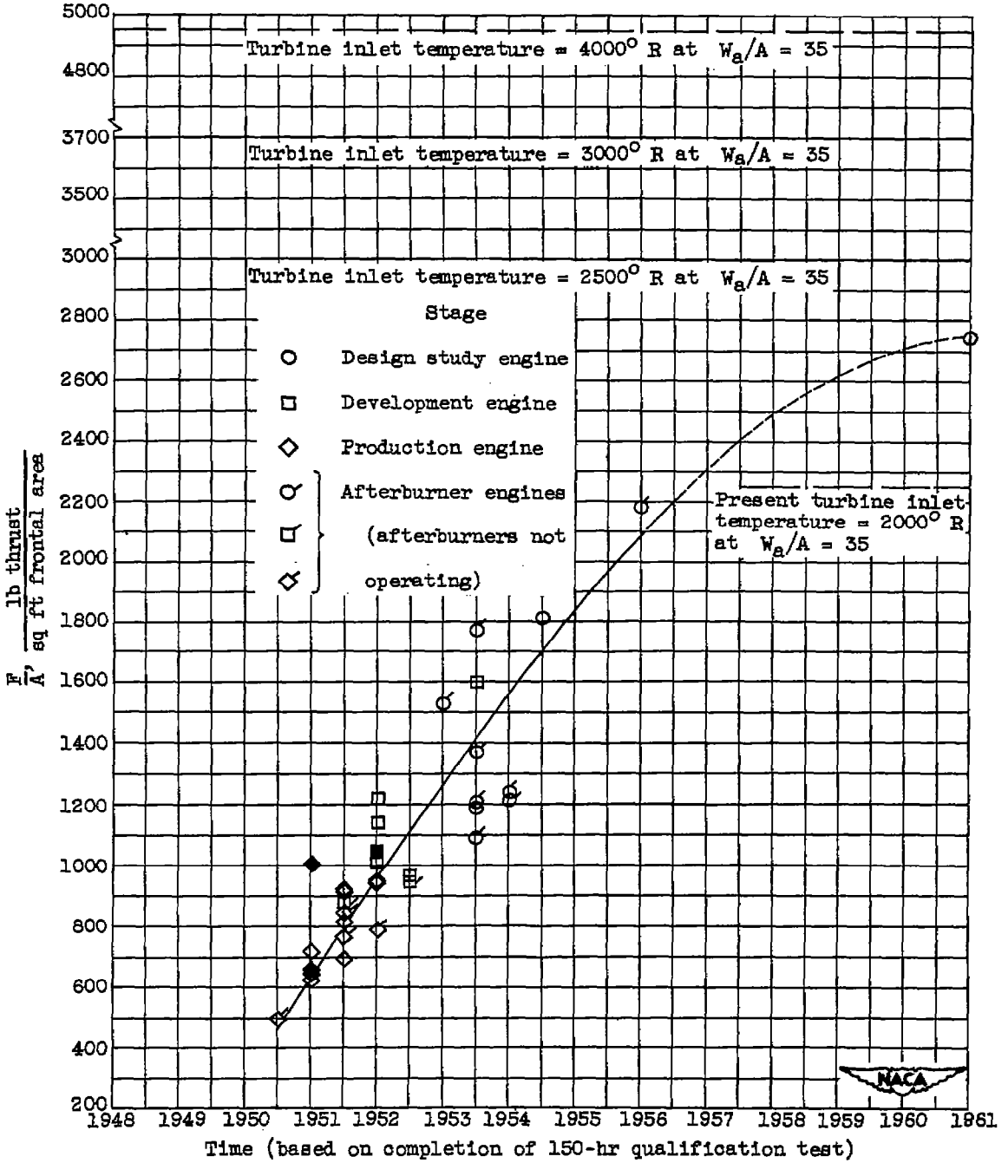

Figure 7. - Variation of engine thrust per unit engine frontal area with time.

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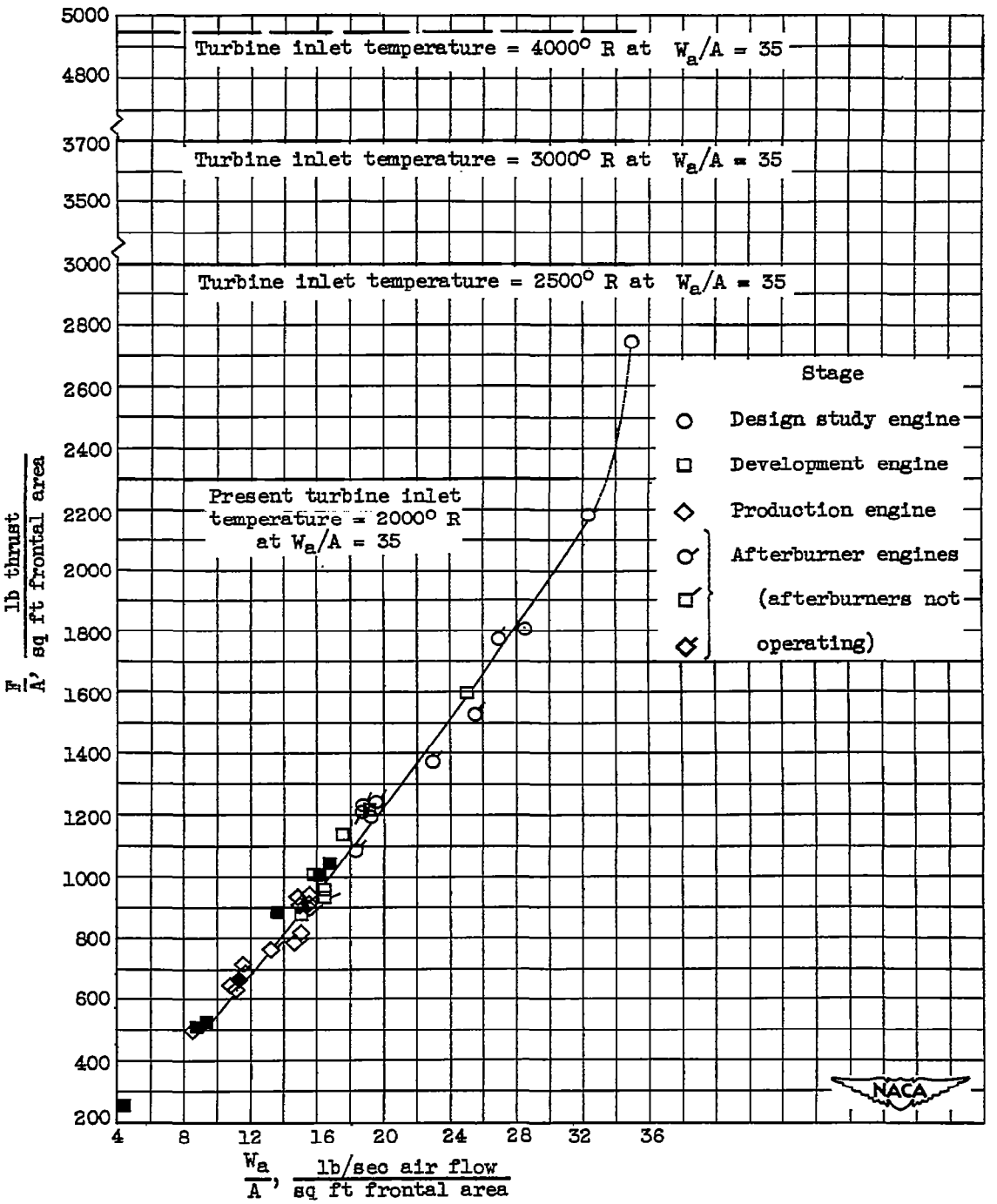

Figure 8. - Variation of thrust per unit engine frontal area with air flow per unit engine frontal area.

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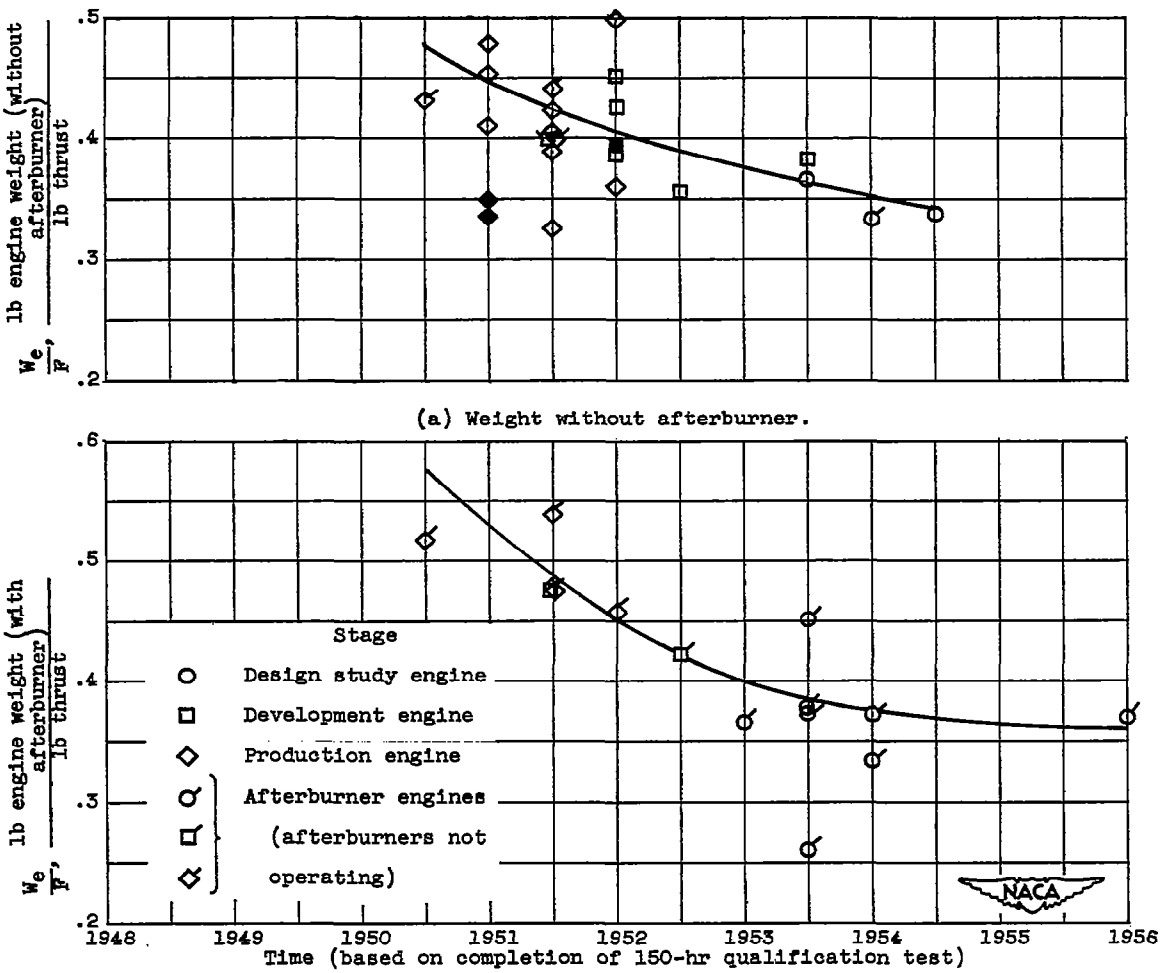

(b) Weight with afterburner.

Figure 9. - Variation of specific weight with time.

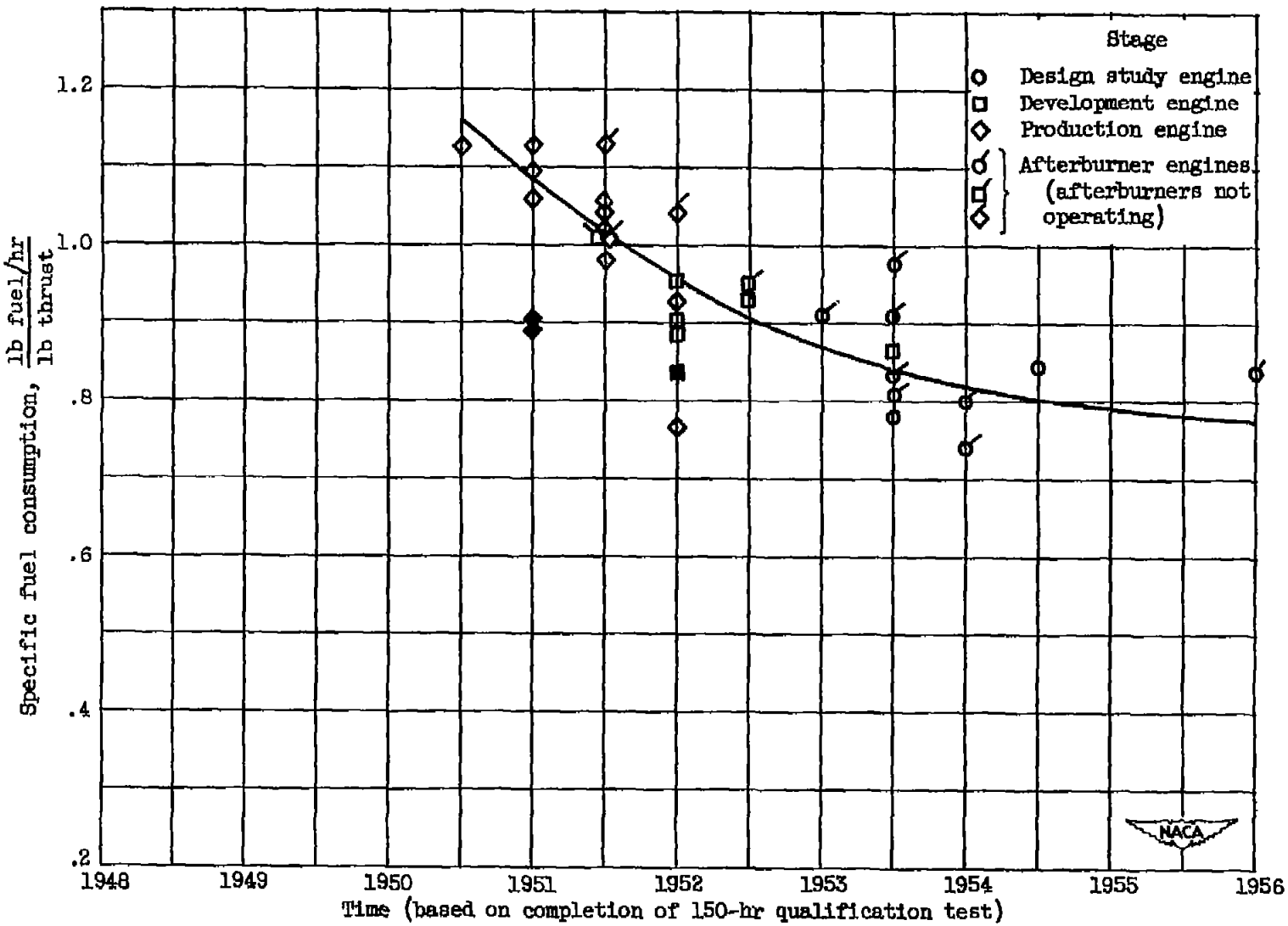

Figure 10. - Variation of specific fuel consumption with time.

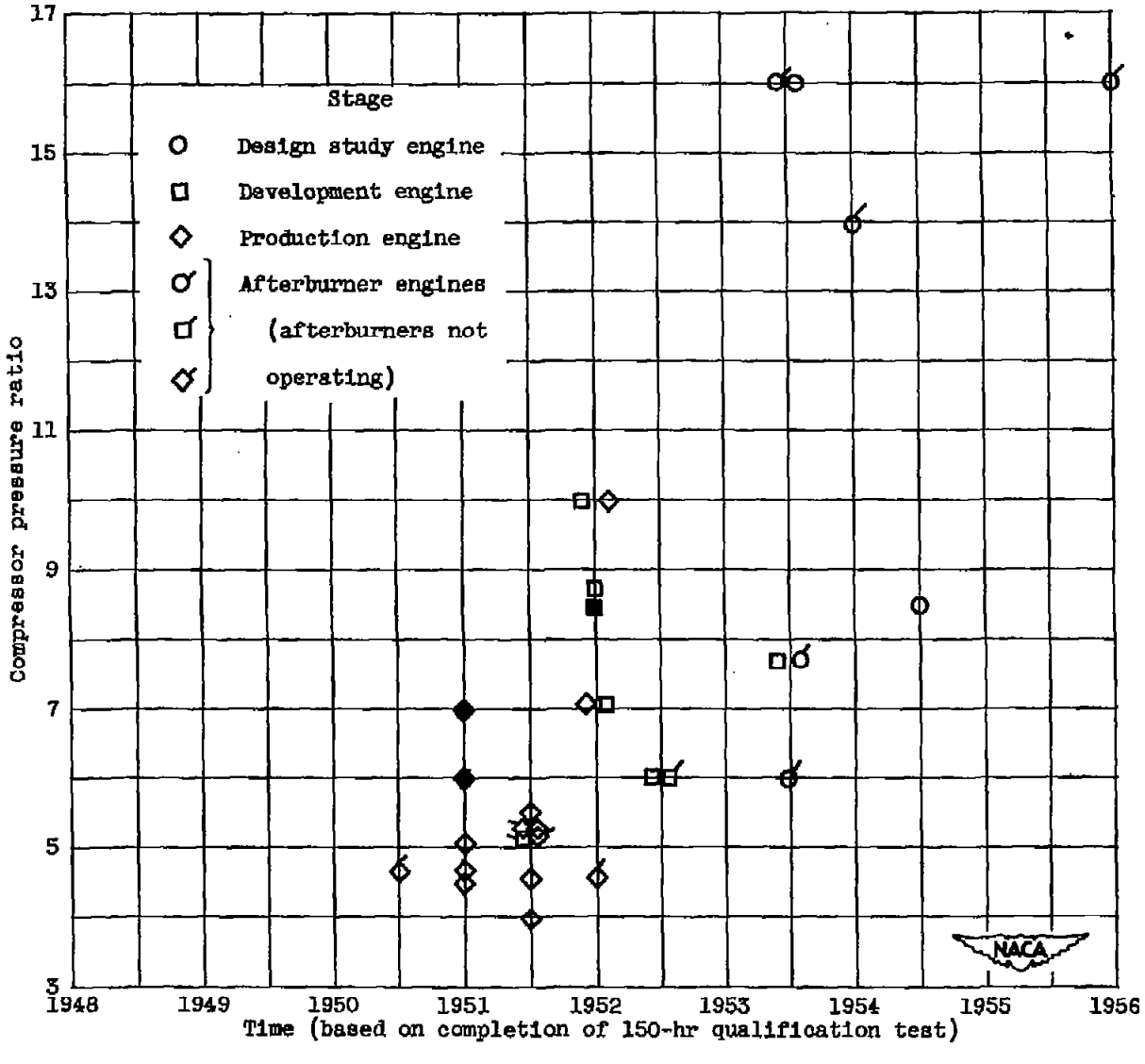

Figure 11. - Variation of compressor pressure ratio with time.

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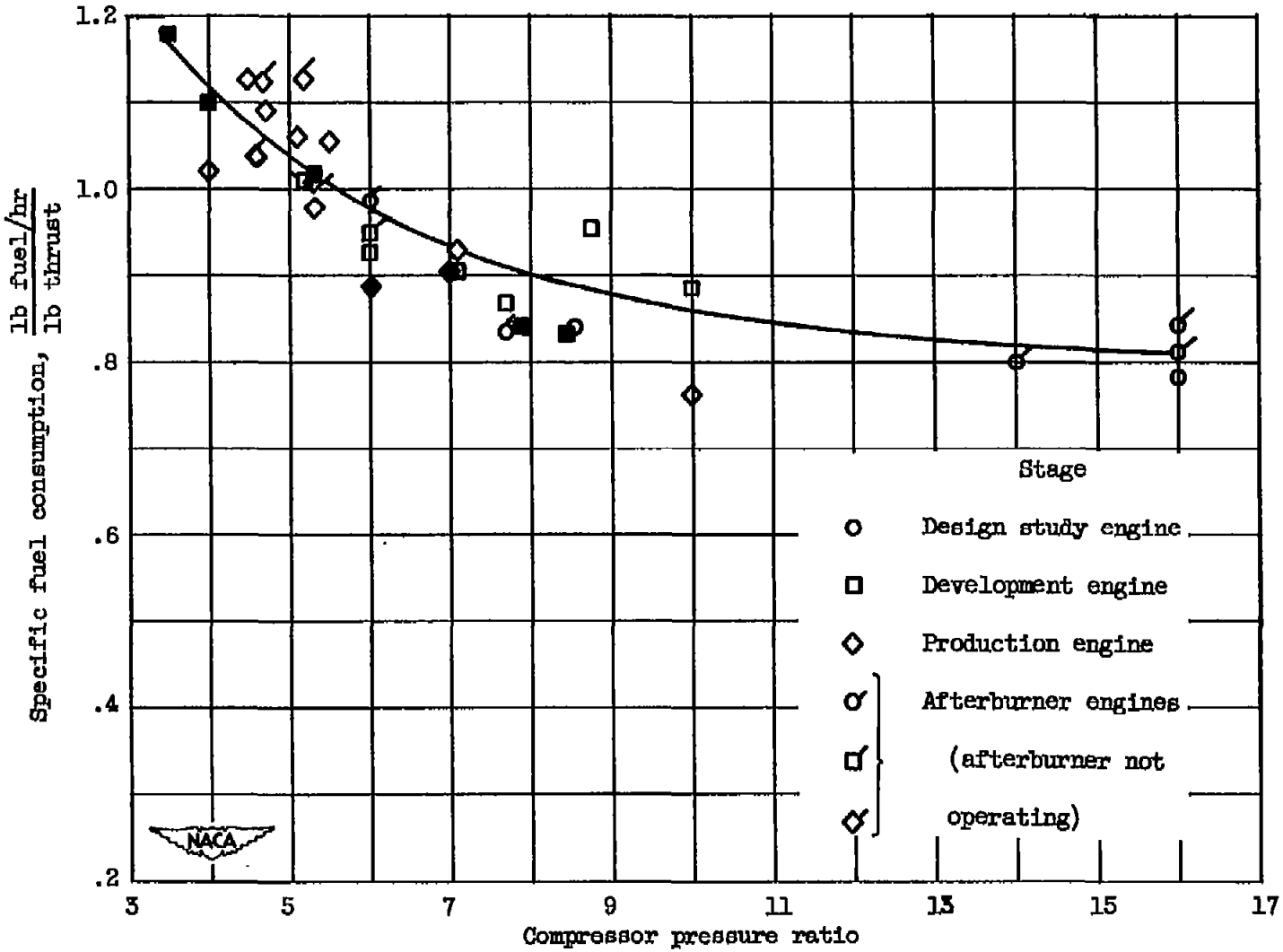

Figure 12. - Variation of specific fuel consumption with compressor pressure ratio.

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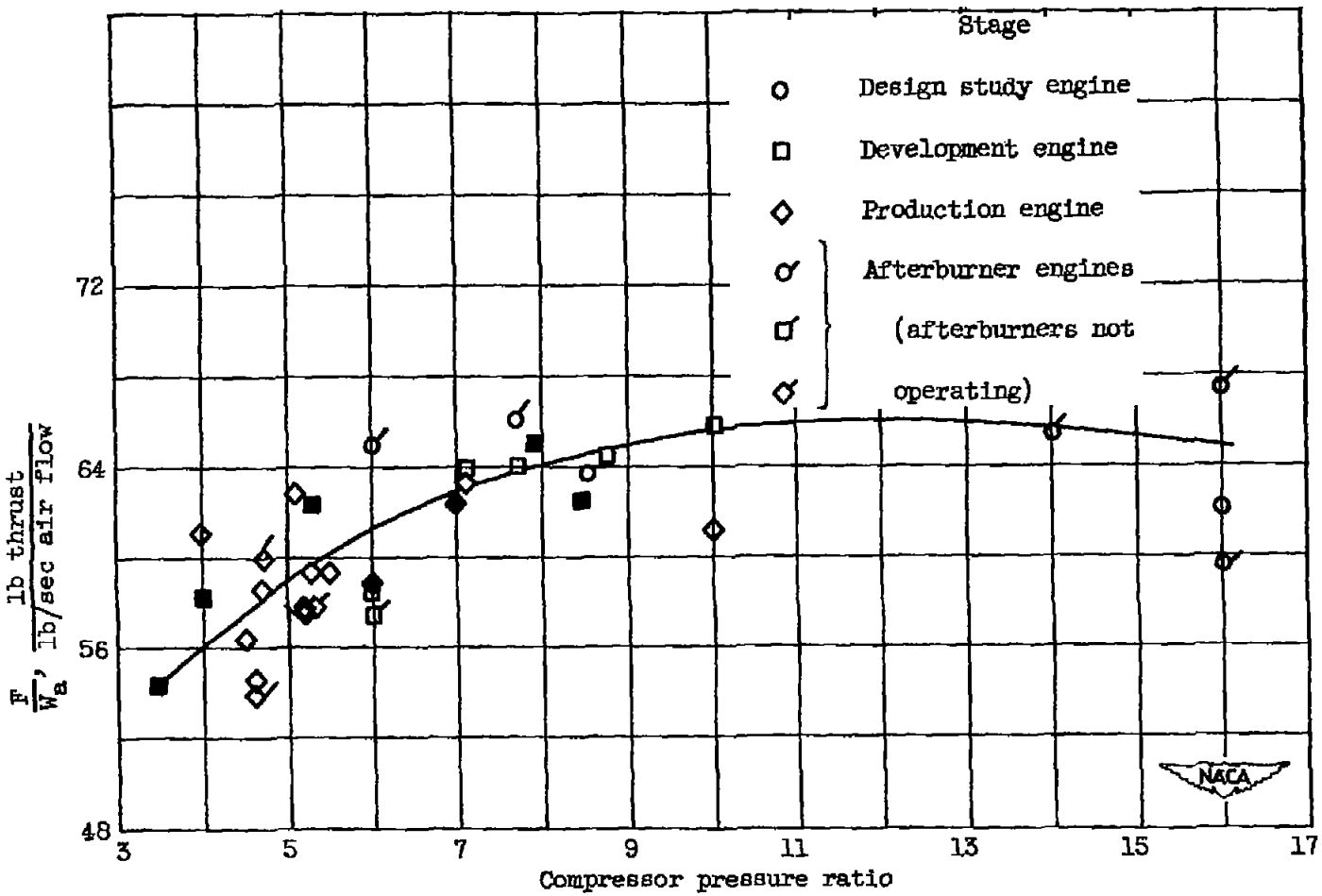

Figure 13. - Variation of thrust per air flow with compressor pressure ratio.

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